# INVESTIGATION OF THE FAIR WEATHER ELECTRIC FIELD IN THE ATMOSPHERE

by

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For Sheila

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# PREFACE

This thesis contains the results of research into aspects of fair weather atmospheric electricity. The work described here is the original work of the author, except where it is clearly indicated that such is not the case.

The first three chapters of the thesis deal with the historical development of the study of fair weather atmospheric electricity, the definitions of the terms and parameters involved, and the relationship between these parameters. It is also shown here how the classical global picture of atmospheric electricity evolved. Numerous quotations from original sources have been used in this part of the work, partly because of their inherent interest and partly because the sources themselves may not always be readily available. These quotations may be easily recognized since they are indented from the rest of the text and have been typed in italic script.

Chapters Four and Five outline the experimental investigations which form the subject of the thesis. This is done in the context both of the problems considered most important by the relevant scientific community, and of the past work done in South Africa. The instumentation, much of which is original, which was developed for the experimental work is also dealt with here.

Chapters Six, Seven and Eight deal with the results of the experimental investigations. The first of these three chapters is devoted to ground level measurements of potential gradients in the atmosphere. The second chapter deals primarily with space charge in the atmosphere, while the third is concerned with the atmospheric electric sunrise effect.

The final chapter contains a summary of the conclusions reached in the course of the work described here and also contains some suggestions regarding future work in this field.

The references quoted in the text are listed alphabetically in three categories at the back of the thesis. The three categories are: research journals, books and unpublished material.

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# Chapter One

## EARLY STUDIES OF ATMOSPHERIC ELECTRICITY

*Thunder is good, thunder is impressive; but it is lightning that does the work.*

Mark Twain (1835-1910)
Letter to an Unidentified Person

### 1.1 INTRODUCTION

The most familiar, and by far the most dramatic manifestation of electricity in the atmosphere is the lightning discharge. The lightning discharge (together with the thunderstorm that gives rise to it) form a convenient topic with which to divide the subject of atmospheric electricity into two sections. On the one hand there is the ionosphere and more remote regions of the upper atmosphere and their effect on the energy radiated from lightning, on the other hand there are the electrical properties of the atmosphere much closer to the Earth's surface. These properties range from electrically quiet conditions to the thunderstorm as the extreme of electrically disturbed conditions. The first of these two major divisions is most properly regarded as constituting the subject called 'space electricity', while the second, called 'atmospheric electricity' will be restricted to mean the electrical properties of, and phenomena which occur in, the atmosphere between the ground and the lower ionosphere.

The ionosphere, or electrified region of the upper atmosphere has been chosen as the boundary between the topics of space electricity and atmospheric electricity. While this region is itself extensively studied by both physicists and electrical engineers it will receive some attention here because of its importance to atmospheric electricity as the subject is defined here.

The subject of atmospheric electricity may be further subdivided into two sections. These are the phenomena associated with electrically disturbed conditions, and those associated with quiet, or non-stormy, conditions. It is the latter which are mainly of concern in this work.

## 1.2 THE BACKGROUND

It is interesting to speculate on the importance to man of electricity in the atmosphere. Clearly the thunderstorm has been known, and the damage caused by lightning recognized, since before the time of recorded history. Lightning and thunder play an important part in both Greek and Norse mythology, and legends on this subject exist among some of the most primitive people. An interesting account of some of these has been given by SCHONLAND (1964 pp 1-15).

It is possible that an intense form of lightning was at one time responsible for the origins of animal life on this planet. It may be that the atmosphere, which is of course vital to the continuation of life on Earth, was once - in a very different form - the environment in which life was first generated through the agency of electricity. These intriguing possibilities were suggested by an experiment conducted in America by MILLER (1953). It was assumed that 2000 to 3000 million years ago the primordial atmosphere consisted of methane, ammonia, hydrogen and water vapour; and that intense and active lightning storms occurred in this atmosphere. Proceeding from this hypothesis, Miller passed a mixture of these gases over a constantly sparking electric arc. After eight days of circulating over the artificial lightning Miller's 'primordial atmosphere' was found to contain a few milligrams of organic substances. The most interesting fact was that some of these substances belonged to the group of amino-acids from which living matter is built up. In this context, too, it is interesting to note that SCHONLAND (1964 p 176) mentions the possible evidence of lightning on the planet Jupiter, which is thought to have an atmosphere somewhat similar to, although much colder than, the mixture of gases used by Miller.

In order to properly consider the early history of atmospheric electricity, it is necessary to consider the early history of electricity. This early history of the study of electricity is dealt with very briefly, if at all, in the various works on atmospheric electricity and consequently some time will be devoted to this interesting subject here. The early studies and theories concerning electricity will be discussed, and the development of the subject of atmospheric electricity will be followed up to the work performed by Kelvin, a little over a century ago.

## 1.3 THE EARLY HISTORY

The following words, attributed to Milton by GREENWOOD (1931), describe in a delightful way the fate of Phaethon, the son of Helios in Greek mythology.

*Him the thunderer hurled*
*From the empyrean headlong to the gulf*
*Of the half parched Eridanus, where weep*
*Even now the sister trees their amber tears*
*O'er Phaethon, untimely dead.*

According to GRAVES (1955), Helios once yielded to the constant pleading of his son Phaethon, and allowed Phaethon to drive the sun chariot. Phaethon, unable to control the horses, drove first so high that the Earth became very cold, and then so low that he scorched the fields. Zeus, in a fit of rage, killed him with a thunderbolt, and he fell into the Eridanus (probably the River Po). Phaethon's sisters, the Heliades, lamented his fate and, while weeping on the river bank, were changed into trees. The tears continued to fall from these trees and, hardened by the sun, they dropped into the water and became amber. Amber (it is sometimes called the tears of the Heliades) is in fact the resin of an extinct species of pine tree which has been fossilized as a result of long submersion in the sea, thus being transformed into a gemstone.

Amber was the most important gemstone in the ancient civilised world, and often fetched prices exceeding those of diamonds. The peculiar property exhibited by amber of attracting other substances to itself when excited by friction was known to the ancient Greeks. It is possible that this phenomenon had exercised the minds of the early Greek philosophers, such as Thales, who lived in the sixth century B.C.

If this phenomenon was studied further in order to try to understand it, then no record of such study survives. As this is most unlikely in view of other records from the same period, one is forced to conclude that no such further study was carried out. There could be several reasons for this; the social, political and religious pressures of the time were not conducive to pure philosophizing, and the many large scale wars would tend to divert effort from philosophical to more practical channels. Whatever the reason, the fact remains that there is very little mention made in scientific work of electrical phenomena between 600 B.C. and about 1600 A.D. This is despite the fact that Roger Bacon (1214 - 1292) and Leonardo da Vinci (1452 - 1519) both lived during this period.

Dr. William Gilbert (1544 - 1603), physician to Queen Elizabeth I of England, is generally regarded as the founder of electrical science. It was Gilbert who discovered that other substances (e.g. glass, sulphur) when they were rubbed exhibited the same property as amber of attracting other bodies. In 1600 he published his work in book form, and Book II of this work contains the experiments on electricity. In 1665 von Guericke constructed a device which produced an electric spark, a spark so weak that it was only visible in the dark and which could only be heard with difficulty. Whether von Guericke recognized his laboratory spark as being similar to lightning is not recorded, and we must assume that this similarity was not recognized.

Ten years later, NEWTON (1675) showed that glass could be used in place of the sphere of sulphur in von Guericke's machine. Newton described the results as follows:

> *So also a Globe of Glass about 8 or 10 Inches in diameter being put into a Frame where it may be swiftly turn'd round its Axis, will in turning shine where it rubs against the palm of ones Hand apply'd to it: And if at the same time a piece of white Paper or white Cloth, or the end of ones Finger be held at the distance of about a quarter of an*

> *Inch or half an Inch from that part of the Glass where it is most in motion, the electrick Vapour which is excited by the friction of the Glass against the Hand, will by dashing against the white Paper, Cloth or Finger, be put into such an agitation as to emit Light, and make the white Paper, Cloth or Finger appear lucid like a Glow-worm; and in rushing out of the Glass will sometimes push against the Finger so as to be felt. And the same things have been found by a long and large Cylinder of Glass or Amber with a Paper held in ones Hand, and continuing the friction till the Glass grew warm.*

The above seems to be the first published account of the glow discharge.

Robert Boyle, in 1675, wrote a book called 'Experiments, notes, etc. about the mechanical origine or production of divers particular qualities' in which he describes some electrical experiments, mostly involving the attraction or repulsion between charged bodies. In 1705 the first well defined sparks were produced in the laboratory by another Englishman, Francis Hauksbee, using a more sophisticated machine built along similar lines to that of Newton. Until this time there is still no record of the lightning discharge being identified with the laboratory spark. This identification was first made by WALL (1708).

Dr. William Wall, an English clergyman, was a friend of Robert Boyle. He was interested in the fluorescence or phosphorescence of compounds distilled from human urine, and in the work which stemmed from this he investigated the 'luminant qualities' of various other substances. It is worth quoting here his own description of some of his work.

> *....I fell to make many Experiments on it and at last found, that by gently rubbing a well polished piece of Amber with my Hand in the dark, which was the Head of my Cane, it produc'd a Light; whereupon I got a pretty large piece of Amber which*

*I caused to be made long and taper, and drawing it gently thro' my Hand, being very dry, it afforded a considerable Light. I then us'd many Kinds of soft Animal Substances, and found that none did so well as that of Wool. And now new Phenomena offered themselves; for upon drawing the piece of Amber swiftly thro' the Woollen Cloth, and squeezing it pretty hard with my Hand, a prodigeous number of little Cracklings were heard, and every one of these produc'd a little flash of light..........Now I make no question but upon using a longer and larger piece of Amber, both the Cracklings and the light would be much greater, because I have never yet found any Crackling from the Head of my Cane, altho' tis a pretty large one; and it seems, in some degree, to represent Thunder and Lightning.*

This, as far as can be told, was the first suggestion of the similarity between lightning and the laboratory spark. The same suggestion was also made by GRAY (1736), an active investigator of electrical phenomena. In a series of three papers, the last one communicated verbally to Cromwell Mortimer M.D., the secretary of the Royal Society, on the day before Gray's death, he describes a number of electrical experiments. These indicate that he had established the principles of electrical conduction and insulation, and the first of these three papers indicates that he had discovered the phenomenon of point discharge. The following quotation is the closing paragraph of this first paper, in which the similarity between the sparks and lightning is suggested:

*By these Experiments we see, than an actual Flame of Fire, together with an Explosion, and an Ebullition of cold Water, may be produced by communicative Electricity; and altho' these Effects are present but in minimis, it is probable, in Time there may be found out a Way to collect a greater Quantity of it; and consequently to increase the Force of this Electrick Fire, which, by several of these Experiments seems to be of the same Nature as that of Thunder and Lightning.*

that

> *.... the knowledge of this power of points be of use to mankind, in preserving houses, churches, ships, etc., from the stroke of lightning, by directing us to fix on the highest parts of these edifices, upright rods of iron made sharp as a needle........*

He then went on to propose an experiment, which later became known as the Philadelphia experiment, to test whether or not thunderclouds were charged.

> *To determine the question whether the clouds that contain lightning are electrified or not, I would propose an experiment to be tried where it may be done conveniently. On top of some high tower or steeple, place a kind of sentry box big enough to contain a man and an electrical stand. From the middle of the stand let an iron rod rise and pass out of the door, and then upright twenty or thirty feet, pointed very sharp at the end.......the rod drawing fire to him from the cloud.*

Of course Franklin's famous kite experiment is well known, but it is of interest to recount it in his own words as written in a letter to his friend Collinson in London in 1752 (MILLER, 1939 pp 84-85; GREENWOOD, 1931 pp 76-77).

> *As frequent mention is made in public papers from Europe of the success of the Philadelphia experiment of drawing the electric fire from clouds by means of pointed rods of iron erected on high buildings, etc., it may be agreeable to the curious to be informed that the same experiment has succeeded in Philadelphia, though made in a different and more easy manner, which is as follows.*

*Make a small cross of two light strips of cedar, the arms so long as to reach to the four corners of a large thin silk handkerchief when extended. Tie the corners of the handkerchief to the extremities of the cross, so you have the body of a kite which, being properly accommodated with a tail, loop and string, will rise in the air like those made of paper; but this being made of silk, is fitted to bear the wet and wind of a thundergust without tearing. To the top of the upright stick of the cross is to be fixed a very sharp pointed wire, rising a foot or more above the wood. On the end of the twine, next to the hand, is to be held a silk ribbon, and where the silk and twine join a key may be fastened. This kite is to be raised when a thundergust appears to be coming on, and the person who holds the string must stand within a door or window, or under some cover, so that the silk ribbon may not be wet, and care must be taken that the twine does not touch the frame of the door or window. As soon as any of the thunderclouds come over the kite, the pointed wire will draw the electric fire from them, and the kite with all the twine will be electrified, and the loose filaments of the twine will stand out every way and be attracted by an approaching finger. And when the rain has wetted the kite so that it can conduct the electric fire freely, you will find it stream out plentifully from the key on the approach of your knuckle. At this key, the phial* (Leyden Jar) *may be charged, and from electric fire thus obtained spirits may be kindled, and all the other electric experiments be performed which are usually done by the help of a rubber, glass globe, or tube and whereby the sameness of the electric matter with that of lightning completely demonstrated.*

Fair Weather Electricity

Franklin's original suggestion of collecting electricity from thunderclouds by means of a point on a high tower or steeple was in fact first carried out in France. The most likely reason for this was the lack of a convenient tower or steeple in Philadelphia. CHALMERS (1967 p 2) states that this so called Philadelphia experiment was first conducted by T.F. d'Alibard in 1752 near Paris. d'Alibard's method depended on the observations of sparks in a spark gap at the top of a tall pole. A more sensitive method of detecting electrification was devised in the same year by Lemonnier. He set up a wooden rod with a pointed iron rod fixed to the top. An iron wire led from the iron rod into a building, without touching anything, where it was joined to a stretched silk fibre. Lemonnier found that dust particles were attracted to the iron wire when electrified. This method was much more sensitive than that of observation of sparks, and showed electrification which was not of sufficient strength to cause sparking. In this way Lemonnier first observed that electrification could exist even in fine weather. At about the same time (1753) de Romas, in an independent experiment, detected the presence of electrical effects under fair weather conditions. (It is of interest to note that IMYANITOV (1962) credits two Russians, LOMONOSOV and G.V. RIKHMAN with the discovery of the existence of an electric field in the absence of clouds. Most writers credit Lemonnier with this discovery. The Rikhman referred to here is the same G.W. Richmann referred to by UMAN (1971 p 3) as a Swede, working in Russia, who was killed by a direct lightning stroke to to a rod in 1753).

The Italian G.P. Beccaria (1775) found a diurnal variation in the electricity of the atmosphere under fair weather conditions. This finding was the result of experiments (using a stretched horizontal wire above the ground instead of a raised point) carried out over a 20 year period. Beccaria, too, first applied the concept of there being two kinds of electricity to electricity in the atmosphere. He showed that while the horizontal wire received a charge which varied both in sign and in magnitude under stormy conditions, under fair weather conditions it generally acquired a positive charge.

New and improved methods of measurement were devised and used by de Saussure between 1766 and 1785 (see CHALMERS, 1967 pp 4-6 and GISH, 1939 pp 149-230). He devised one of the first, if not the first, electrometers using balls of elder pith suspended on fine silver wires. The method used involved a conductor connected by wire to the electrometer. The conductor was first earthed then quickly raised to about 1 metre above the Earth. The resultant deflection of the electrometer was found to be proportional to the electric field strength. Using this method de Saussure also discovered that the conductor received no charge from outside the system, since when the raised conductor was lowered the deflection of the electroscope disappeared. de Saussure confirmed the diurnal variation in field strength first detected by Beccaria and in addition he detected a seasonal variation in field strength.

At this time it was considered that the phenomena of atmospheric electricity could be explained by supposing that the air carried a positive charge which increased with altitude. This view was championed by Volta, who postulated that the effects were due to electrical separation of charge which accompanies the change of state of water from liquid to vapour. This was in spite of the fact that in his work with LaPlace and Lavosier in Paris in 1781 Volta had failed to discover such charge separation. Volta did not use a sharp point as a 'collector', but instead used a small lighted candle or burning fuse placed at the top of an insulated rod which was set vertically in the electric field and which was connected to the electroscope. This method adopted by Volta stemmed from an observation made by Franklin in the year of Volta's birth. Franklin had noticed that a flame or incandescent solid had the property of discharging electrified bodies when brought close to such bodies. The type of collector which used the burning fuse or candle responded more rapidly to field changes and gave greater accuracy than did a point.

Other important experiments were conducted in 1785 by Coulomb who, after experimenting with charged bodies exposed in air, concluded that the air is not a perfect insulator and that electric charge may be dissipated through it. Coulomb stated that the charge on an isolated body diminished in geometrical progression as the time increased in arithmetical progression. More conventionally this may be expressed as

$$\frac{dQ}{dt} = -kQ$$

where Q represents the quantity of charge on a body at time t and k is known as the coefficient of dissipation. This important discovery of Coulomb's received little attention in the field of atmospheric electricity for more than a hundred years.

The idea that the phenomena of atmospheric electricity could be accounted for by the Earth being negatively charged instead of the air carrying positive charge was first postulated by Paul Erman in Germany in 1804.

Peltier in 1842 confirmed and extended the ideas of Erman, proposing that there was an original permanent negative charge on the Earth, and attempting to explain the observed variations in the field in terms of some of this charge being carried away by water vapour. He made no attempt to account for the long term effect of the loss of charge. In spite of the work of Erman and Peltier, the original charge distribution theory continued to be considered as the most likely explanation until the publication of the work of William Thomson clarified the situation.

## The work of Kelvin and the concept of space charge

Virtually no work of any importance was done in England on the subject of atmospheric electricity from the time of Gray (1736) until the work of William Thomson about a hundred years later. It was suggested by his biographer, THOMPSON (1910), that William Thomson, later Baron Kelvin of Largs, had his interest in atmospheric electricity stimulated by a visit to a German by the name of Dellmann. In fact, with the help of Joule, Kelvin had already conducted various experiments in atmospheric electricity. Certainly he appeared to have been impressed with Dellmann's work, in particular with the electrometer made by Dellmann. He reported at the meeting of the British Association for the Advancement of Science in 1856 (THOMSON, 1856) as follows:

> *The electrometer used by Mr. Dellmann is of his own construction, and it appears to be very satisfactory in its operation. It is, I believe, essentially more accurate and sensitive than Peltier's .......*

In July, 1856, he wrote in a letter to his brother James Thomson of his visit to Dellmann in Germany

> *There is almost always an effect of one kind (indicating a negative electrification of the Earth's surface), but when the sky is much overcast, little or none. Detached clouds often alter the quality of the effect quickly, and give a great amount of reverse effect, and the first drops of a shower generally do so.*

One of Kelvin's most important contributions to the study of atmospheric electricity was the initiation of regular observations at the Kew meteorological observatory. He also developed a water-dropper potential equalizer which he described in a letter to Helmholtz in 1859, and in detail to the meeting of the British Association in that year (THOMSON, 1859). In this report it is also apparent that Kelvin clearly established the importance of having a quantitative estimation of the potential gradient at a point; together with the concept of a negative charge residing on the Earth while the air carries a positive charge. The following extract is quoted from this report:

> *The author gave the result of a determination which he had made, with the assistance of Mr Joule, on the Links ...............*
> *........... The result showed a difference of potentials between the Earth (negative) and the air (positive).........*
> *...... equal to that of 115 elements of Daniel's battery, and, therefore, at that time and place the aerial electromotive force per foot amounted to that of thirty-eight Daniel's cells* (This is equivalent to about 130 $V\ m^{-1}$).

In the following year, at the B.A. meeting held in Oxford (THOMSON, 1860a) Kelvin describes experiments which he carried out to compare values of the potential gradient obtained simultaneously at two different places. He accounted for the results he obtained in terms of local concentrations of electrification of the air, thus introducing the important concept of space charge. This idea was further developed in the discussion of negative charge in the atmosphere, and in the following extract from his report to this meeting of the B.A.

> *I have repeatedly observed the electric potential in the neighbourhood of a locomotive engine, at work on a railway, sometimes by holding the portable electrometer out of a window of one of the carriages of the train, sometimes by using it while standing on the engine itself, and sometimes while standing on the ground beside the line. I have thus obtained consistent results, to the effect that the steam from the funnel was always negative, and the steam from the safety valve always positive. .....I have found strong negative indications in the air after an engine had disappeared round a curve, and its cloud of steam had dissolved out of sight.*

In this work Kelvin also referred to changes in the electric field associated with lightning discharges. In an attempt to explain certain negative fields observed, Kelvin concluded that the lowest layers of the atmosphere contained negative charges, while at higher levels the charge remained positive. A similar effect was found at the Eiffel Tower by Chauveau in 1900. CHALMERS (1967 p 9) states that this effect, called the Kelvin-Chauveau effect by COLLIN, RAISBECK and CHALMERS (1963), has not yet received any satisfactory explanation.

Finally it is worth noting that Kelvin should be credited with having made the first suggestion of the existence of a conducting region in the upper atmosphere (the ionosphere) although this credit is normally accorded to Balfour Stewart who suggested in 1878 that such a region existed, probably at a height of 5-10 miles. Kelvin made his suggestion in 1860 (THOMSON, 1860b) and further advanced the hypothesis that the Earth and this ionized region formed a large capacitor. Kelvin's estimate of the altitude of this region being about 100 miles is closer to the truth than was Balfour Stewart's estimate. The following extract is from THOMSON (1860b pp 217-218).

*In reality we know that air highly rarefied by the air pump, or by other processes, as in the construction of the 'vacuum tubes' by which such admirable phenomena of electric light have recently been seen in this place, becomes extremely weak in its resistance to the transfer of electricity through it, and begins to appear rather as a conductor than an insulator. One hundred miles or upwards from the Earth's surface, the air in space cannot in all probability have resisting power enough to bear any such electric forces as those which we generally find even in serene weather in the lower strata. Hence we cannot, with Peltier, regard the Earth as a resinously charged conductor, insulated in space, and subject only to accidental influences from temporary electric deposits in clouds, or air round it; but we must suppose that there is always essentially in the higher aerial regions a distribution arising from the self-relief of the outer highly rarefied air by disruptive discharge. This electric stratum must constitute very nearly the electro-polar complement to all the electricity that exists on the Earth's surface, and in the lower strata of the atmosphere - in other words, the total quantity of electricity, reckoned as excess of positive above negative, or of negative above positive, in any large portion of the atmosphere, or on the portion of the Earth's surface below it, must be very nearly zero. The quality of non-resistance to electric force of the thin interplanetary air being duly considered, we might regard the Earth, its atmosphere and the surrounding medium as constituting respectively the inner coating, the di-electric (as it were glass), and the outer coating of a great Leyden phial, charged negatively; and even if we were to neglect the consideration of possible deposits of electricity through the body of the di-electric itself, we should arrive at a correct view of the electric indications discoverable at any one time and place of the Earth's surface.*

The work of Kelvin may well be regarded as the climax of the early period in the study of atmospheric electricity. It may equally well be regarded as the foundation upon which modern studies of atmospheric electricity are based.

# Chapter Two

## THE DEVELOPMENT OF THE CLASSICAL PICTURE OF ATMOSPHERIC ELECTRICITY

*His theory is therefore this, that God made the thunder, but that the lightning made itself.*

Thomas Macaulay (1800-1859)
Mr. Robert Montgomery's Poems.

### 2.1 INTRODUCTION

Since the time of Kelvin, the subject of fair weather electricity has developed quite rapidly. These more recent developments are well described by GISH (1939), by WORMELL (1953), by CHALMERS (1954 and 1967), by STOW (1969) and by ISRAEL (1971).

One of the most fundamental advances made in the more recent work was the rediscovery by Linss in 1887 of Coulomb's finding concerning the conductivity of the air. Linss in fact made twice daily determinations of the dissipation coefficient at Darmstadt in Germany, and found that the values were a maximum in summer and a minimum in winter. Elster and Geitel subsequently found that the dissipation coefficient tended to increase or decrease when the electric field intensity decreased or increased. They also found that more charge was dissipated in unit time in pure air than in air containing elements which reduced visibility. Elster and Geitel also found that charge was dissipated more rapidly in pure mountain air than in pure air at lower altitudes; and that a negatively charged body lost its charge more rapidly than did a positively charged body. This latter effect was readily detected when experiments were performed on a mountain, but was not apparent in lowland experiments.

These findings will be mentioned again shortly, and reasons will be advanced to explain them, but it is first necessary to introduce some of the parameters of atmospheric electricity.

## 2.2 THE VERTICAL ELECTRIC FIELD, SPACE CHARGE, CURRENT, CONDUCTIVITY AND IONIC MOBILITY

The fundamental electrical phenomenon of the lower atmosphere is a vertical electric field which, with a clear sky and a clean atmosphere, is directed downwards and has a magnitude of the order of 100 V $m^{-1}$. This magnitude of field involves a negative charge density of some $-8.9 \times 10^{-10}$ C $m^{-2}$ on the surface of the Earth. This direction of the field is defined as positive and the resulting potential gradient is regarded as positive.

Observations made with balloons have shown that the potential gradient decreases with increasing altitude, being only a few percent of the surface value at 10 km. This means that the lower atmosphere contains positive space charge, in order to account for the fairly rapid fall off in the magnitude of the potential gradient.

As was found by Coulomb, and later Linss, air acts as a slight conductor of electricity. This is due to the presence of ions, which arise from two main sources. Any natural process which gives rise to ionization in the atmosphere presumably results in equal numbers of positive and negative ions. If by some means a mass of air acquires a preponderance of ions of one particular sign, then that mass of air is said to have a space charge of that sign.

The sources of ionization may be either terrestrial in origin (e.g. natural radioactivity in the soil) or extra-terrestrial (cosmic rays). Over the sea, and at heights over the land cosmic rays will be the major source of ionization, while closer to the surface over the land cosmic rays and $\beta$-particles and $\gamma$-rays from the soil will all cause ionization. (In addition to sources of ionization, there also exist sources of space charge such as, for example, the emissions from motor-car exhausts, smoke stacks).

The primary ionization consists of the ejection of an electron from a molecule. The electron almost immediately becomes attached to another neutral molecule and in this way there soon exists a number of small ions of each sign, consisting of a positively or negatively charged molecule surrounded by a cluster of a few neutral molecules. These small ions have a mobility of the order of $1.5 \times 10^{-2}$ m $s^{-1}$ in a field of 100 V $m^{-1}$ ($1.5 \times 10^{-4}$ $m^2 s^{-1} V^{-1}$). The small ions disappear, either by recombination, or by becoming attached to much larger neutral particles such as condensation nuclei or pollution particles. These large ions, as they are known, have much reduced mobility ($10^{-6}$ $m^2 s^{-1} V^{-1}$) and it is for this reason that Elster and Geitel found that a charged body lost its charge more rapidly in pure air than in air containing a number of pollution particles. Table 2.1 summarises the situation under various conditions.

| | Rate of production (ion pairs $cm^{-3}$ $s^{-1}$) | | Number of ions present ($cm^{-3}$) | |
|---|---|---|---|---|
| | Due to radioactivity | Due to cosmic rays | Small ions | Large ions |
| Oceanic air | 0 | 2 | 700 | 200 |
| Country air | 8 | 2 | 600 | 2000 |
| City air | 8 | 2 | 100 | 20000 |

Table 2.1 Ions in the atmosphere (WORMELL, 1953)

Because of the vertical field, and the fact that air is slightly conducting, an electric current flows vertically through the atmosphere to the ground. This is termed the conduction current and in fair weather it is a downward flowing positive current. Thus, positive ions move downwards, negative ions upwards. The magnitude of the conduction current density (j) may be expressed as

$$j = eE \sum_r ({}_r n_1 \cdot {}_r w_1 + {}_r n_2 \cdot {}_r w_2) \text{ A m}^{-2} \qquad (2.1)$$

where E = vertical potential gradient (V $m^{-1}$)

e = electronic charge (C)

${}_rn_1$ = number density of positive ions of type r ($m^{-3}$)

${}_rn_2$ = number density of negative ions of type r ($m^{-3}$)

${}_rw_1$ = mobility of positive ions of type r ($m^2s^{-1}V^{-1}$)

${}_rw_2$ = mobility of negative ions of type r ($m^2s^{-1}V^{-1}$)

The conductivity of the air increases fairly rapidly with increasing altitude. The two main reasons for this increase are firstly, the ionic mobility increases with decreasing air density and secondly, the number of ions present increases due to the increased ionization by cosmic rays at greater altitudes. The result of this is that the vertical current is independent of altitude and is maintained through a considerable vertical thickness of the atmosphere despite the decrease in the vertical field at higher levels.

## 2.3 THE ELECTROSPHERE

Because of the increasing conductivity of the atmosphere with increasing altitude, a height will be reached where the atmosphere may be regarded for many purposes as a conducting surface. The height of this region has been estimated at above 50 km by CHALMERS (1967 p 34) and at above 50 to 60 km by MALAN (1967). This is the region which has been called the equalizing layer and, by Chalmers, the *electrosphere*.

Chalmers made use of the electrosphere in defining atmospheric electricity as electrical phenomena between the electrosphere and Earth, thus excluding the properties of the ionosphere. However, as will be see later, some regard must be paid to these properties.

As has already been seen, the idea of the existence of this conducting region was first mooted by Kelvin in 1860 (THOMSON, 1860b). Since this region may be as low as 50 km, and since, in fact, almost the whole of the difference of potential between the electrosphere and the Earth occurs in the lower 10 km which are accessible to balloon observations, the magnitude of the potential of the electrosphere may be reliably estimated from direct measurements. A mean value of about 280 kV has been obtained from observations spanning a 12 period by MÜHLEISEN (1971).

The picture which now evolves is one of two conducting surfaces, the electrosphere and the Earth, separated in distance by some 50 km and in potential by about 280 kV, between which a current flows through the conducting atmosphere. It is possible to relate some of the parameters which have been introduced, and this is done below, with reference to Figure 2.1:

V = potential of electrosphere.

R = columnar resistance of a column of atmosphere 1 $m^2$ in cross-section stretching between Earth and electrosphere.

r = resistance of the bottom 1 m of this column.

Thus, the potential gradient is $E = \frac{r}{R} V$ and $r = 1/\lambda$, where $\lambda$ is the conductivity of the atmosphere where E is measured. The current flowing down the column is the current density

$$j = E/r = E\lambda$$

and

$$j = V/R$$

$$\text{or } E = j/\lambda = V/R\lambda \qquad (2.2)$$

## 2.4 RELAXATION TIME OF THE ATMOSPHERE

The relaxation time is a measure of the time required for a system of reacting particles to change or relax from the original state to their final state. A body carrying a charge Q C and having an area S $m^2$ which is exposed to the atmosphere will gradually lose its charge because of ionic conduction. The rate at which this charge is dissipated may be used to give a time constant, or relaxation time, for electrical phenomena in the atmosphere. If the charge Q is uniformly distributed over S, then the surface density of charge $\sigma = Q/S$ is uniform. The potential gradient E in the space near the charged body may be expressed in terms of the

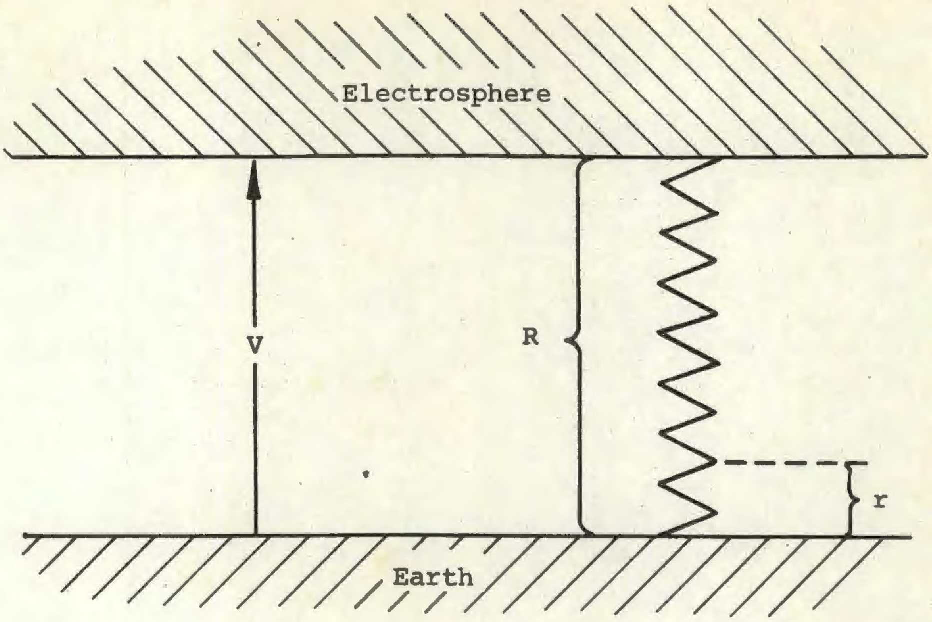



Figure 2.1 Illustrating the concept of columnar resistance.

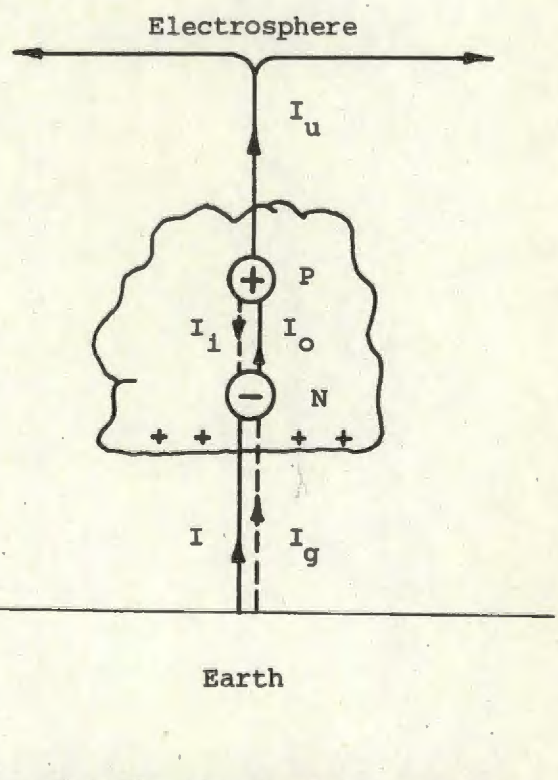



Figure 2.2 The thundercloud generator.

charge density on the surface by means of Gauss's law as $E = -\sigma/\varepsilon_0 = -Q/S\varepsilon_0$ where $\varepsilon_0$ is the electric space constant, and the charge is taken to be negative. The current density is then given by (2.2) as

$$j = \lambda_1 E = -\lambda_1 Q/S\varepsilon_0$$

where $\lambda_1$ is the conductivity of the positive ions. Thus the total current flowing to the charged body is

$$i = jS = -\lambda_1 Q/\varepsilon_0 = dQ/dt$$

Integrating

$$\int_{Q_0}^{Q} \frac{dQ}{Q} = -\int_0^t \frac{\lambda_1}{\varepsilon_0} dt$$

$$\ell n\ (Q/Q_0) = -\lambda_1 t/\varepsilon_0$$

$$\text{or} \quad Q = Q_0 \exp(-\lambda_1 t/\varepsilon_0) \qquad (2.3)$$

where $Q_0$ is the initial charge on the body. The time $t = \tau$ taken for the charge to become $Q_0/e$ is called the relaxation time. (Thus, in atmospheric electricity the relaxation time may be defined as the time $\tau$ taken for the charge of a body or an air parcel to fall to 1/e of its original value by ionic processes. When this happens purely by electrical conduction due to positive ions its value is $\tau = \varepsilon_0/\lambda_1$). These results are only valid if $\lambda_1$ is constant and if Ohm's law holds.

Some actual values of relaxation times (given by CHALMERS, 1967 p 40) are: Air near the Earth's surface, 5 to 40 minutes depending on pollution; air at 18 km, 4 s; the electrosphere at 70 km, $10^{-8}$ s; the Earth's surface $\leqslant 10^{-6}$ s.

Thus if the entire Earth is uniformly negatively charged with a charge density of $-8.9 \times 10^{-10}$ C m$^{-2}$ (corresponding to a positive potential gradient of 100 V m$^{-1}$) it will lose most of its charge in something over 5 minutes. Since, although the charge on the Earth and the potential gradient vary, the average charge density remains fairly constant, some mechanism must be responsible for maintaining the Earth's charge.

In addition to the conduction current due to the movement of atmospheric ions under the influence of the ambient field, there are various other currents which may be as large as, or even larger than, the conduction current. Changes in the prevailing field will give rise to displacement currents, vertical transport of charge (due to turbulence or convection) constitues a convection current, charge carried by rain, snow etc., is called precipitation current, while in the vicinity of thunderstorms point discharge currents will be important. While two of these currents may oppose the conduction current at times, namely the displacement and the convection currents, they may also enhance the conduction current at other times. Thus none of these may be regarded as a satisfactory mechanism for maintaining the charge on the Earth, rather they underline the need for finding such a mechanism.

The magnitude of the conduction current may be estimated for a given set of conditions as follows: Assuming a clean atmosphere with a relaxation time of 5 minutes, equation (2.3) leads to a value of conductivity of $\lambda_1$ of about $3 \times 10^{-14}$ mho $m^{-1}$. If the prevailing field is 100 V $m^{-1}$, then equation (2.2) shows that the conduction current density is about $3 \times 10^{-12}$ A $m^{-2}$.

Gauss's law shows that the surface density of charge ($\sigma$) of the Earth is related to the electric field (E) by $\sigma = -\varepsilon_0 E$. If the charge density changes with time, this gives a displacement current of $d\sigma/dt = -\varepsilon_0 dE/dt$. It may readily be seen that if E changes by, say, 400 V $m^{-1}$ in 1 hour then $d\sigma/dt \approx 1 \times 10^{-12}$ A $m^{-2}$ which is of the same order of magnitude as the fair weather conduction current density.

## 2.5 THE GLOBAL CIRCUIT

The electric field near the ground is in a state of continuous fluctuation about its mean value. Fairly rapid variations, with periods of the order of seconds can usually be ascribed to turbulence and an uneven space charge distribution. Much more rapid variations are detected and have been shown to be due to lightning discharges. Other variations may be ascribed to variations in the pollution level and, as shall be seen shortly, to thunderstorm activity. Significantly, it is found that the direction of the electric field reverses close to, and directly underneath, most thunderclouds; while the field changes associated with lightning discharges show that most discharges to ground convey negative charge to the Earth.

WILSON (1920) first suggested that lightning discharges to ground formed part of the primary mechanism responsible for the maintenance of the Earth's charge. The negative charge which predominates in the lower part of a thundercloud induces a positive charge on the neighbouring part of the Earth's surface and hence an equal negative charge appears on remote parts of the Earth. The difference in potential within a thundercloud may be enormous compared with the potential of the electrosphere and as a result a vertical current can be driven upwards into the highly conducting electrosphere.

The thundercloud may thus be regarded as an electrostatic generator suspended in an atmosphere of low conductivity between the two conductors formed by the Earth and the electrosphere. By means of physical processes which need not be specified here both positive and negative charges are produced in the cloud. These charges are attached to hydrometeors and due to the actions of vertical air currents and gravity they are separated into a positive region P and a negative region N, as shown in Figure 2.2, which is due to MALAN (1967). The vertical separation of charge into P and N may be regarded as constituting a charging current $I_o$. When the potential between P and N is high enough, spark-over (intra-cloud lightning discharge) will occur, neutralizing equal amounts of positive and negative charge, resulting in an intermittent current $I_i$. In addition, when the potential between N and the ground reaches about $10^8$ V, electrical breakdown takes place between the cloud and the ground by the well known leader- and return- stroke process. As a result, negative charge is removed from N, leaving P unaffected. This is shown by the intermittent current $I_g$ in the diagram. In addition to these currents, there will be the conduction current I between the cloud and the ground (flowing upwards in the reversed thundercloud field) and according to Wilson's theory a current $I_u$ between the cloud and the electrosphere.

A significant discovery was made by MAUCHLY (1921 and 1923) when he found that there was a diurnal variation in the potential gradient with an amplitude of some 15% of the mean value. This variation, which was discovered from measurements taken during the voyage of the 'Carnegie', was of a simple nature and over a wide range of longitudes was dependent on universal time. Furthermore, a similar variation was discovered at seven places in the Arctic and Antarctic regions. It thus appeared that there was a global variation in the potential of the electrosphere, although local effects might easily mask this global effect.

In 1922, Wilson pointed out that the theory which sought the origin of the fine weather potential gradient in thunderstorms would predict a global maximum in electrosphere potential at the time when global thunderstorm activity reached a maximum (see WORMELL, 1953). Wilson tentatively suggested that Mauchly's results were significant in this regard, and WHIPPLE (1929) succeeded in showing a very good correlation between the diurnal variation of potential gradient and the incidence of thunderstorm activity. This aspect of the theory will be discussed more fully in Chapter Three, Section 3.2.1, but it should be mentioned here that some considerable doubt has been cast on Whipple's findings, and as a result possibly on certain aspects of the entire theory.

## 2.6 THE CLASSICAL PICTURE

The picture which has evolved thus far is known generally as the classical picture of atmospheric electricity. It may be summarized as follows: All thunderstorms convert thermodynamical, mechanical and possibly chemical energy into electrical energy with the result that the electrosphere

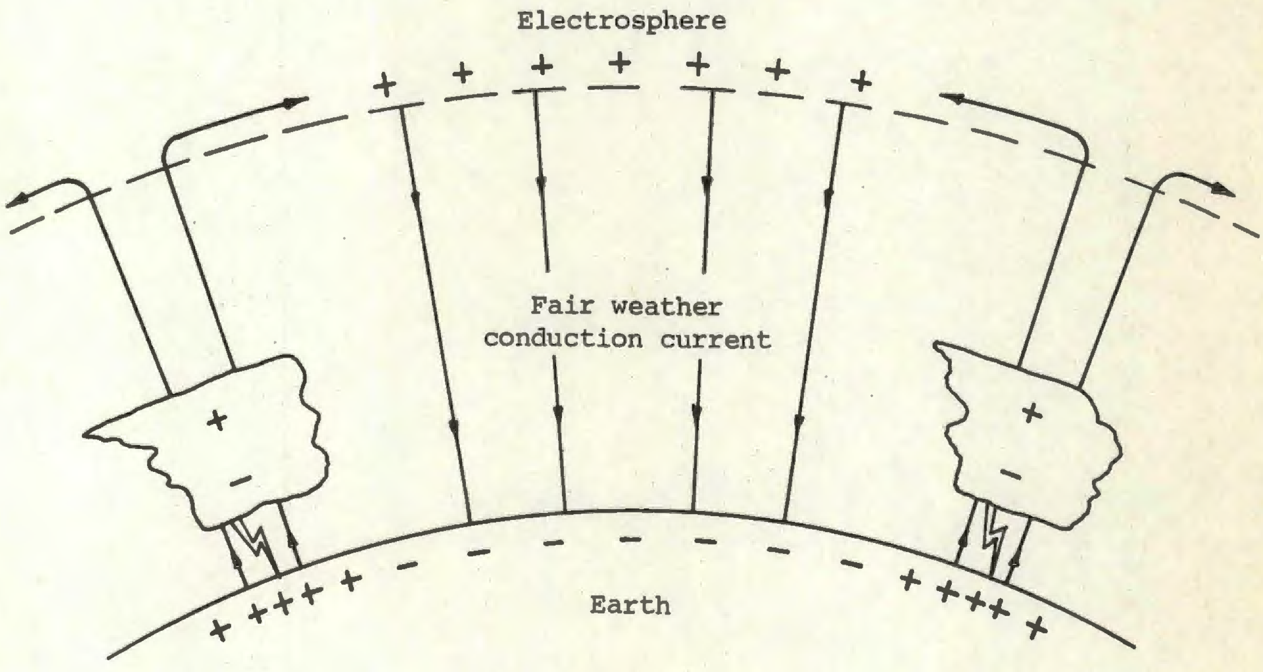



Figure 2.3 The classical picture of atmospheric electricity.

is raised to, and maintained at, a high potential relative to the ground. Because these thunderstorms exist in the weakly conducting atmosphere between two concentric spherical conducting surfaces formed by the Earth and the electrosphere, the problem is sometimes considered as one of a spherical capacitor with a leaking dielectric. The electrosphere potential in the vicinity of a thunderstorm rises as a result of the thunderstorm, and because of the high conductivity of the electrosphere this increase in potential is almost immediately communicated to the electrosphere over fair weather regions of the Earth. Thus the fair weather field increases, and as long as the conductivity remains constant, equation (2.2) shows that the vertical conduction current between Earth and electrosphere will increase. The classical picture is represented in Figure 2.3.

# Chapter Three

## A SUMMARY OF MORE RECENT WORK IN ATMOSPHERIC ELECTRICITY

*The main obstacles are the inadequacy of our language and the novelty of my subject-factors that entail the coinage of many new terms.*

Lucretius (99 - 55 B.C.)
De Rerum Natura

### 3.1 THE FUNDAMENTAL PROBLEM

As has been shown in Chapter Two, the classical global picture of atmospheric electricity is one of thunderstorms, suspended in a weakly conducting atmosphere, acting as generators which drive a conventional current upwards from the conducting Earth to the conducting region above about 50 km known as the electrosphere. The return path for this current is in the fair weather regions of the Earth where a conventional current flows downwards through the atmosphere to ground.

Although this classical global picture may appear to have answered many of the questions raised in atmospheric electricity, it will be seen that some of the findings on which the picture is based must be treated with reservation. As a result some doubts have been cast on the validity of at least some aspects of this picture. One fact which emerges very clearly is that the study of atmospheric electricity cannot be divorced entirely from the subject of space electricity since the connection between the two may be more important than was previously realized. Many workers have tended to adhere rather closely to the classical picture, and the topics of atmospheric and space electricity have been quite separate as is illustrated by CHALMERS (1967 p 34) in his definition of atmospheric electricity.

The fundamental problem of fair weather atmospheric electricity is the identification of the sources or origins of the electric current which is known from measurement to flow through the atmosphere to ground. In this way the validity of the classical global picture may be tested and those aspects of it which need changing may be changed.

The classical picture will now be examined in more detail from two different standpoints, those of the generators and of the electrosphere. The various atmospheric electric parameters will then be discussed in terms of their bearing on the classical picture.

## 3.2 THE CLASSICAL PICTURE

### 3.2.1 Generators in atmospheric electricity

The generators in atmospheric electricity are those agencies responsible for charging the Earth, the electrosphere or both. The thunderstorm is only one of several such generators, and following DOLEZALEK (1972), these should be classified as 'local','regional' or 'global' generators.

Local generators are processes which transform some other form of energy available in the atmosphere into electrical energy in such a way that the generator charges only the Earth in the vicinity of the generator. The thundercloud might be classed as a local generator if no current flows between the cloud top and the electrosphere. The emission of space charge into the atmosphere, for example by fires, industrial processes, the bubbling at an air-water interface, would also constitute a local generator. Another example would be the evaporation generator described by MÜHLEISEN (1958). (Mühleisen's experiments in a closed room indicated that the evaporation of water generates a negative space charge in the air, while warming of the air produced a positive charge).

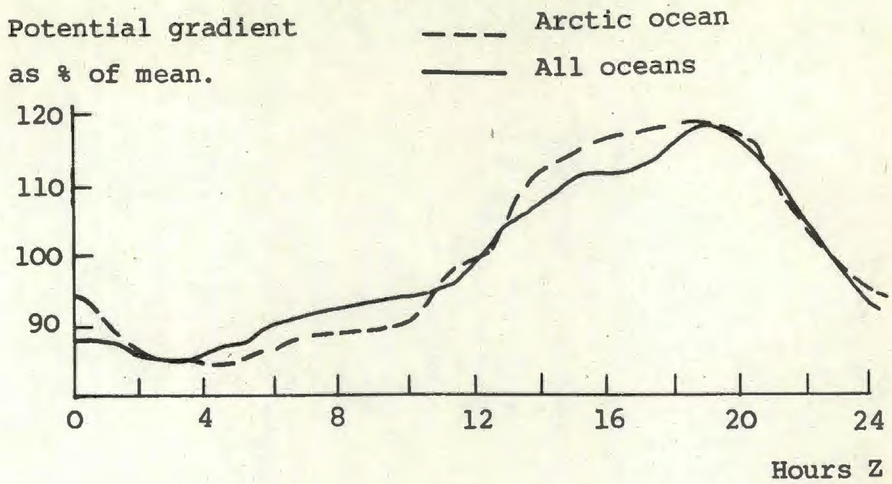
A global generator is one which changes the potential of the electrosphere and, as a result, becomes apparent on a global scale. The classical picture of the thundercloud supplying charge to both the Earth and the electrosphere would constitute a global generator. The transition from local to global generator is a smooth one in that the magnitude of the current flowing into the global circuit is a measure of the global nature, or scale, of the generator.

Regional generators affect an area greater than do local generators, but they are not on a global scale. According to DOLEZALEK (1972) it is not known whether such generators exist. (It is one of the contentions of this thesis that at least one such generator probably does exist. This is dealt with in Chapter Eight).

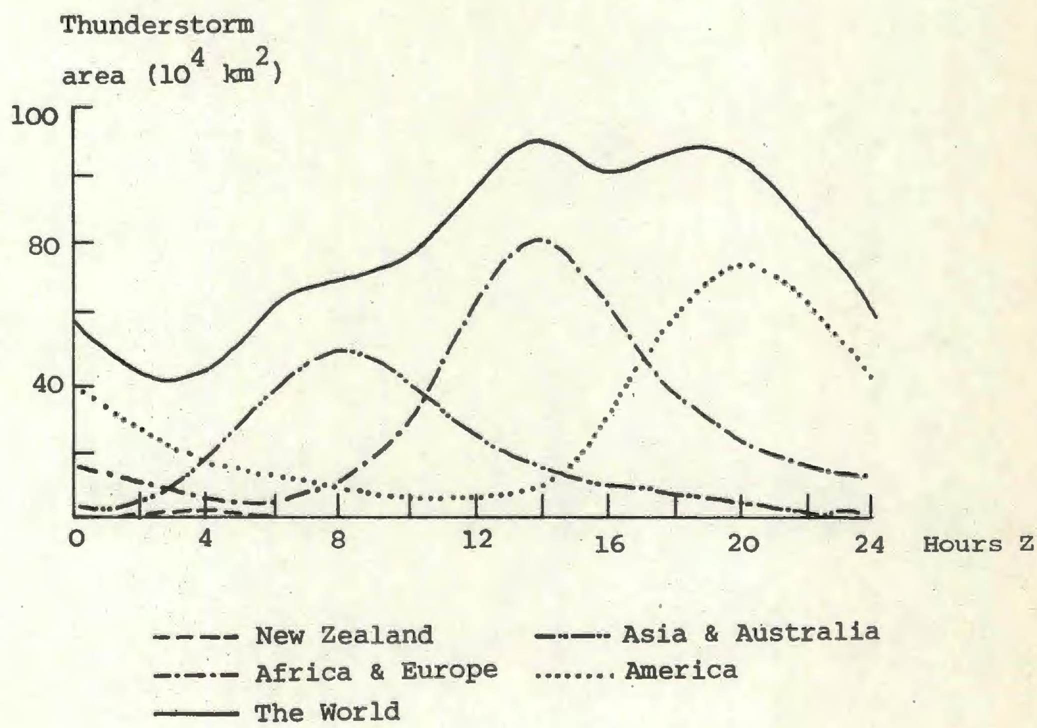
The generator for the classical global circuit consists of all the thunderstorms active at any instant. The statistical correlation between global thunderstorm activity and the diurnal variation of potential gradient as measured at sea on the famous voyages of the 'Carnegie' and the 'Maud' are shown in Figure 3.1. Figure 3.1 (a) shows the potential gradient measured in the Arctic region alone, and on all voyages. The diurnal variation is quite well defined, with a maximum in potential gradient at about 19h00 Z and a minimum at about 03h00 Z. Figure 3.1 (b) shows an estimate of the area of the globe over which thunderstorms are active. The three curves, for the Americas in the west, Africa and Europe close to the Greenwich meridian and Asia and Australia in the east, each show a maximum of activity in the local afternoon. Plotted against universal time and added to yield a pattern of global thunderstorm activity, the result is at least similar to the shape of the diurnal potential gradient curve. Figure 3.2 is a direct comparison of these two curves with the ordinates suitably scaled. Those stations which effectively reproduce this diurnal variation have been referred to as globally representative stations.

It must be noted that the potential gradient measurements made at many land stations do not show this diurnal variation, presumably because it is masked by other local effects. Furthermore, the estimation of the thunderstorm activity on which WHIPPLE and SCRASE (1936) based the curves in Figure 3.1 (b) was necessarily very approximate. This was because there existed no network of land stations from which a count of thunderstorms could be made, and information concerning oceanic storms was non existent.

DOLEZALEK (1972) has examined the thunderstorm generator in some detail and has paid particular attention to the apparent correlation between




(a) Diurnal variation of potential gradients over the oceans.




(b) Diurnal variation of land thunderstorm areas.

Figure 3.1 Diurnal variations of fair weather potential gradients and global thunderstorm activity. (After WHIPPLE and SCRASE, 1936).

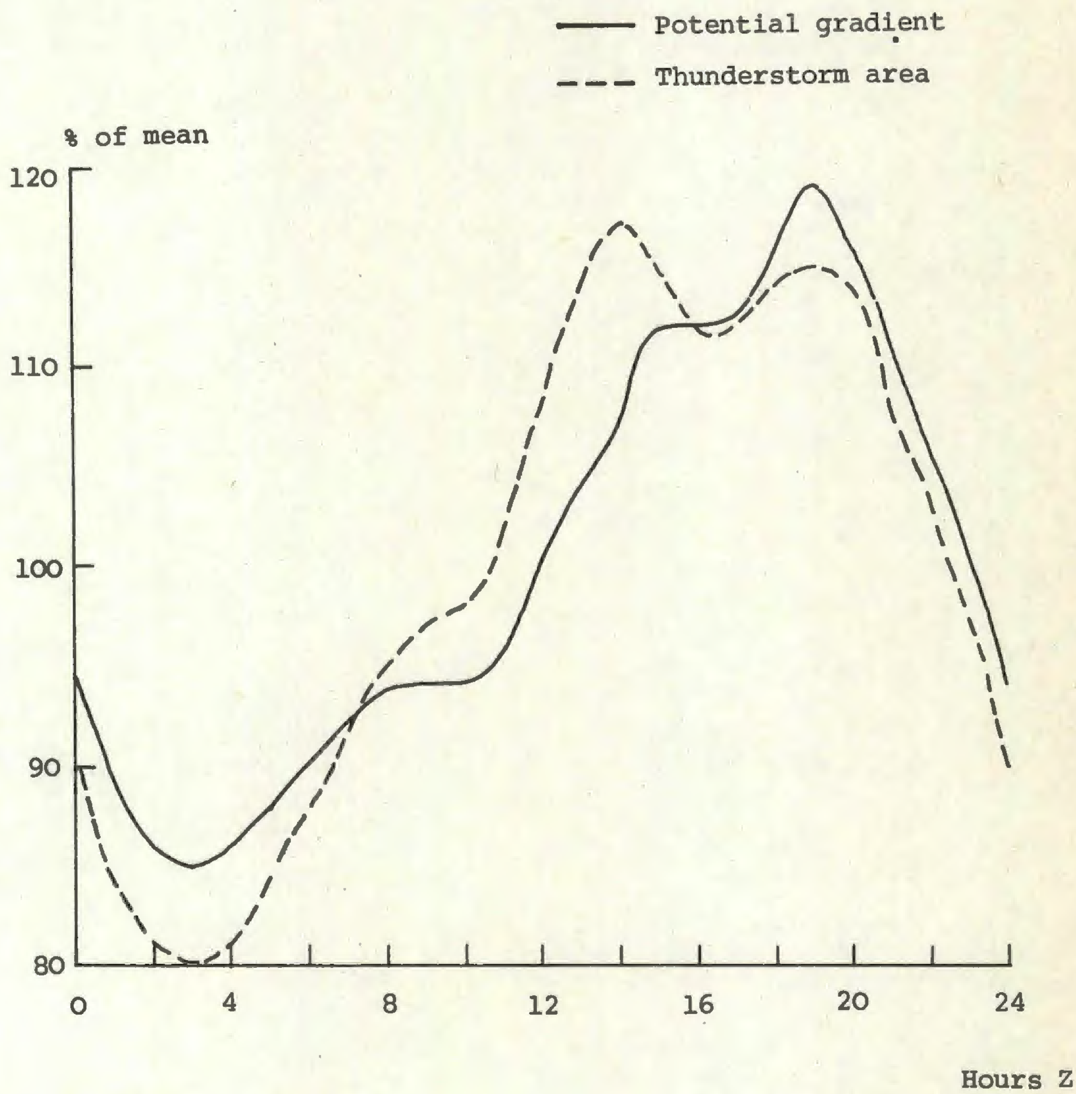



Figure 3.2 Direct comparison of the diurnal variation of the fair weather potential gradient with the total (i.e. including constant ocean area) thunderstorm area variation.

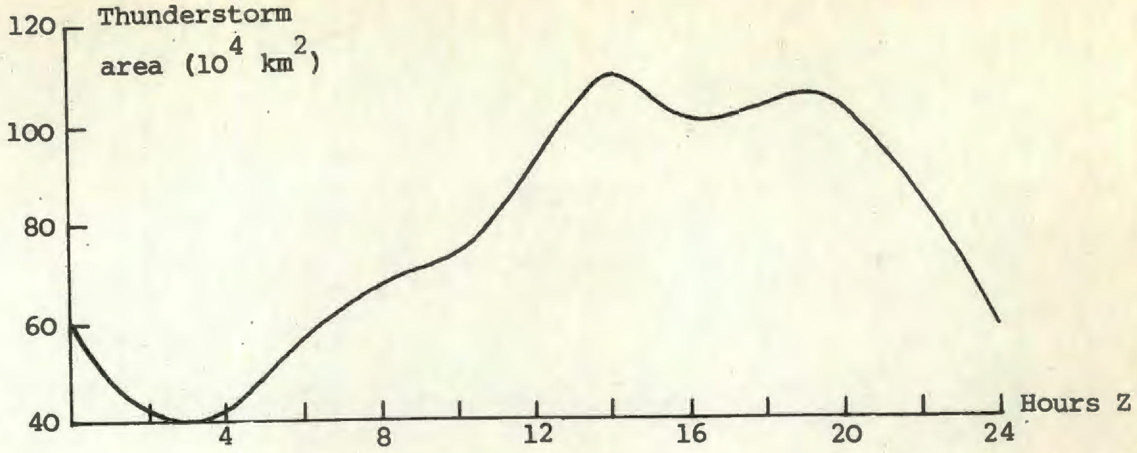
thunderstorm activity and potential gradient variation. By re-examining the data from which Whipple and Scrase arrived at the curves of Figure 3.1, Dolezalek concluded that the Whipple-Scrase curve for diurnal variations was not truly representative and indeed could not be confirmed by later investigations. He found that taking monthly average curves, and combining the results of several years, the correlation found by Whipple and Scrase appeared to be an accidental result; and that the similarity between his results and the Whipple-Scrase diurnal curve almost vanished. Dolezalek gives a curve of thunderstorm activity, and this is compared with the Whipple-Scrase curve in Figure 3.4 (a).

Several points emerge from this work of Dolezalek's. Firstly, much more information is needed on the currents flowing above and beneath thunderclouds, and also on the conductivity of the air above, within, and beneath, thunderclouds. Secondly, more information is needed about different types of thunderstorms such as frontal storms or isolated storms, thunderclouds formed over the ocean and those formed at high altitudes, and so on. From a study of point discharge currents ETTE and UTAH (1973a) made the suggestion that tropical and sub-tropical storms were more effective in charging up the Earth-electrosphere capacitor system than were temperate storms. Thirdly, it is necessary to know more about the actual number of thunderstorms active over the globe at any instant of time. It is possible that artificial Earth-satellite observations will in the future provide some information in this last regard.

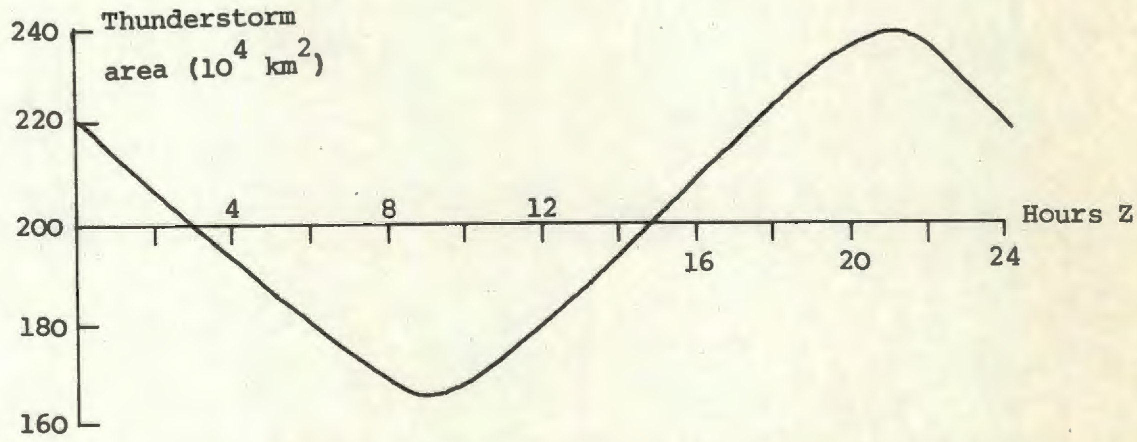
Thunderstorm activity has also been found to vary according to solar activity. Evidence in support of this has been published by LIKHTER (1966), who used the intensity of atmospherics as a monitor of thunderstorm activity, and by CLARENCE (1969) in a discussion of the sources of whistling atmospherics. The variation of thunderstorm activity referred to by both these workers is not necessarily due to variations in the number of thunderstorms. It may well consist of changes in the current flowing in the lightning channel, the number of discrete strokes per flash and so on.

The basic difficulties may be summarized as follows. The number of thunderstorms occurring on a global scale is almost completely unknown. While some land areas are sufficiently inhabited to provide fairly accurate data on thunderstorm incidence, much larger areas yield no data at all. In addition, the oceans, which cover about 71% of the surface area of the globe, yield almost no information in this regard. The very great difficulty associated with determining the number of thunderstorms is compounded by the fact that it is unlikely that all thunderstorms are equally effective as generators. A further complication is the fact that cloud systems other than thunderclouds may play an important part in the global charge generating mechanism. For instance, WEED and KELLOGG (1974) have measured electric fields above a raining cloud which was not a thundercloud. They found values of the field which were much higher than the fair weather field, and they determined a value of 0.12 A as the air-Earth current due to the storm.

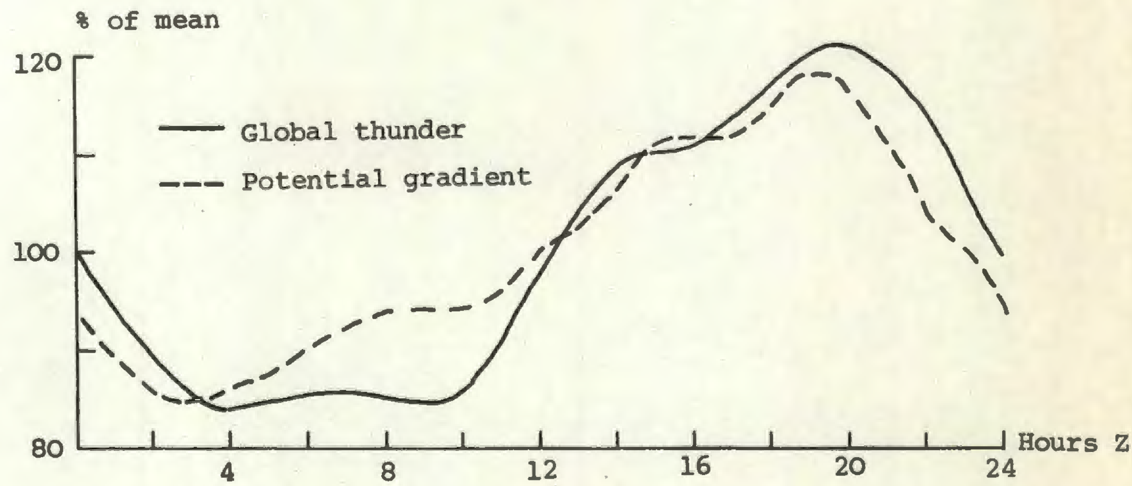
Recently an attempt has been made by TRENT and GATHMAN (1972) to investigate oceanic thunderstorms using as a data base some seven million synoptic observations made by ships at sea. One of the major weaknesses of the Whipple and Scrase estimate of thunderstorm activity was the assumption made that storms at sea were so well distributed, spatially and temporally, that they were equally likely to occur at any hour. The area of ocean assumed to be affected by thunderstorms was thus regarded as a constant, and the value assumed for this was $1.11 \times 10^6$ $km^2$. (This means that the shape of Figure 3.1 (b) is due to the sparse information available concerning overland storms alone). Trent and Gathman found that the mean ocean area affected by thunderstorms was $2.02 \times 10^6$ $km^2$ and that far from being constant, the amplitude of this area varied on a diurnal basis by about 18% of the mean. The maximum area occurred between 18h00 and 24h00 Z and the minimum between 06h00 and 12h00 Z. Figure 3.3 represents an attempt to incorporate the results of Trent and Gathman into those of Whipple and Scrase. A smooth variation of oceanic thunderstorm area has been assumed and this curve has been added to that given by Whipple and Scrase for the land areas. The result shows the same




(a) Whipple-Scrase curve for land areas only.




(b) Assumed variation applied to the TRENT and GATHMAN (1972) data for the oceans.




(c) Comparison of the modified global thunderstorm area with the potential gradient variation.

Figure 3.3 The modified Whipple-Scrase global thunderstorm activity curve.

general trend as the original Whipple and Scrase curve. Although somewhat better agreement is obtained between the potential gradient variation and the estimate of total global thunderstorm area (as shown in Figure 3.3 (c)), the fact that the ocean thunderstorm area was originally considered a constant does not appear to have given a significantly wrong curve, (see Figure 3.2).

Figure 3.4 (a) compares directly the original Whipple-Scrase curve, the modified Whipple-Scrase curve and the Dolezalek curve. It will be noticed that the amplitude of the Dolezalek curve is about twice that of the Whipple-Scrase curves. The reason for this may be that the ELF data on which Dolezalek based his curve was sensitive to cloud-to-cloud or intracloud lightning discharges to a greater extent than were the thunderstorm reports upon which the Whipple-Scrase curves were based. The thunder generated by cloud-to-ground discharges is very much more audible than that resulting from other discharges, but cloud-to-ground discharges are considerably less numerous (by a factor of more than 6 (MALAN, 1967)) than are the other types of discharge. It will be seen from Figure 3.4 (a) that while the three curves have a similar general shape, there are some very marked differences between them.

Working at Lanehead in England, SHARPLESS, ASPINALL and HUTCHINSON (1971) obtained a diurnal potential gradient variation which was remarkably similar to the Whipple-Scrase curve. They concluded that the dependence of potential gradient on universal time was similar both at widely separated places on the Earth (the ocean voyages of the 'Carnegie' and the 'Maud'; and at Lanehead, a land station) and also for times nearly half a century apart ('Carnegie' voyage 1929, Lanehead results for 1967-69). The diurnal variation in potential gradient found by these workers is shown in Figure 3.4 (b).

OGAWA (1960) in Japan found no evidence that the diurnal variations in atmospheric electric parameters were caused by local generators other

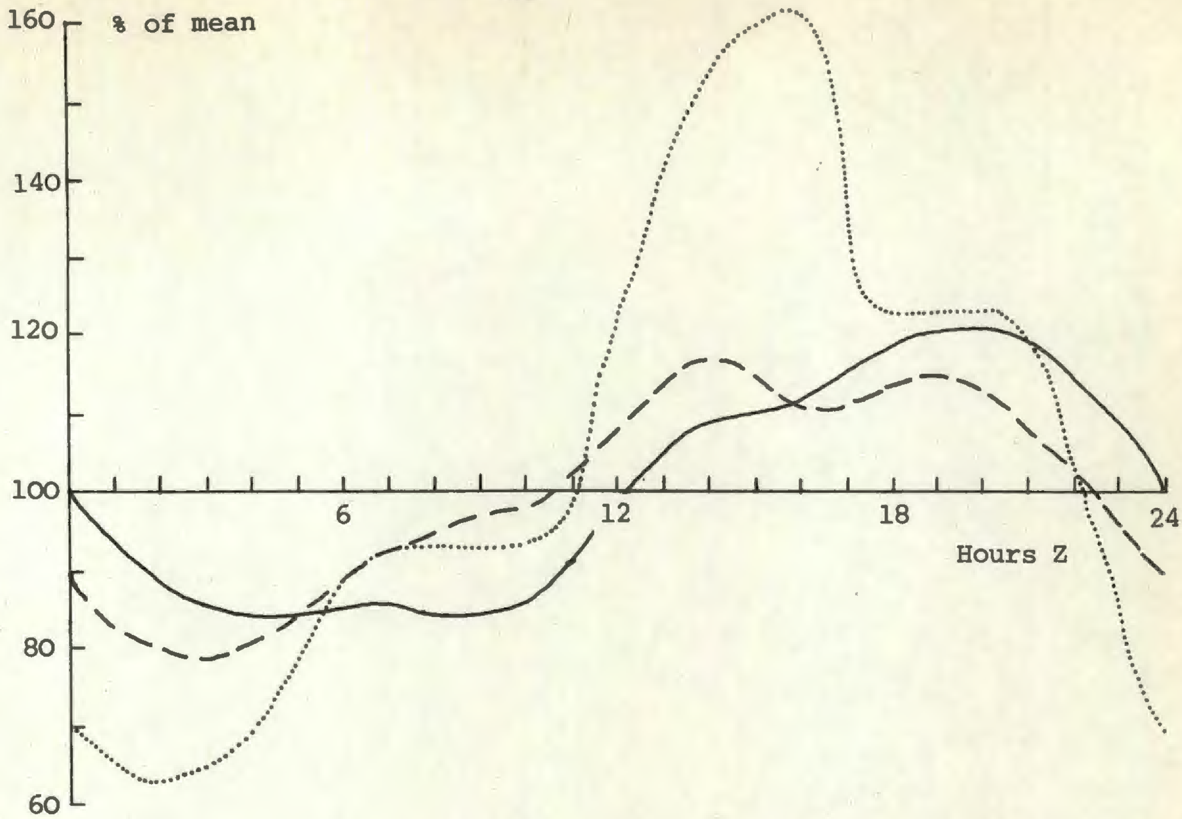



Figure 3.4(a) Comparison of the original Whipple-Scrase thunderstorm activity curve (---) with the modified curve (——) and the DOLEZALEK (1972) curve (···).

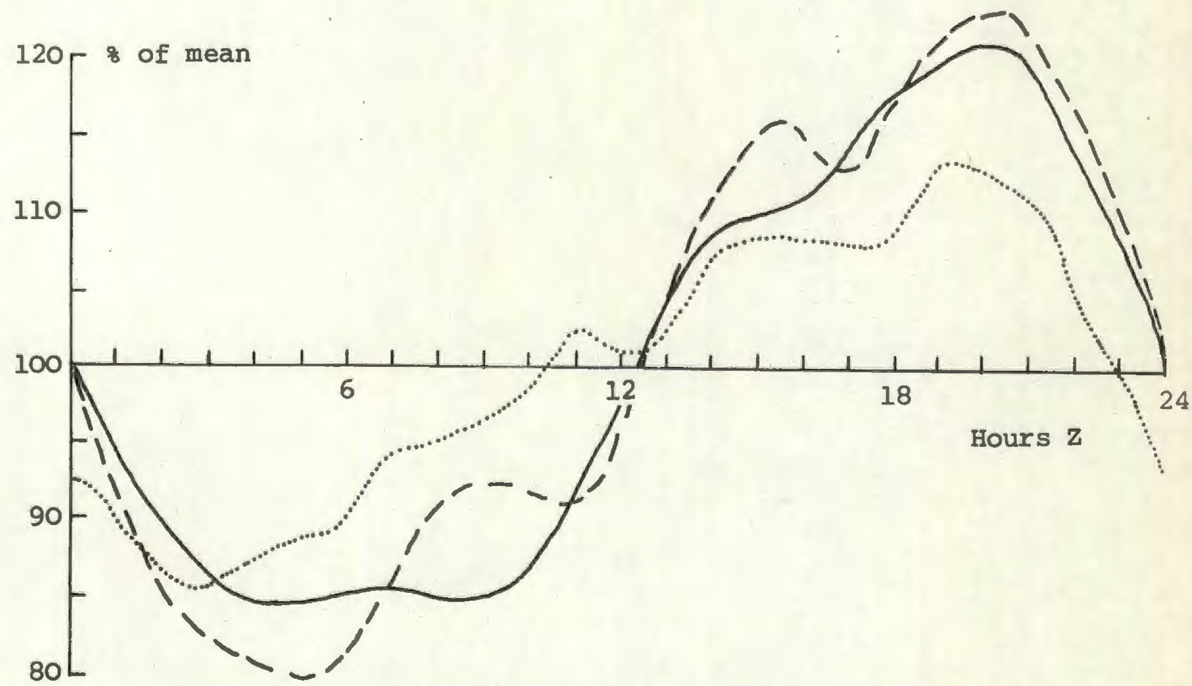



Figure 3.4(b) The diurnal potential gradient variation due to ASPINALL, SHARPLESS and HUTCHINSON (1971) (···) and that due to KASEMIR (1972) (---) compared with the modified Whipple-Scrase thunderstorm activity curve (——).

than the thunderstorm generator.

Results obtained in Greenland, by KASEMIR (1972), of the diurnal variation in potential gradient show a general agreement with the Whipple-Scrase potential gradient curve. These results, together with those of SHARPLESS, ASPINALL and HUTCHINSON (1971) are compared with the modified Whipple-Scrase thunderstorm activity curve in Figure 3.4 (b).

Summary Clearly a lot more information is needed, both on the individual generators and on the global census. While the correlation between the global incidence of thunderstorm activity and the potential gradient may not be as clear cut as was first suggested by WHIPPLE and SCRASE (1936), it may well not be quite as confused as suggested by DOLEZALEK (1972). The effective reproduction of the Whipple-Scrase curve by SHARPLESS, ASPINALL and HUTCHINSON (1971) and by KASEMIR (1972) for two land stations is considered particularly significant in this regard.

### 3.2.2 The electrosphere

In classical terms the electrosphere is that region of the upper atmosphere or lower ionosphere which may be regarded as an equipotential surface, or shell, surrounding the Earth. It is often regarded as a perfect conductor, thereby isolating the space outside the electrosphere from electrical activity in the atmosphere, and likewise shielding the atmosphere from electrical events occurring above the electrosphere. CHALMERS (1967 p 34) regarded this as the reason why solar activity apparently had little, if any, effect on the phenomena of atmospheric electricity. More recently, however, it has become apparent that a degree of coupling exists between events above and below this region.

In this thesis the electrosphere is regarded as being the lower boundary of the highly conducting region. In the idealized case, this may be considered as a thin equipotential spherical shell lying below the conventional ionosphere.

SAO (1967) found that in polar regions the potential gradient appeared to correlate well with solar activity measured at a radio frequency of 1 GHz. Sao's explanation of the phenomenon was that during times of intense solar activity the columnar resistance (R) of the atmosphere decreased, particularly near the top of the column. This had the effect of lowering the electrosphere at this point, and as a result of the decrease in R in the equation $E = V/R\lambda$ (equation (2.2)) the potential gradient E increased, even if the potential of the electrosphere (V) did not.

Various attempts have been made to determine the effects of solar eclipses on the atmospheric electric parameters. KAMRA and VARSHNEYA (1967) found that the potential gradient recorded during the eclipse of 20th May 1966, in India, showed deviations from the normal pattern. They did not advance any explanation of their results, and indeed these results would be difficult to explain convincingly in terms of solar interaction with the electrosphere. The total duration of the eclipse in this case was 2 hours 26 minutes and at its maximum only about 25% of the sun was eclipsed. The most difficult feature to explain would be the negative field recorded for some of the time during the eclipse. The eclipse of the 7th March 1970, in North America, was investigated using both airborne and ground based equipment by MARKSON and KAMRA (1971). They found that the potential gradient at the ground appeared to decrease while that aloft was enhanced. The negative fields recorded in the earlier experiment by Kamra and Varshneya were not confirmed. In the North American experiment the eclipse had a duration of 2 hours 34 minutes, and was total for 3 minutes. This same eclipse was investigated elsewhere in North America, where it reached 95% of totality by ANDERSON and DOLEZALEK (1972). They found perturbations in the atmospheric electric parameters and tentatively sought to explain these in terms of a decrease in, and subsequent restoration of, eddy turbulence near the ground.

It is felt that the explanation of Anderson and Dolezalek, or a similar one also based on thermal effects in the lower atmosphere, is most likely to be the true one. The cause is unlikely to lie in changes in the electrosphere because the duration of the eclipse is too short for any ionospheric changes to occur on a noticeable scale. Furthermore, the actual illuminated area of the electrosphere which is affected by the eclipse may be small in comparison with the surrounding electrosphere which is not affected and so, again, a noticeable effect easily detected at the ground seems unlikely.

WEBB (1968) contended that thermally driven tidal motions in the lower ionosphere should be regarded as the ultimate source of the electrical activity of the atmosphere (and also of the phenomena of aurorae, airglow, electrojets and radiation belts). Webb used the well known dynamo theory of ionospheric current generation and explained the negative charge on the Earth in terms of a postulated potential difference assumed to exist between the solar plasma on the one hand, and the Earth and its ionosphere inside the plasmapause on the other. The dynamo circuits are linked via high impedance paths (the lower atmosphere) to the Earth, with the result that a continuous current flows to Earth. This current is very much smaller than those flowing in the dynamo circuits because of the very high impedance of the path. However, in order to maintain the potential difference between ionosphere and Earth it is necessary that there be some return path for current to flow from Earth back into the dynamo circuits. It is Webb's contention that thunderstorms, and in particular lightning discharges, provide this path.

While it is felt that Webb's theory is a very interesting relook at the whole theory, the only real change it brings about is to effectively reverse the roles of thunderstorm and electrosphere, since, in terms of the classical picture, the thunderstorm is the generator and the electrosphere the current path linking fair weather and thunderstorm regions of the globe. What Webb has done, is to underline the complex nature of the electrosphere. Use will be made of some of the findings of Webb's theory in Chapter Eight of this thesis.

Having mentioned Webb's alternative to the classical theory, a more recent alternative theory due to WÅHLIN (1973) should also be considered. This theory basically contends that the wind blowing across the surface of the Earth loses negative charge to the Earth, leaving the air above the surface with a positive space charge. The negative charging of the Earth is an electro-chemical effect. The positive space charge in the lower atmosphere is regarded as the source of both the fair weather potential gradient and the conduction current through the atmosphere.

While this theory of Wåhlin's may well have merit in describing . contributory source of positive space charge in the lower atmosphere, it cannot be regarded as the primary source of atmospheric electricity. In particular it cannot account for the existence of a potential gradient and conduction current in still air; it does not account for the increase of conductivity with altitude, nor indeed for variations in conductivity, and it cannot account for global variations in potential gradient.

Even more recently, at the Fifth International Conference on Atmospheric Electricity, KASEMIR (1974) proposed a new, and very elegant, theoretical model of the global atmospheric electric circuit. The most fundamental changes suggested were that the Earth carries a driving potential of about -300 kV, and that the ionosphere has a potential of about -30 μV, zero potential being at infinity. The conductivity was assumed to increase exponentially with altitude to infinity. This would seem to be a very convenient model in terms of which to consider some of the aspects of atmospheric electricity which are not easily explicable in terms of the spherical capacitor model. While generally a very satisfactory theory, on account of the assumption regarding conductivity, it is unsuited for problems concerning the electrosphere or ionosphere. The model, however, can be adapted to take account of such problems by introducing these parameters in the form of a suitable resistive path between the Earth and the zero potential at infinity. Suitable boundary conditions have to be chosen to solve the equations, the solutions of which are in general by no means trivial. This theory receives further consideration later in this thesis.

REITER (1971) has published evidence that following $H_\alpha$ solar flares, both the potential gradient (E) and the conduction current density (j) at the ground increased significantly. He found that the values of E and j appeared to start to increase on the day preceding the $H_\alpha$ flare and that the increases persisted until the second or third day following the flare. There also appeared to be an increase in thunderstorm activity coinciding with the increases in E and j. The suggestion was made that the increased thunderstorm activity led to an increase in electrosphere potential (V) and hence to the increases in E and j, since $E = V/R\lambda$ and $j = V/R$ (equation 2.2)). The precise mechanism whereby the thunderstorm activity increased was not defined. In a later paper, REITER (1972) extended the observations already mentioned and succeeded in showing correlations between E and j and other solar radiations, in particular with the 3 GHz radiation.

MÜHLEISEN (1971) has investigated in some detail the potential difference between the electrosphere and Earth. He found a mean value of 280 kV with an inverse correlation between electrosphere potential and sunspot number over an 11 year cycle. This would seem to imply that increased solar activity does not mean an increase of electrosphere potential. Other evidence which supports this finding was provided some years earlier by LIKHTER (1966) who found from studies of the intensity of atmospherics that thunderstorm activity appeared to be at a minimum during years of maximum solar activity, and at a maximium during the years of minimium solar activity. Thus the findings of Mühleisen would be the expected result in terms of the thunderstorm generator theory. One other significant aspect of this work was the correlation found to exist between V and E which also tends to confirm the classical global theory.

MARKSON (1971) has discussed in some detail the influence of solar and lunar activity on the parameters of atmospheric electricity and on thunderstorms. He made the interesting suggestion that galactic cosmic radiation may be the agency responsible for enhancing thunderstorm activity and the potential gradient. He pointed out that if this were so it must be expected that the ionosphere potential should correlate inversely with solar activity since galactic cosmic radiation is inversely correlated with the 11 year sunspot cycle. It has already been seen that this correlation was reported by MÜHLEISEN (1971).

DOLEZALEK (1972) has posed the question of whether the electrosphere, as seen from below, may be regarded as an equipotential surface or not. If not, then he argued that there should exist horizontal electric fields in the electrosphere. Dolezalek in fact stated that there can no longer be any doubt that such horizontal fields do exist. Measurements of horizontal fields have been made at 26 km and at 34 km altitude by MOZER (1972). Orders of magnitude of the horizontal and vertical fields were 20 mV $m^{-1}$ and 80 mV $m^{-1}$, respectively, meaning that the horizontal component was some 25% of the vertical component.

BOSSOLASCO et al (1972) have found that thunderstorm activity appeared to become a maximum 4 days after an $H_{\alpha}$ flare. In fact, they claim that on the fourth day following the occurrence of such a flare the global thunderstorm activity becomes 50 - 70% higher than normal. (The technique of evaluating thunderstorm activity which was used here involved the monitoring of 10 kHz sferics). The hypothesis put forward to explain these results was that corpuscular streams which are emitted by the sun at the time of the flare travel at about $10^3$ km $s^{-1}$ and reach the lower stratosphere and troposphere 40 to 60 hours later. These corpuscular streams then result in some way in increased thunderstorm activity. Bossolasco and his co-workers also found that the daily mean number of sferics relative to the five quiet sun years, 1962 to 1966, was about 7% greater than the daily mean number of sferics during the active years, 1961 and 1967 to 1970. This latter finding would appear to agree with the inverse correlation between solar activity, as measured by sunspot number, and electrosphere potential as discovered by MÜHLEISEN

(1971), discussed earlier in this section, and is further support for the findings of LIKHTER (1966).

UCHIKAWA (1972) suggested that the ionospheric potential was probably a function of where the measurement was made, e.g. over land, sea, polar regions etc. This concept would again lead to the necessity of the existence of horizontal fields. In a paper presented at the Fifth International Conference on Atmospheric Electricity, which took place recently in Germany, MÜHLEISEN (1974) produced evidence for the existence of a potential difference of 60 kV between two points in the electrosphere above two stations on the ground a distance of 6600 km apart. In very simple terms this would constitute a horizontal potential gradient in the electrosphere of about 9 mV $m^{-1}$.

Recently, PARK and DEJNAKARINTRA (1973) have suggested that giant thunderclouds may be an important source of localised electric fields which could give rise to magnetic field aligned electron density irregularities in the ionosphere and magnetosphere.

Summary. While it is often useful and convenient to regard the electrosphere as an equipotential surface, it must be realised that this is an oversimplified picture of the real situation. There is evidence that horizontal electric fields exist in the electrosphere and the potential of this region is not related in any simple way to solar activity. As has been seen, there is evidence of an inverse correlation between electrosphere potential and sunspot number over an 11 year solar cycle, but there is also evidence for a direct correlation between potential gradient values and the occurrence of $H_\alpha$ flares, and also between thunderstorm activity and $H_\alpha$ flares. (In terms of the classical picture, one would expect a direct correlation between thunderstorm activity and electrosphere potential). The influence of solar activity on the electrosphere will be dealt with in more detail in Chapter Eight, on the sunrise effect. There is also evidence that events outside the electrosphere can influence the electrical behaviour of the atmosphere below this region, and likewise it seems at least possible that thundercloud fields may penetrate into space well beyond the electrosphere.

## 3.3 THE PARAMETERS OF ATMOSPHERIC ELECTRICITY

### 3.3.1 Electric fields

The potential gradients in both the Arctic and the Antarctic polar regions have been investigated by KASEMIR (1972). He found in general that both areas produced diurnal variations in potential gradient which were of the same shape as the curve resulting from the 'Carnegie' voyage, but of smaller amplitude. Kasemir was of the impression that, besides thunderstorm activity, another (unspecified) modulating influence existed. This influence was more pronounced in the period from February to July than it was in the August to January period. Clearly, if Kasemir is correct in his contention, then this modulating influence is not seasonal since its maximum effect occurs simultaneously in both polar regions, and likewise its minimum effect.

It is generally recognized that one of the major factors obscuring global changes in potential gradient is the local influence of the lower atmosphere. The region of the lower atmosphere in which most of the air and its contents are fairly well mixed extends upwards to a definite level, usually visible as the level of fair weather cumulus clouds, or the top of the haze layer. The thickness of this layer, called the exchange layer, or austausch region, depends on meteorological conditions particularly the variation of temperature with altitude. CHALMERS (1967 p 44) gave the height of this region as being anything up to 3 km, while MANI, HUDDAR and SRIVASTAVA (1971) found that, in India, the height was 1-3 km in winter and 6 km in summer. They also found that the potential gradient decreased exponentially with height above the exchange layer, and that large variations in potential gradient were associated with clouds, dust, haze and aerosol layers. SAGALYN and FAUCHER (1954) found that the exchange layer varied between about 300 m and 3000 m with an average height of about 1800 m. They further found that the exchange layer exists over mountains, although its height above the ground is reduced, and that the height is subject to a seasonal variation, reaching a maximum in summer.

Many experiments have been designed to measure the potential gradient above the exchange layer and the approximately exponential decrease in value with increasing altitude mentioned above is well known. GISH (1944) gave the following relationship between potential gradient, E in V $m^{-1}$, and altitude, z in km:

$$E = 81.8 \exp(-4.52z) + 38.6 \exp(-0.375z) + 10.27 \exp(-0.121z).$$

This expression is plotted in Figure 3.5 where it is compared with the results of several balloon flights extracted from KOENIGSFELD (1953). It will be seen that the average experimental data show reasonable agreement with the empirical expression given by Gish above about 3 km. One particular balloon flight made on a clear day gave results which were more or less consistently about twice the magnitude of the empirircal curve.

In another balloon experiment, MOZER (1972) confirmed that the vertical electric field at altitudes of up to 36 km stemmed from fair weather atmospheric electricity sources. This conclusion resulted from simultaneous observations of the vertical component of the field at two spatially separated balloons, where it was found that similar variations in the field occurred at each balloon, and that the gradient measured at the higher balloon was always less than that measured at the lower balloon.

There have of course been many more observations of the potential gradient near the ground than there have been airborne experiments. This is largely because of the much simpler nature of the experiments involved, but it is also because many experiments have been deliberately designed to investigate the electrode effect close to the ground. The electrode effect will be discussed in the next section. An early investigation of

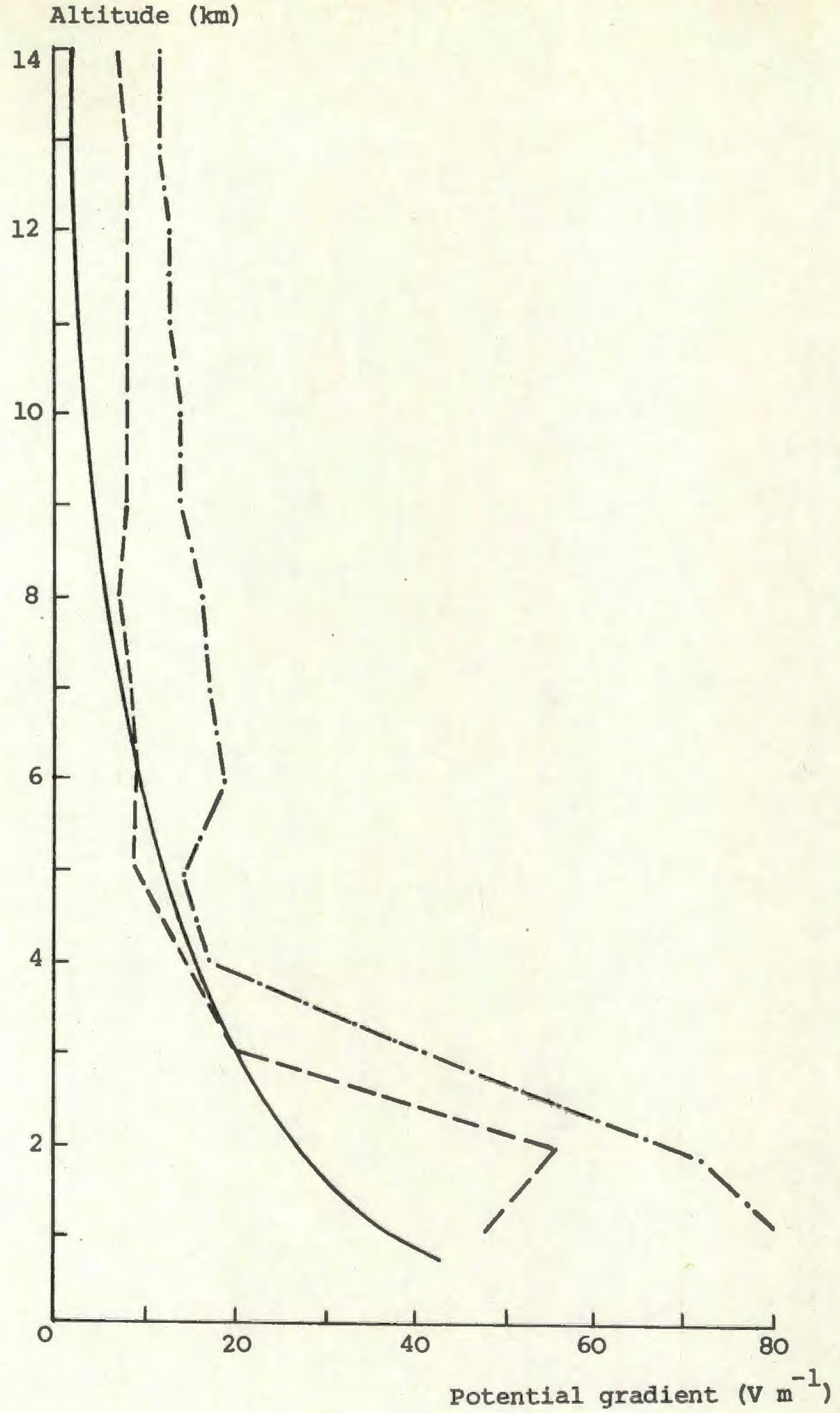



Figure 3.5 The variation of potential gradient with altitude. The empirical relationship of GISH (1944) (——) compared with the average results of ten balloon ascents, from KOENIGSFELD (1953) (- - -). A single balloon ascent which gave particularly high values is also shown (- · - · ).

the variation of potential gradient with height within a few metres of the ground was made by SCRASE (1935). In this experiment the potential gradient was measured at two fixed heights and the meteorological conditions under which observations were made were divided into two classes. The first class comprised those conditions which appeared to favour the accumulation of space charge, and the second those conditions where mixing would tend to prevent the accumulation of space charge. Scrase found that the ratios of potential gradient corresponding to the one class of condition showed no striking differences from the ratios associated with the other class. This general result, which appears rather surprising, has been confirmed in more recent work by MUIR (1972) (See Chapter Seven).

Short term variations in potential gradient have been investigated by KAMRA (1969a; 1969b). These variations, sometimes called 'agitation', have a magnitude which increases with increasing potential gradient. The agitation may be regarded as an oscillation superimposed on the ambient potential gradient and in general this oscillation varies both in amplitude and frequency. Kamra attributed the agitation to space charge due to the electrode effect in fair weather and to the aerosol content in disturbed weather. Furthermore, it was found that negative potential gradients were often encountered at high wind speeds. These values were attributed to the presence of negatively charged dust particles. Recently YERG and JOHNSON (1974) investigated variations in the potential gradient with periods ranging from about 17 seconds to about 4 minutes. These fluctuations were found to be caused by wind borne clouds of space charge 135 - 425 m in diameter near a level of 1 m above the ground.

HARRIS (1971) has investigated the potential gradients in northern Nigeria during the dry season. Of particular interest are the results associated with the dry dust-laden wind emanating from the Sahara desert and known as the Harmattan. Harris found large negative fields ($-5000\ V\ m^{-1}$) and explained these in terms of a layer of negative charge of surface charge density $5 \times 10^{-8}$ C $m^{-2}$ in the atmosphere close to the ground. This charge could conceivably have compromised the entire dust layer, all negatively charged, or it could have resulted from a dipole layer with the upper region positive and the lower negative. Harris regarded this latter explanation as being the more likely, but did not explain how the charge separation could occur. (The mono-polarity dust particle layer would require that the positive charge associated with the negative dust charge be left elsewhere, e.g. at the place of origin of the dust. An additional difficulty of the mono-polarity layer lies in accounting for the observation made that the field reversal vanished during the night and reappeared near sunrise).

The field reversals associated with the Harmattan have also been investigated by ETTE (1971). He reasoned that the electrification of the dust particles occurred at the instant of their dispersal into a cloud and quoted experimental evidence for the fact that in silica dust clouds the larger and heavier particles acquired positive charge, while the finer and lighter ones became negatively charged. The Harmattan dust particles ranged in size from 0.1 to 0.4 μ and were kept aloft by convection during the day. At night, when the lapse rate became stable and surface winds died down, the heavier particles settled under the influence of gravity. Particles within the lowest layers acquired positive charge, probably through the nighttime electrode effect. With the destruction around sunrise of the night inversion by convection, the electrode effect disappeared, the surface haze slowly cleared (the haze was due to the positive charges resulting from the electrode effect which acted as condensation nuclei), and drier dust particles at higher levels were dispersed and brought down through austausch to produce a cloud of negative space charge near the ground.

BARNES (1973) favoured photoionization as the prime mechanism of charge generation relating to the Harmattan on account of the low moisture content of the atmosphere, but this seems unlikely in view of the earlier finding by KASEMIR (1956) that no ionization caused by sunlight has been observed in the air near the Earth. Barnes contended that Ette's explanation did not account for the fact that there was no field reversal at night, even when a dust haze persisted, and neither did it account for the fact that the field reversal still occurred when there was no visible dust haze.

Simultaneous measurements of space charge density at two different heights during the Harmattan have recently been reported by OLUWAFEMI and ETTE (1974). They have found evidence that negative charges responsible for initiating diurnal reversals in the air-Earth current and potential gradient moved downwards from aloft under the action of convection currents. They further found that a 3 m deep electrode effect layer seemed to be a regular feature at night during the Harmattan season.

It is apparent from the foregoing that the potential gradient is particularly sensitive to any form of electrical pollution of the atmosphere. It is certain that most pollutants, even if uncharged, have an effect on the electrical behaviour of the atmosphere. Consequently, radioactive fallout should be noticeable. This was predicted by PIERCE (1957) and in a recent paper, PIERCE (1972) produced evidence from six stations in Britain, Portugal and Japan which supported his prediction. The effect of the radioactive fallout was to cause a build up of surface radioactivity which enhanced the conductivity of the lower atmosphere. As equation (2.2) shows, $E = V/R\lambda$, so if V and R remain constant, while $\lambda$ increases, E must decrease. Pierce found evidence of such a decrease during the years 1950 to 1964 when most nuclear testing was carried out. Pierce's results have been extended and his findings generally confirmed by COLLINGBOURNE (1972).

Another aspect of atmospheric nuclear testing has been dealt with by HOLZER (1972), who measured the potential gradient at ground level in the vicinity of nuclear explosions. It was found that the explosions produced dipoles, with the negative charge uppermost, with moments of a few coulomb kilometres. The electric field due to the nuclear cloud was observable for several minutes after the explosion and the dipole moment of the cloud appeared to increase as it moved upwards. This dipole effect of a nuclear explosion will have a much shorter duration and a much more local effect than will the subsequent radioactive fallout.

The electrode effect. Reference has already been made on several occasions to this effect and it is necessary to clarify the precise meaning of the term when applied to atmospheric electricity.

The electrode effect may be described as follows: It is assumed that ions are generated only in the region between the electrodes so that no positive ions can reach the anode (the electrosphere) and no negative ions the cathode (Earth). Thus, as an electrode is approached there is an increasing depletion of ions having the same sign as the electrode. The resulting space charge in the vicinity of the electrode is termed the electrode effect. BENT and HUTCHINSON (1966) have proposed a general definition of the electrode effect as follows:

> *In atmospheric electricity the electrode effect is the modification of elements such as space charge distribution, conductivity and potential gradient near an earthed electrode, which may be a raised object or the surface of the Earth itself, because in the prevailing electric field ions of one sign are attracted towards the electrode, whilst those of opposite sign are repelled from it.*

The electrode effect has been the subject of various investigations, both experimental (e.g. CROZIER, 1963) and theoretical (e.g. LATHAM and POOR, 1972). One important finding is that the effect is generally difficult to detect except under conditions of extreme atmospheric stability. Further mention of this is made in Chapter Eight.

### 3.3.2 Electric currents in the atmosphere

There are five electric currents which may flow in the atmosphere, excluding lightning discharges. These are conduction current, displacement current, convection current, precipitation current and point discharge current. Of these, only the first three are of importance in fair weather electricity; although clearly all five, together with the lightning discharge current, are of importance in the global picture of atmospheric electricity.

Conduction current. This is the current which results from the movement of ions under the influence of the prevailing electric field. Under normal fair weather conditions, positive ions move downwards, negative upwards, so that a conventional current flows downwards through the atmosphere. If the conduction current is the only current flowing in the atmosphere, then the current density must be constant at all altitudes between Earth and electrosphere.

For various reasons it is extremely difficult to measure the conduction current density accurately. Very often the easier measurements of potential gradient (E) and conductivity ($\lambda$) are made, and the current density calculated from $j = E\lambda$. ($\lambda$ here is the total conductivity due to both positive and negative ions, $\lambda = \lambda_1 + \lambda_2$). However; since this procedure assumes that Ohm's law applies it is clearly of no use in testing the validity of the law when applied to the atmosphere. COBB (1968) has found that in Hawaii the calculated value $j = E\lambda_1$ was more in agreement with the measured value than was $j = E\lambda$. It would thus seem to be necessary to test the validity of Ohm's law in this case.

Most observers have found that the conduction current shows a global variation in accord with the global variation in potential gradient (see CHALMERS, 1967 p 216). The conduction current is also quite strongly dependent on wind speed and on the presence of pollutants, since these change the conductivity. These effects have been shown by OGAWA and

KODERA (1971) and this aspect is discussed more fully in Section 3.3.3.

Displacement current. It has already been shown, in Section 2.4, that any variation of the potential gradient produces a displacement of the bound charge on the collector. This displacement current may be large enough to introduce very significant errors into the measurements of the true current flowing to Earth. One attempt at overcoming this was made by ADAMSON (1960) who devised a compensating system to make allowance for the displacement current component in the total air-Earth current. Earlier, KASEMIR (1955) showed that, as long as the conductivity of the atmosphere remains constant, the effect of displacement current may be eliminated by suitably matching the time constant of the collector circuit to the relaxation time of the lower atmosphere.

Convection current. The two distinct methods used to determine the air-Earth current are the direct measurement with a collector, and the indirect method involving the use of Ohm's law mentioned above. In order to compare the results of the two methods, it is necessary to eliminate the displacement current component from the direct measurement. If, having done this, the results obtained by the two methods do not agree, and if Ohm's law is assumed to apply, then it is reasonable to suppose that the conduction current given by the indirect method does not constitute the total current. Some additional vertical current must be present and this current is due to mechanical transport of charge vertically in the vicinity in which the direct measurement is made. This component of the total current is termed the convection current.

While some workers have found that the convection current is unimportant, the difference between the results of the two methods being less than 10%, (e.g. NOLAN, 1940), recent work by ASPINALL (1972) has indicated that the convection current almost entirely governs the diurnal variation of the air-Earth current. As a result of his findings, Aspinall expressed considerable doubt about statements made concerning global conditions which were based on variations of total current.

Precipitation current. Although the charge carried to ground on precipitation of various sorts does not properly constitute a phenomenon of fair weather electricity it is mentioned here as an important facet of the global picture. A report of recent work on precipitation current, describing some of the techniques used to measure it, has been published by LANE-SMITH (1972). Clearly the effect of this current must be taken into account when attempts are made to investigate the global charge balance situation. Various estimates (CHALMERS, 1967 p 304) put the precipitation current contribution at between 20% and about 65% of the total fair weather conduction current contribution to the global charge balance situation.

Point discharge current. Again, this is not strictly a fair weather phenomenon, but it is included here to complete the picture. In the vicinity of thunderstorms when the potential gradient near the ground may become very high it is found that many objects, particularly if pointed, act as sources of current flowing between the Earth and the atmosphere. Examples of such pointed objects are trees, towers and even blades of grass. One global mean value of point discharge current density, given by ETTE and UTAH (1973b), was $-1.3 \times 10^{-9}$ A $m^{-2}$. The negative sign indicates that this current flows in the opposite direction to the fair weather conduction current.

### 3.3.3 The conductivity of the atmosphere

The conductivity of the atmosphere depends essentially on the mobility of the various ions in the atmosphere. Generally, small ions have greater mobilities than do large ions and consequently air with a larger proportion of small to large ions will have a higher conductivity than will air with more large ions.

Conductivity generally increases with altitude and GISH (1944) has given the following expression for altitudes, z, greater than 10 km:

$$\lambda = \left(2.71 \exp(0.121z)\right) \times 10^{-13}\ \Omega^{-1}\ m^{-1}.$$

There are other expressions for the increase in conductivity with altitude, but they all show the same general trend although specific values differ.

As has been mentioned, conductivity is dependent upon particle size. The presence of pollutants in the air, either as aerosols or as heavier particulate matter, tends to lead to an increase in the number of large ions. In this way the conductivity decreases, and from the equation $j = E\lambda$ it is seen that when the current density is constant, E must increase. Measurements of conductivity have been used in attempts to monitor the level of atmospheric pollution. OTTEVANGER (1972) attempted to relate changes in conductivity to the onset of fog, but it was apparent that the connection between the two was too dependent on meteorological elements to be regarded as a problem of atmospheric electricity alone. COBB (1973) found that in most of the oceanic regions of the world, the natural aerosol level has remained unchanged by the activities of mankind. Significant exceptions noted were the paths of aerosol pollution which extended eastward from North America, from Japan, and southward from Asia. According to Cobb, most of this pollution was due to the combustion of fossil fuels and it follows that present levels of pollution should decline with the inevitable change to other forms of energy production.

ANDERSON and LARSON (1974) have shown that it is possible for naturally occurring radon in the atmosphere to have a direct measureable effect on conductivity. This was particularly apparent when a temperature inversion existed. This evidence they interpreted as indicating that the area in question would not be suitable for industrialization because of future pollution problems.

The 'columnar resistance' of the atmosphere, that is the resistance of a column of atmosphere 1 $m^2$ in cross-sectional area stretching between the conducting Earth and the conducting electrosphere, is also very much a function of conductivity. The greater part of the columnar resistance is in the exchange layer and, as a result, it is subject to a diurnal variation and has also been found by OGAWA and KODERA (1971) to be influenced by surface wind. UCHIKAWA (1972), in Japan, has noticed that the columnar resistance showed very marked seasonal variations, and that it was also affected by nuclear explosions.

DOLEZALEK (1972) has found that, generally, variations in columnar resistance above the exchange layer were negligible compared with those occurring lower down in the atmosphere. He also tentatively suggested that it may be possible for a potential difference to occur somewhere in the resistance column which was not due to the drop in potential caused by the vertical current flow. Such potential differences would be due to external sources, and these would constitute regional generators according to Dolezalek's definition. The precipitation of charged particles in the upper atmosphere in polar regions may be one such external source.

### 3.3.4 Space charge in the atmosphere

In any region of the free atmosphere there are always positive and negative ions present. Very often these ions occur in roughly equal numbers, so that a volume of the atmosphere has no net charge. If however, there is an excess of one type of ion over the other, then the volume has a net charge which is referred to as space charge. The net space charge over land stations has been stated by BENT and HUTCHINSON (1966) to be about -10 pC $m^{-3}$ on average.

Techniques of measuring space charge will be discussed later (Chapter Seven), while some of the general findings concerning this parameter of atmospheric electricity will be dealt with here.

SCRASE (1935), in an early space charge experiment, found that both large and small ions contributed to space charge. He also found that space charge concentration did not show the dependence on atmospheric turbulence which might have been expected. This somewhat surprising result has been confirmed by other workers, e.g. MUIR (1972), and this fact has already received mention in Section 3.3.1 of this chapter. BROWN (1933) found that at sunrise the space charge at 1 m rapidly diminished, while 1 hour later the space charge at 15 m began to decrease. Brown stated that these decreases quite evidently resulted from turbulence and vertical convection. He found that on overcast, or foggy, mornings these changes either didn't occur at all, or they were very greatly diminished. (The particular behaviour of the atmospheric electric parameters at sunrise, called the sunrise effect, is dealt with in Chapter Eight).

LAW (1963) found at Cambridge that the space charge was typically positive by day and negative by night. He used this change in the sign of the space charge to explain the sunrise effect in terms of a convection current component in the total air-Earth current.

CROZIER (1965) found that, during the day, and at night when the wind speed exceeded 1 m $s^{-1}$, the space charge near the ground was positive and both space charge density and potential gradient decreased monotonically with altitude. This finding was consistent with the effect and eddy diffusion. However, under conditions of very low wind at night, Crozier found that a dense positive charge layer about 0.25 m thick covered the ground, with negative space charge of moderate density above this up to 3 m. This observation was explained in terms of a rate of ion production within 20 cm of the ground which was considerably greater than at higher levels. Above the stratum of strong ionization, and perhaps within its upper part, the density of upward moving negative ions could easily exceed the density of downward moving positive ions and negative space charge would result.

VONNEGUT et al (1961) have shown that it is a fairly simple matter to modify the fair weather electric field over a large area. An elevated horizontal wire, maintained at a negative potential of 12 kV with a corona current of about 1 mA flowing, was found to reverse the normal fair weather field for a distance of more than 10 km downwind. Later experiments by VONNEGUT et al (1962) have confirmed these results and further shown that when there was convection, the charge was rapidly carried aloft by thermal updraughts. Large perturbations in the potential gradient and space charge density were observed. YERG and JOHNSON (1974) have found that wind borne clouds of space charge of diameter between 135 and 425 m produced variations with frequencies of 0.004 to 0.06 Hz in potential gradient measurements. The source, or sources, of the space charge clouds were not identified.

It may be shown, following MOORE et al (1962) that space charge density is sensitive to the vertical distribution of conductivity in the atmosphere. It has been shown that $E\lambda = j$ where $E$ is the vertical potential gradient, $\lambda$ is the conductivity and $j$ the conduction current density. The variation of potential gradient with altitude is then

$$\frac{dE}{dz} = \frac{d}{dz}(j\lambda^{-1}) = -j\lambda^{-2}\frac{d\lambda}{dz} + \lambda^{-1}\frac{dj}{dz}.$$

For steady state conditions, where $j$ is constant with altitude, i.e. $dj/dz = 0$,

$$\frac{dE}{dz} = -j\lambda^{-2}\frac{d\lambda}{dz}.$$

Now, Poisson's equation gives

$$\frac{dE}{dz} = \frac{-\rho}{\varepsilon_0}$$

where $\rho$ is the space charge density and $\varepsilon_0$ is the electric space constant. Equating these expressions yields

$$\rho = \frac{\varepsilon_0 j}{\lambda^2}\frac{d\lambda}{dz}.$$

Thus, if $\rho$ is positive $d\lambda/dz$ is positive so that $\lambda$ must increase as $z$ increases. Also, for a layer over which $\lambda$ is constant, $d\lambda/dz = 0$ and it follows that $\rho = 0$. If $\lambda$ decreases with $z$ then $\rho$ is negative. As a result of this it may be concluded that whenever a current is flowing an accumulation of space charge will be found at boundaries and layers where the conductivity of the air changes. For example, in a layer of haze, which has low conductivity, downward moving positive ions should accumulate at the top of the haze to form a layer of positive space charge, while at the bottom upward moving negative ions form a region of negative space charge.

Generally, vehicle and stationary engine exhaust gases are highly electrified, and MÜHLEISEN (1956) has catalogued the following sources of space charge:

| Positive | Negative |
|---|---|
| Exhaust (petrol and diesel) | Petrol fire - open |
| Chimney smoke | Alcohol fire - open |
| Coal powder fire | Wood fire - open |
| Engine steam | Water vapour (pure from a metal jet) |
| Steam cloud (gas works) | |

Work at Durham, in England, by BENT et al (1965) has shown that the space charge produced by point discharge is typically about -500 pC $m^{-3}$ (about 3000 electronic charges per cubic centimetre). MOORE et al (1962) have found that a plume of positive space charge extended downwind from a television mast on certain occasions. This was explained as being due to the electrode effect in the enhanced field near the mast where apparently the radii of curvature of the surfaces near the top of the mast were too large to permit point discharge to take place.

BENT and HUTCHINSON (1965) working in Durham found space charge densities of the order of -880 pC $m^{-3}$ up to 1 m, with positive charge of density +120 pC $m^{-3}$ between 1 and 21 m when observations were made over rapidly melting snow. The negative charge was released into the atmosphere by the melting snow, while the positive charge above 1 m was explained in terms of space charge generated by distant wind blown snow. These results have been generally confirmed by MUIR (1972) working at the same site in

Durham. At this site also, OGDEN and HUTCHINSON (1970) found pulses of space charge of uncertain origin. These pulses had a sharp leading edge and their amplitude of about 50 pC $m^{-3}$ was often large enough to change the sign of the ambient space charge. The pulses were observed in sunny weather and they did not extend more than a few metres above the ground. They lasted for typically seven minutes and were of either sign. Ogden and Hutchinson show that bouyant plumes of convection carrying space charge could not be responsible for the pulses.

GATHMAN and HOPPEL (1970) considered the bursting of bubbles at the air-sea interface, in conjunction with the electrode effect, to be the source of the positive space charge generally found over the sea. This aspect of the generation of space charge is dealt with in Chapter Seven.

Finally, it may be said that the distribution of space charge in the lower atmosphere is highly variable, both with respect to quantity and sign, and clearly this variability will be particularly noticeable in urban areas. Factors which markedly affect the space charge density are pollution, radioactivity, convection and so on. It follows then, that if the space charge in the lower atmosphere is responsible for the initiation of electrification in cumulus clouds, as has been suggested by VONNEGUT and MOORE (1958), then this must also be a highly variable process.

### 3.3.5 Relations between atmospheric electric parameters and meteorology

It has been stated by LUAN and JORDAN (1970) that there has been a 50% to 60% increase in the number of cloudy days over many large cities in the last 50 years. This is due to the general increase in aerosol and particle pollution of the atmosphere, with the corresponding increase in the number of condensation nuclei. Luan and Jordan noticed in their work that the rate at which fog droplets precipitated appeared to be affected by the presence of ions, but only when ions of both sign were present.

OTTEVANGER (1972) tried to relate the formation of fog with the electrical conductivity of the atmosphere and came to the conclusion that conductivity measurements did not provide significantly better fog forecasts than resulted from studying the trend of synoptic reports. The conductivity measurements must clearly relate to the pollution present as has been seen, and it is interesting to note that KOCMOND and MACK (1972) have found significant increases in Aitken and cloud nuclei within 30 km (and sometimes 80 km) downwind of pollution sources.

SIVARAMAKRISHNAN and SELVAM (1971), working in India, found that surface values of potential gradient increased while conduction current decreased in fog and mist. These changes occurred about 1 to 2 hours before the onset of fog, while the reverse changes occurred ½ to 1½ hours before the dissipation of the fog. These results, they claimed, would possibly be of use in short term weather forecasting.

CHALMERS (1952) and GROOM and CHALMERS (1967) showed that negative potential gradients often existed in mist and fog and that these may be explained in terms of negative space charge being liberated at overhead high tension power lines under such weather conditions. In Hawaii, TAKAHASHI (1972) has shown that in fine weather, the majority of particles between 1 and 40 μ in diameter were positively charged. However, under conditions of high humidity, negatively charged particles were frequently observed.

MANI, HUDDAR and SRIVASTAVA (1971) have made the general observation that all meteorological events are accompanied by characteristic changes of the various atmospheric electric parameters. The particular case of the connection between values of the potential gradient and simultaneous values of various meteorological elements has been investigated by BHARTENDU (1971). He found that both the rate of increase of temperature and the rate of decrease of relative humidity appeared to influence the potential gradient.

Much of the effort which has gone into investigating the relationships between atmospheric electricity and meteorology has been devoted to the study of thunderstorm electrification. VONNEGUT and MOORE (1958) argued for a theory of thunderstorm electrification in which fair weather space charge was the agency responsible for initiating the electrification of the thundercloud. This theory, generally referred to as Vonnegut's theory, is only one of a large number of theories which have emerged from time to time to try to explain the difficult problems involved in thundercloud electrification. A competent survey of this subject was published recently by SARTOR (1973), although interestingly enough, no reference is made in this work to Vonnegut's theory.

The effect of wind on potential gradient measurements has also been the subject of some study. BHARTENDU (1971) concluded that the effect of wind was unimportant, while KAMRA (1969b) found that high wind speeds tended to reduce the value of fair weather potential gradients. It is, of course, a well known phenomenon that the agitation in potential gradient measurements is closely allied with wind speed. Under calm conditions, the output of a field mill recorded on a chart recorder will yield a 'clean' trace. In windy conditions, rapid fairly large amplitude variations in potential gradient - the so-called agitation - are evident. These variations are attributed to wind borne pockets of space charge.

Space charge associated with dust storms has been investigated by KAMRA (1972). (See also HARRIS, 1971 and BARNES, 1973). Kamra found that under dust storm conditions the space charge density reached values of the order of $10^5$ pC $m^{-3}$, while the potential gradient could be many kilovolts per metre.

The importance of meteorology to atmospheric electricity was pointed out by ANDERSON and LARSON (1974). They found that when current density was computed as a product of measured conductivity and measured potential gradient in a region where there was a temperature inversion, Ohm's law was obeyed and the current density was essentially constant with height. However, over the ocean nearby turbulent transport phenomena did not permit of any such simple findings. They concluded that representative electrical measurements should not be attempted without investigating possible interfering conditions.

A recent study by WILCOX (1975), while not specifically concerned with atmospheric electricity, should be included here. This study concerns the broad field of the relationship between solar activity and meteorology. His major finding is that not much conclusive evidence relating meteorology to solar activity has been forthcoming over the last 75 years! However, in spite of this, he concludes that there is a connection between these phenomena. In another recent survey, KING (1975) concludes that Sun-weather relationships should become a major field of research in the next decade.

In conclusion, it may be said that while many of the effects of meteorological elements on the parameters of atmospheric electricity are well known, not many of them have been really satisfactorily explained. The entire subject of investigating whether observations of various atmospheric electric parameters will help to understand, explain, observe or predict meteorological conditions is being actively pursued in many parts of the world.

# Chapter Four

## AN OUTLINE OF THE EXPERIMENTAL INVESTIGATION

*In the discovery of secrets and in the investigation of the hidden causes of things, clear proofs are afforded by trustworthy experiments rather than by probable guesses and opinions.........*

William Gilbert (1544-1603)
'De Magnete'

### 4.1 INTRODUCTION

The three main parts of the experimental investigation described in this thesis comprise measurements of potential gradients; determinations of space charge densities and investigations of the sunrise effect. The instrumentation developed for the work is described in the next chapter. The experiments, and the results obtained, are dealt with fully in Chapters Six, Seven and Eight. In this chapter, an outline only of the experiments will be presented, in order to account for the instruments required.

Before dealing with the experiments, it is desirable to review both the past history of similar work in South Africa and the priorities with which the outstanding problems are currently viewed.

### 4.2 HISTORY OF ATMOSPHERIC ELECTRICITY IN SOUTH AFRICA

HALLIDAY (1931) has given a brief account of the early work in fair weather electricity conducted in South Africa. Principally this involved measurements of potential gradients made by W. A. Douglas Rudge. RUDGE (1912) expressed the feeling that some sort of relation should exist between the value of the potential gradient due to the charge existing in the air and the altitude of the place of observation. To obtain information in this regard he used a portable electrometer to make observations at as many places as possible between sea level and an elevation of nearly 2150 m above sea level. As a result of his observations, Rudge concluded that the potential gradient due to the normal electrification of the atmosphere varied inversely with altitude. During the course of these experiments, Rudge also found the expected large amount of negative electrification in the vicinity of a waterfall. The conclusion regarding the variation of potential gradient with altitude must be treated with considerable reserve since observations at different places were made at different times on different days, often with varying weather conditions and presumably with differing degrees of industrial, domestic and natural pollution of the atmosphere.

A systematic observation of potential gradients at a single site was reported on by RUDGE (1914) following his work in Bloemfontein. These observations covered a six month period from July to December, 1912. The major findings noted by Rudge were that dust in the atmosphere was negatively charged and could cause large perturbations in the ambient field, and that the rain which fell during the period of observation was invariably negatively charged.

E.C. Halliday, who as a student had been associated with B.F.J. Schonland at the University of Cape Town, joined the University of the Witwatersrand as a lecturer in 1927. Feeling that practically nothing was known of the electrical conditions over the surface of the southern part of Africa, with only the work of Rudge having been done in this field, he embarked on a program of potential gradient measurements in Johannesburg. Observations were made from February, 1929, until November, 1930, and the findings reported by HALLIDAY (1933). Halliday paid considerable attention to the influence of pollution and local meteorological conditions on the values of potential gradients obtained. He found that most of the deviations which his results showed when compared with those of other places in the world could be adequately explained in terms of the effects of pollution, of wind and of cloud cover.

Atmospheric physics research in South Africa at about this time, and for many years afterwards, tended to revolve around Dr. B.F.J. Schonland.

Schonland started work in Cape Town in the field of disturbed weather atmospheric electricity about 1928. In 1937 the Bernard Price Institute for Geophysical Research was founded with an endowment given by Dr. Bernard Price of the Victoria Falls Power Company. Schonland moved to Johannesburg as the first Director of the B.P.I. which, in 1938, had on its staff as Research Assistants J.W. van Wyk and J.S. Elder, both with an interest in lightning. Honourary Research Associates at this time were Prof. D.B. Hodges in Durban and Dr. D.J. Malan in Cape Town. Halliday, who had returned to the University of the Witwatersrand after a period in Britain, retained some interest in atmospheric electricity.

During the second world war most of this group were actively involved in the development of radar in South Africa and after the war, in 1946, Malan left Cape Town to join Schonland as Principal Research Officer at the B.P.I. This move marked the beginning of the most productive phase in lightning research at the B.P.I. An active group at the University of Natal, in Durban, retained an interest in atmospheric electricity, initially under Hodges, and later under his successor as Professor of Physics, N.D. Clarence.

The retirement of Schonland and, later, the death of Malan marked the end of lightning research at the B.P.I. Halliday had joined the Council for Scientific and Industrial Research and, shortly after joining, transferred his attention to the problems of atmospheric pollution. Currently, the National Electrical Engineering Research Institute, and to a lesser extent the National Physical Research Laboratory, of the C.S.I.R.; the Electricity Supply Commission and, to a small degree, the National Institute for Telecommunications Research of the C.S.I.R. constitute the only bodies actively engaged in lightning research in South Africa. In the field of fair weather electricity, only the University of Natal in Durban has retained an interest.

Finally, summarising the work in fair weather electricity, it must be noted that the only observations made were observations of potential gradient. Systematic potential gradient records were obtained during a six month period in 1912 in Bloemfontein and during the two years, 1929 and 1930, in Johannesburg. In addition to these, a few scattered records were obtained by RUDGE (1912), as already seen, while PAGE-SHIPP (1968) obtained a few records during 1967 at sites in and near Durban.

## 4.3 SOME OF THE OUTSTANDING PROBLEMS OF FAIR WEATHER ATMOSPHERIC ELECTRICITY

The Fifth International Conference on Atmospheric Electricity took place in Garmisch-Partenkirchen, West Germany, in September 1974. Circulars advising all interested persons about the conference were sent out fairly regularly, beginning in April, 1971. One of the major functions of these early circulars was to ask intending participants to outline the problem areas as they saw them.

As a result of the responses to the circulars the final program was drawn up. The conference was conducted in 9 sessions and the titles of these sessions outline in very broad terms the problems and topics considered most important by those working in the field of atmospheric electricity. The 9 sessions were:

1. Ions, basic research.
2. Ions, applied research: Atmospheric electricity and meteorology.
3. Principles and problems of instrumentation, methods of calibration, data handling.
4. Cloud physics, non-convective clouds and precipitation.
5. Thunderstorms and showers.
6. Global circuit and ten-year program*.
7. Atmospheric-space coupling, solar terrestrial effects, atmospheric electricity of other celestial bodies.

8. and 8a. Physics of lightning and sferics.

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* The ten-year program was a program initiated by Dolezalek in 1967 following the meeting of the Joint Committee on Atmospheric Electricity (a committee of IAMAP, IAGA, UGGI and ICSU) in Paris, 1965. The aims of the program were to facilitate the exchange of data and to foster 'global' experiments.

## 4.4 THE EXPERIMENTS

The experimental investigations which form the subject of this thesis can now be briefly outlined in the context of the history of previous South African work and of the outstanding problems in the field.

### 4.4.1 Measurements of potential gradients

DOLEZALEK (1972) has cast some doubts on the correlation between global thunderstorm activity and fair weather potential gradient variations. It was decided to look at this aspect of the work quite specifically over a period of at least several months during which predominantly fair weather could be expected. For this purpose two possible sites were available, either in Durban or in Kloof, some 20 km inland from Durban at an elevation of about 550 m above sea level. Shortage of equipment and the difficulties experienced in processing too large a quantity of data precluded the use of both sites together. The Kloof site was chosen for the experiment since the atmosphere is comparatively unpolluted in this area. Since both industrial and sea generated pollution levels were low, it was felt that records obtained at Kloof would have a better chance of exhibiting global variations than would those obtained in Durban.

In a preliminary experiment, some potential gradient records were obtained from two sites at Ballito Bay on the coast north of Durban during August and September, 1972 and May, 1973. All of these records are described in detail in later chapters. Further coastal environment work was carried out subsequently on the Zululand coast in July, 1975.

All potential gradient measurements were made with conventional field mill techniques. The actual field mills developed for this work are described in the next chapter.

### 4.4.2 Determinations of space charge densities

A technique of utilizing field mills which are separated vertically has been developed by the author to determine space charge densities. The first results of using this technique were obtained in England in 1971. The technique is described in detail and these first results are discussed in Chapter Seven.

Space charge densities have been determined at Ballito Bay and Mtunzini on the coast and at Kloof, inland from the coast. In order to investigate the role of the surf action in the generation of space charge at Ballito Bay during the second experiment there in 1973 a knowledge of the wind speed and direction was required. For this purpose a recording anemometer was developed, and this instrument is described in detail in the next chapter.

### 4.4.3 The sunrise effect

The author has recently suggested in the literature, MUIR (1975), that the increase in potential gradient which commences at about dawn, and which is known as the sunrise effect, is possibly of ionospheric origin. The investigation of this sunrise effect is dealt with in detail in Chapter Eight.

For this investigation it was necessary to know the air temperature and the relative humidity, and to these ends a recording aspiration psychrometer was developed. This instrument is, like the others, described in detail in the next chapter.

# Chapter Five

# INSTRUMENTATION

*He made an instrument to know*
*If the moon shine at full or no.*

Samuel Butler (1612-1680)
Hudibras, part II

## 5.1 FIELD MILLS

### 5.1.1 Introduction

The field mill is a device which is widely used for determining the atmospheric electric potential gradient at the Earth's surface. Various types of mill have been used and a review of field mills, together with the theory of their operation, has been given in a paper by MAPLESON and WHITLOCK (1955). The basic principle of operation consists of alternately exposing an insulated metal plate to, and shielding it from, an electric field. The insulated plate is connected to ground through a high resistance and during the exposing and shielding process a displacement current flows to and from the plate through the high resistance. The output is thus in the form of an alternating voltage whose amplitude can be shown to be proportional to the magnitude of the field.

The waveform of this alternating voltage depends on the shape of the measuring plate (stator) and the shielding plate (rotor). The waveform undergoes a phase change of $\pi$ when the field reverses sign.

### 5.1.2 Mechanical construction

The instruments developed for this work and described here incorporate several unusual features. These instruments were developed for continuous operation under severe climatic conditions with a minimum of attention.

Initially field work was carried out at a site at Ballito Bay on the coast to the north of Durban. This region has a sub-tropical climate and the content of salt in the atmosphere is high. Although mains power was available for the field station operation, no facilities existed for the installation of laboratory equipment, so that each field mill had to contain its own miniature chart recorder. Further, since it was desired that the field mills should also be suitable for use in more remote areas where no mains power was available, it was decided that they should be d.c. operated.

The measuring plate is a circular steel plate about 15 cm in diameter mounted on PTFE insulators. The rotor, cut to the shape shown in Figure 5.1(a) is mounted on a shaft passing through a hole in the centre of the measuring plate. The shaft and rotor are turned at about 3000 r.p.m. by a brushless d.c. electric motor. A bias plate, of the same shape as the rotor, is mounted on insulators above the rotor as shown in Figure 5.1(b). A negative potential applied to the bias plate causes the zero of the recording instrument to be offset, allowing the instrument to discriminate between positive and negative fields. This sign discrimination is described more fully in Section 5.1.3.

The stator-rotor-bias plate assembly is mounted on either the top or bottom (for the inverted field mill) of an aluminium box. The box, which is about 30 cm × 25 cm × 21 cm also houses the motor, all electronic circuits and controls and the miniature chart recorder. The chart width is about 5.4 cm, and since these recorders use a dry recording process on pressure sensitive paper they are well suited to the present application. Photographs of the field mills are shown in Figure 5.2.

### 5.1.3 Electronic and electrical circuitry

The amplifier. The final amplifier design developed for the field mills is shown in Figure 5.3 and the list of component values is given in Table 5.1. Integrated circuit operational amplifiers are used for all stages. The

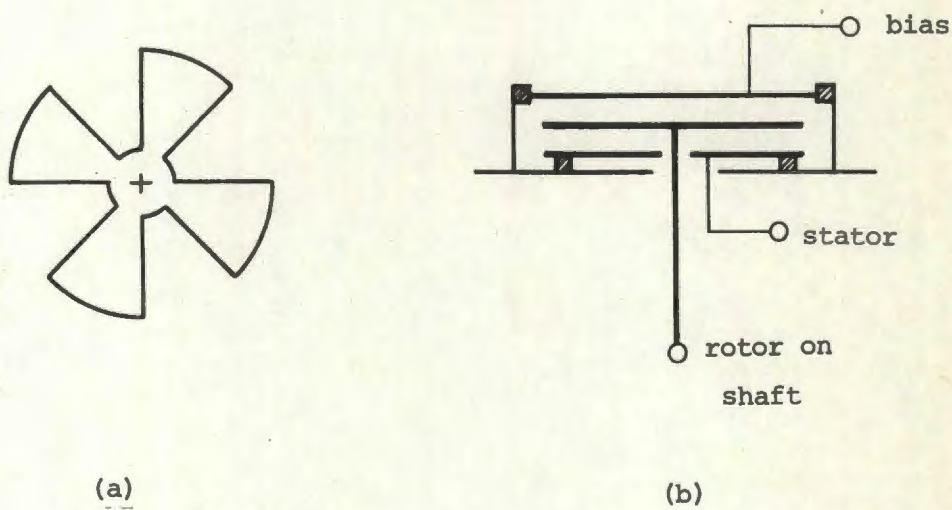
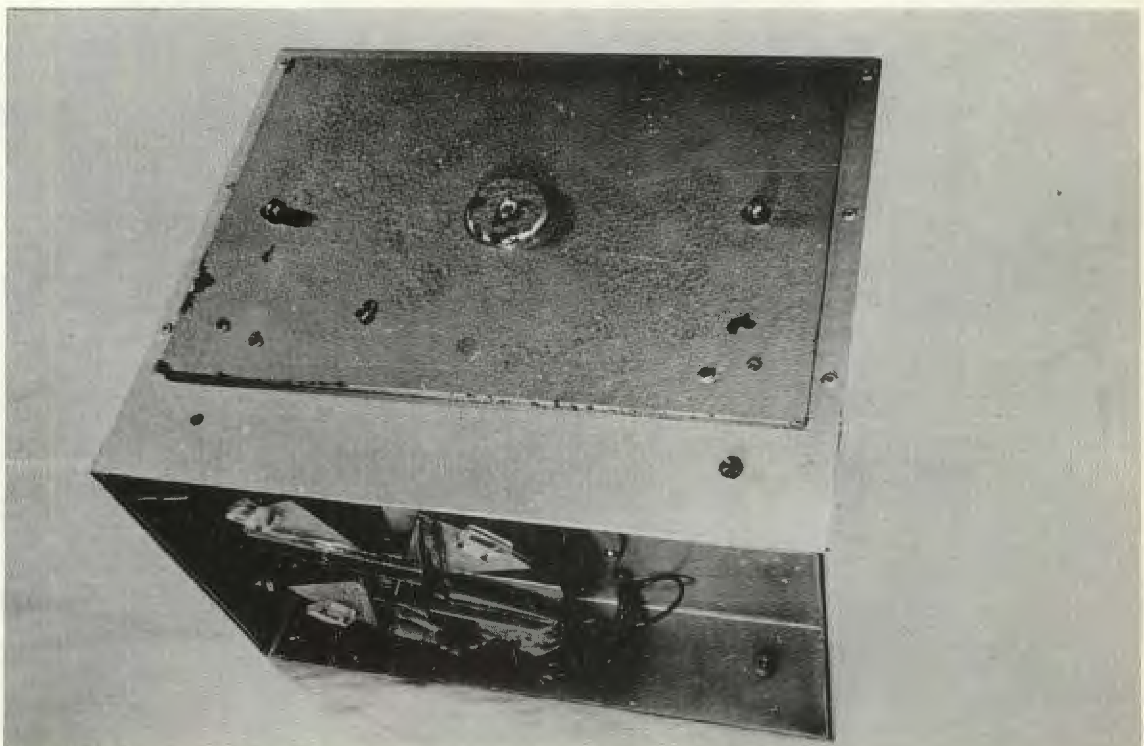



Figure 5.1 Details of the field mill construction:

(a) The shape of the rotor and bias-plate.

(b) The stator, rotor and bias-plate assembly


(a) Upright type, cover door removed to show controls and miniature recorder in position.



(b) Inverted type, cover door in position.

<u>Figure 5.2</u> The field mills.

first stage is a high input impedance follower which is used to prevent loading the mill measuring plate. The input to the first stage is protected against voltage surges resulting from nearby lightning discharges by a pair of diodes.

Because of the high input impedance it was found that there was considerable pick-up of 50 Hz hum. To counter this, the second stage is an active 50 Hz hum rejector filter. The values of resistors $R_6$ and $R_7$ may be varied to vary the degree of attentuation at 50 Hz, but the total ($R_6 + R_7$) should remain fixed.

The third stage is a conventional a.c. amplifier, while the final stage uses a four-diode bridge in the feedback loop as a detector. The meter, an Esterline-Angus Minigraph recorder, has a 0 - 100 μA movement.

<u>The power supply.</u> For d.c. operation, all power requirements are supplied by two 12 V lead plate accumulators connected in series. These accumulators are regularly recharged using a small petrol driven battery charger. For operation from a.c. mains supply when this is available, suitable power supplies have been developed. These have outputs of +9 V and -9 V for the operational amplifier supplies, +24 V for the chart recorder motor drive and +19 V for the field mill motor drive. The circuit diagram of the power supply is shown in Figure 5.4 and the components used are listed in Table 5.1.

<u>Sign discrimination.</u> As mentioned in the introduction, the output voltage waveform of the field mill undergoes a phase change of π when the ambient field changes sign. The amplitude of the waveform can be made to be proportional to the amplitude of the ambient field and the shape of the waveform is a function of the shape of the rotor and stator. The phase change of π caused by the reversal in the sign of the ambient field was used by MAPLESON and WHITLOCK (1955) with a reference signal generator and a phase sensitive detector to determine the sign of the ambient field. This

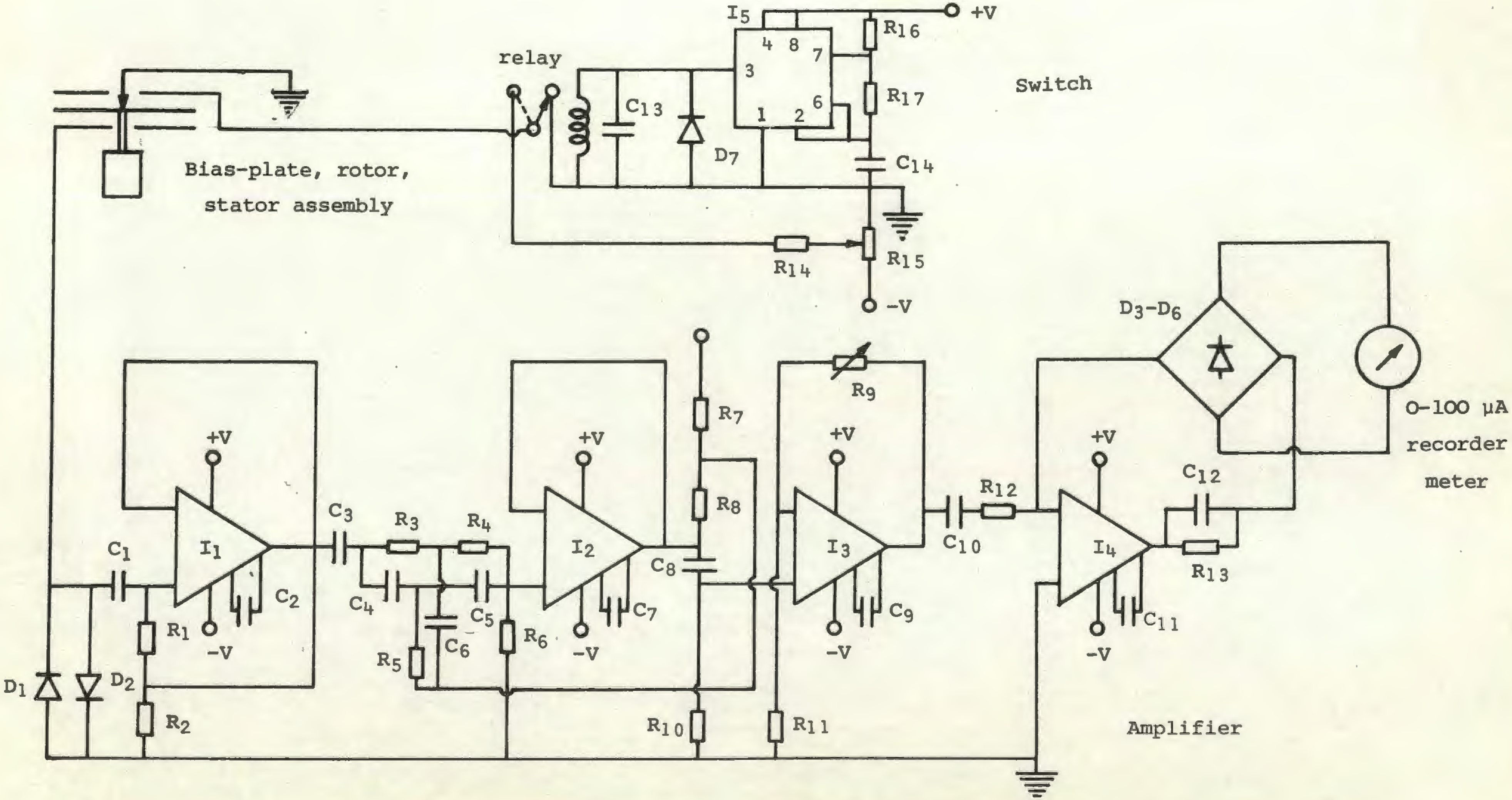



Figure 5.3 The field mill amplifier circuit diagram.

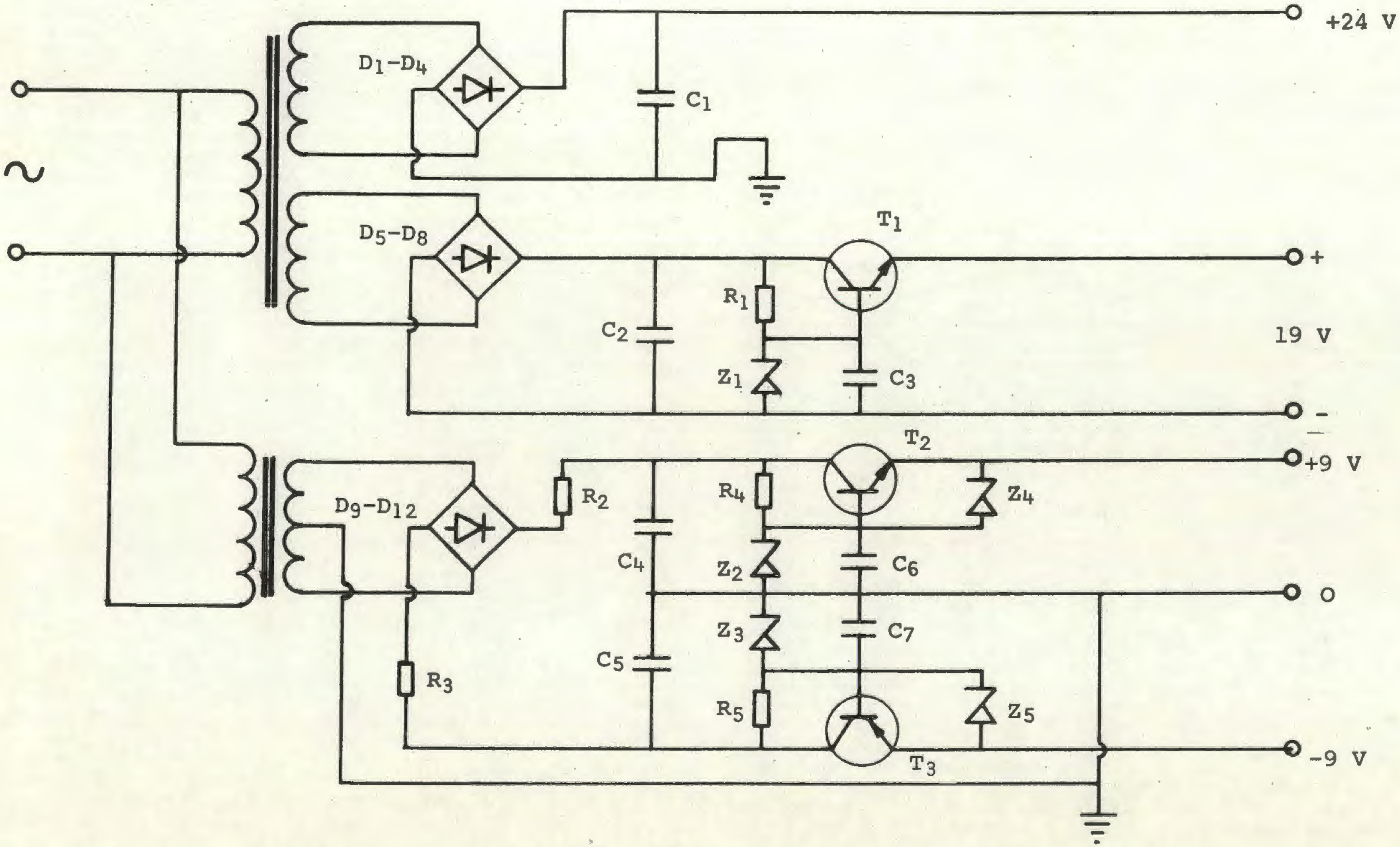



Figure 5.4 Field mill power supply circuit diagram.

method is very susceptible to drifts of the zero caused by variations in the amplitude of the reference signal.

The use of a constant reference signal applied to a bias plate above the rotor has been a popular device. Successfully used by HIGAZI and CHALMERS (1966), among others, this technique effectively makes use of an artificial field which is then modulated by the ambient field. Experiments conducted near Durban with this technique in a humid, salt laden coastal atmosphere have shown it to be unreliable. In fact the zero drift could approach 100% of the ambient field at times.

The technique developed by LANE-SMITH (1967) of using specially shaped stator and rotor blades to give an asymmetrical waveform has many advantages. The sign of the asymmetry depends on the sign of the field and this is detected as a steady positive or negative current. The stability and noise rejection of this device are its main advantages. The disadvantages are the slight loss of signal amplitude due to the decrease in stator area and the temperature sensitivity of the detector circuit.

The Lane-Smith mill, like the others so far discussed, involves the use of a centre-zero instrument or recorder to indicate the field value and sign. This is a disadvantage when chart recorders are being used as the final output and when fair weather fields (predominantly positive) are being investigated. Under these conditions only half the chart width is being used for much of the time and with miniature recorders the reduction in accuracy may be severe. One way of overcoming this is to make occasional spot checks on the polarity while using an end-zero recorder for the output. This technique has been used by HARRIS (1971), but it is clearly of no use for automatic field station operation.

A technique of sign discrimination suitable for use with photographic recording (and hence very short-term field studies) was developed by MALAN and SCHONLAND (1950). This method involves an increase in the area of the stator exposed on every ninth cycle of the output waveform. As a result, the amplitude of either the peak or the trough of every ninth cycle is increased depending on whether the field is positive or negative.

An auxillary generator has been used by COLLIN (1962) to give a similar result to that of Malan and Schonland, but in a manner better suited to long term studies and chart recorder output. The rotor of the field mill is connected to ground or to the reference generator by means of an electro-mechanically controlled switch. The result is a small positive or negative going pulse superimposed on the output depending on whether the field is positive or negative. A really good connection of the rotor to ground is of vital importance to the accurate operation of the field mill and extensive tests made in Durban over a period of several years with the Collin device have shown it to be unreliable, particularly for automatic operation.

The technique of sign discrimination which has been developed here is essentially a combination of the Collin method with the advantage of full utilization of the chart width, and of the bias plate method of off-setting the zero with a reference field. The bias plate is switched between ground and the reference voltage (the -9 V of the operational amplifier supply circuit) by a relay which is controlled by an electronic switch (described in Section 5.2). Using the component values listed under the amplifier components in Table 5.1 the bias plate is grounded for about 4 minutes and then connected to the reference voltage for about 1 minute. The result is that the trace on the chart recorder is interrupted for about 1 minute in every 5 and the small dot produced during this 1 minute will lie on the high current side of the trace if the field is positive and on the low current side if the field is negative. A section of typical chart record is shown in Figure 5.5. It has been found that the time intervals of 4 and 1 minute suit the fair weather measurements being made and the type of recorder used.

The advantages of this technique are that the full chart width is

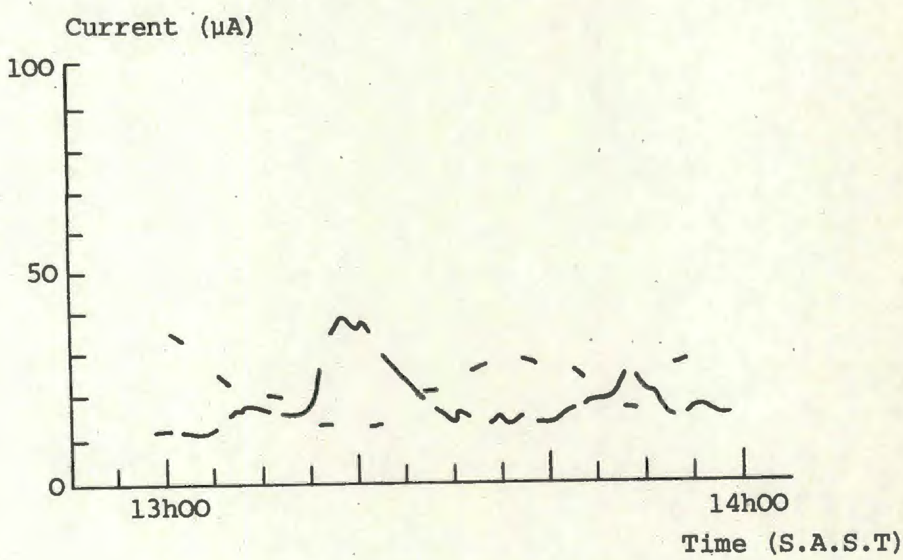



Figure 5.5 Reproduction of a typical section of field mill chart record. This particular record was made at Kloof on 23/8/74 between 13h00 and 14h00 S.A.S.T. The change in the polarity of the field with the passage overhead of a cumulus cloud is clearly seen.

always available and that the rotor is always well grounded. Any drift in the bias plate voltage affects only the spacing between the main trace and the polarity pulse and not the accuracy of the main trace. The main disadvantage of this technique is that rapid changes of polarity would not be detected. There is also the possibility of some ambiguity in the sign of fields of very small magnitude. Experience has shown however, that neither of these constitute a real problem with fair weather fields.

Wiring diagram. The field mill wiring diagram is shown in Figure 5.6.

### 5.1.4 Calibration and performance

The upright field mills are calibrated using a pair of parallel aluminium plates 5 cm apart with a hole cut in the lower to accommodate the rotor-stator-bias plate assembly of the mill. The lower of the parallel plates is arranged to be flush with the stator of the mill and known fields can be established between the pair of plates. The gain of the field mill amplifier is adjusted to give the desired sensitivity and a series of readings of recorder current and applied field are obtained which yield the calibration curve of the mill. The parallel plate unit is then removed and replaced by a cylindrical calibration cover, as shown in Figure 5.7. Without altering the gain control of the field mill, the voltage applied to the calibration cover is then adjusted to produce a suitable reading on the field mill chart recorder and values of this reading and the voltage applied are noted. The calibration cover is then used to check calibration when the mills are installed in the field. This, or the calibration of the inverted mills, is simply done by applying the required voltage to the cover and then adjusting the field mill amplifier gain control to give the pre-determined output. The bias voltage is then adjusted so that the polarity pulse is easily visible alongside the main trace.

Some typical calibration curves are reproduced in Figure 5.8. The maximum sensitivity which can be used is generally determined by the noise

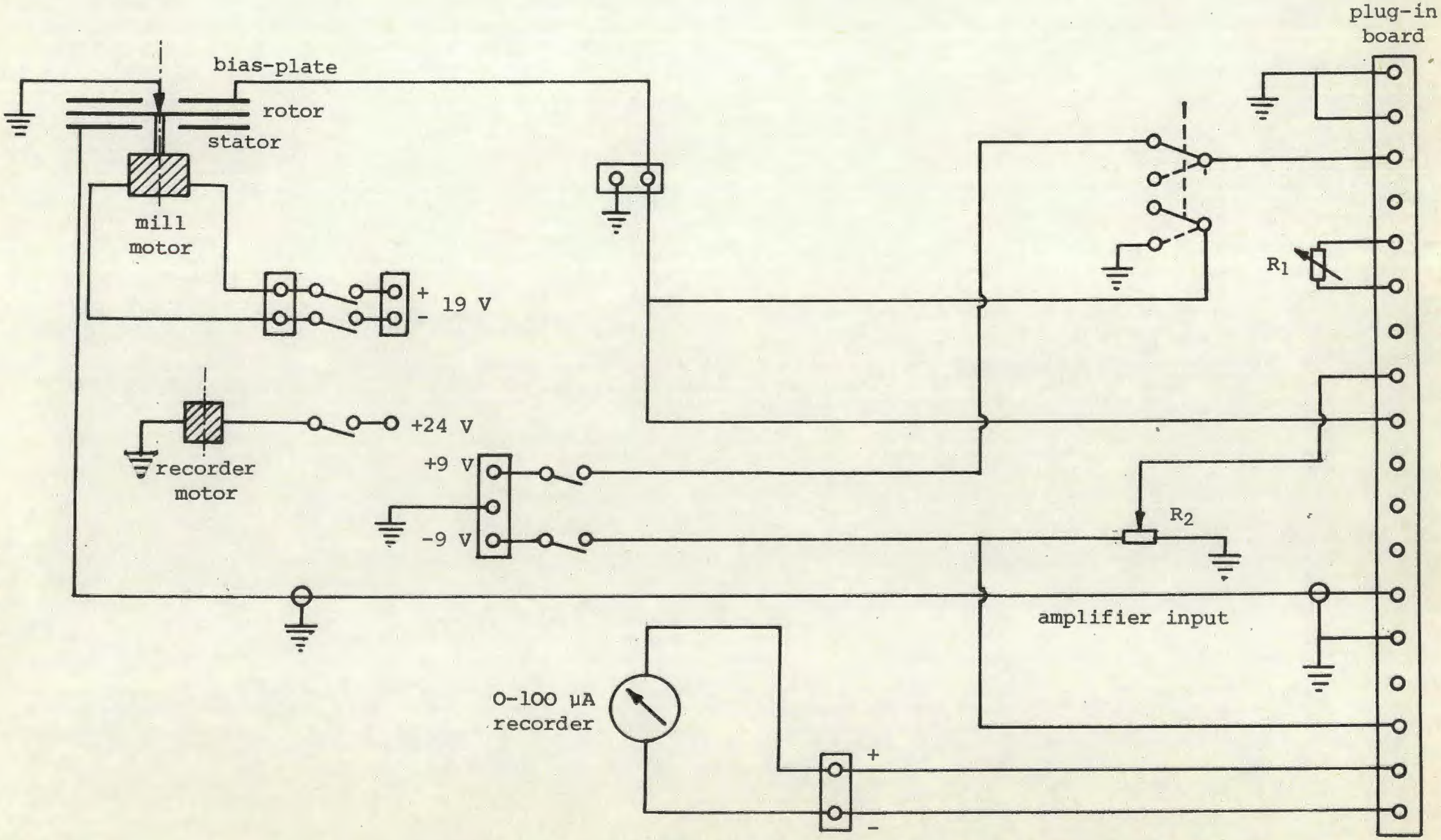
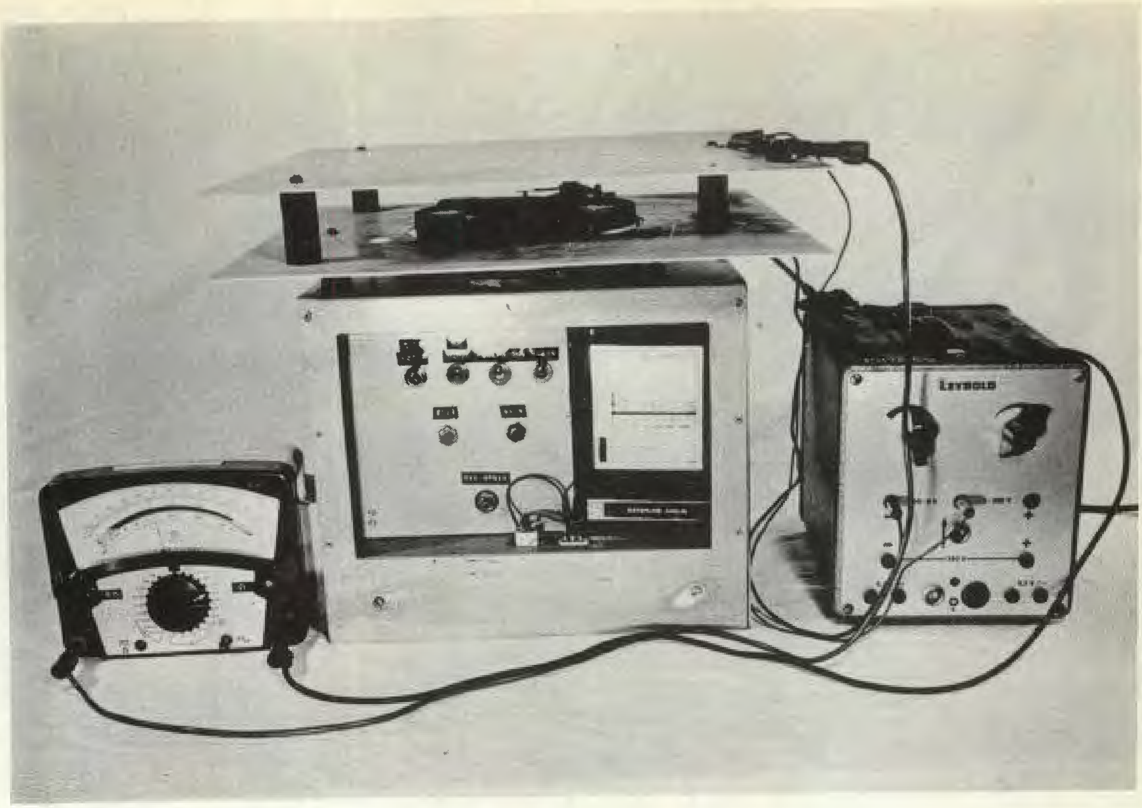



Figure 5.6 Field mill wiring diagram.




(a) Laboratory calibration using calibration plates.

(b) Field calibration using using the cover and portable voltage source.

<u>Figure 5.7</u> Photographs of the field mill calibration techniques.

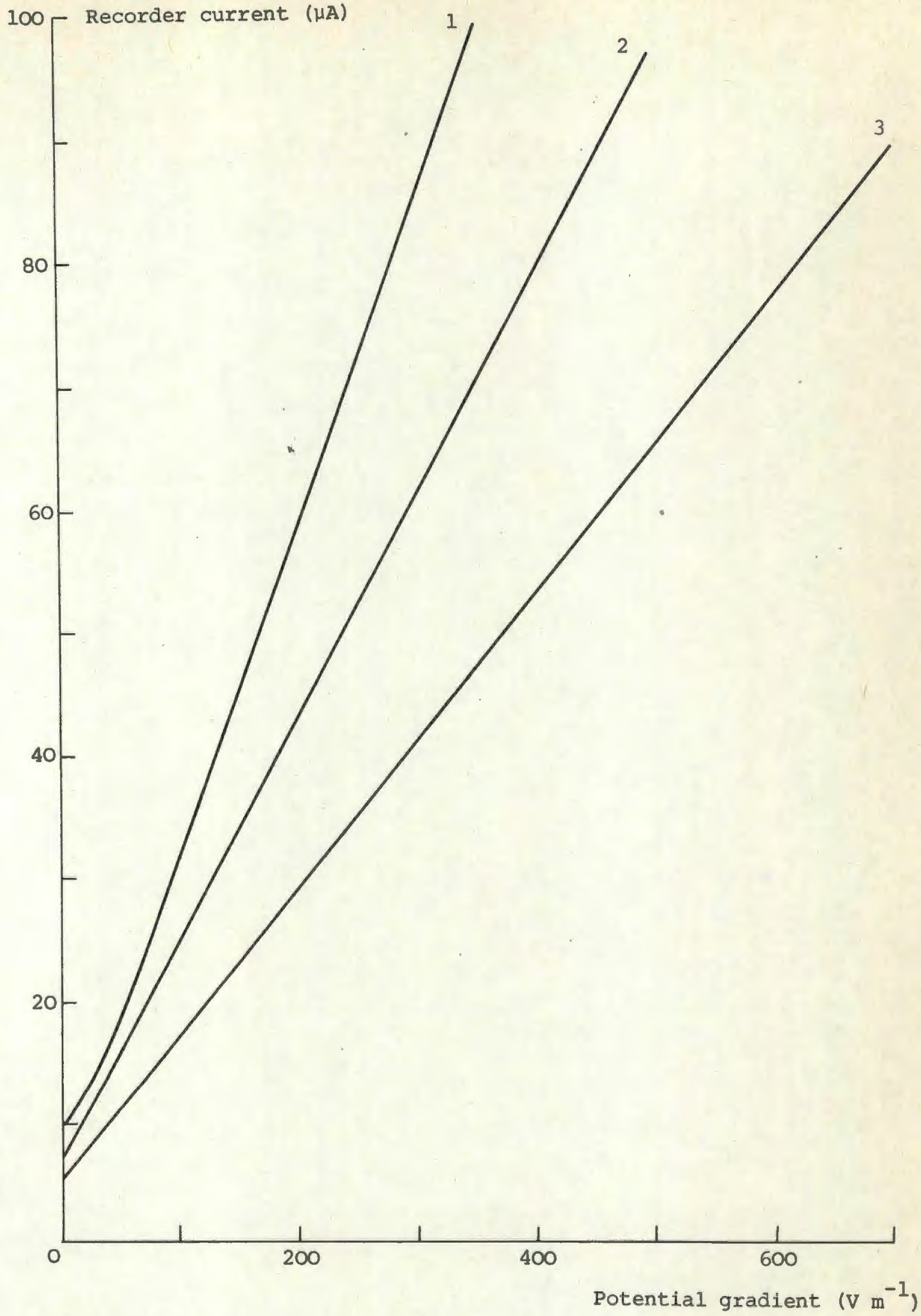



Figure 5.8 Typical field mill calibration curves. Curves 1 and 2, with sensitivities of 26 μA and 18 μA per 100 V $m^{-1}$ respectively , were widely used in the Kloof experiment. Curve 3 represents a sensitivity of 12 μA per 100 V $m^{-1}$.

level which can be tolerated in addition to the maximum field which is likely to be of interest. These limits have to be determined by experience.

## 5.2 ELECTRONIC SWITCHES

All of the equipment described here makes use of electronic switches based on a particular integrated circuit device. This IC is essentially just an astable multivibrator, but it has the particular property that it can give intervals in either mode of anything from a few microseconds up to about 1 hour. The basic connections of the device are shown in Figure 5.9. The charge time (output high) is given by

$$t_1 = 0.693(R_A+R_B)C \text{ seconds,}$$

while the discharge time (output low) is

$$t_2 = 0.693\ R_B\ C \text{ seconds.}$$

Clearly, choice of appropriate values of $R_A$, $R_B$ and C allow for different cycles of the switch to suit different applications. In all of the applications described here the output of the IC is connected to a relay which then does the actual switching in the appropriate circuit.

## 5.3 RECORDING ANEMOMETERS

### 5.3.1 Introduction

It was considered necessary for some of the work described in this thesis (principally the coastal environment experiment) to have some knowledge of wind speed and direction. In order to achieve this aim a recording anemometer was developed.

Different types of anemometer have been designed to meet different requirements and descriptions of the more common types are given in most

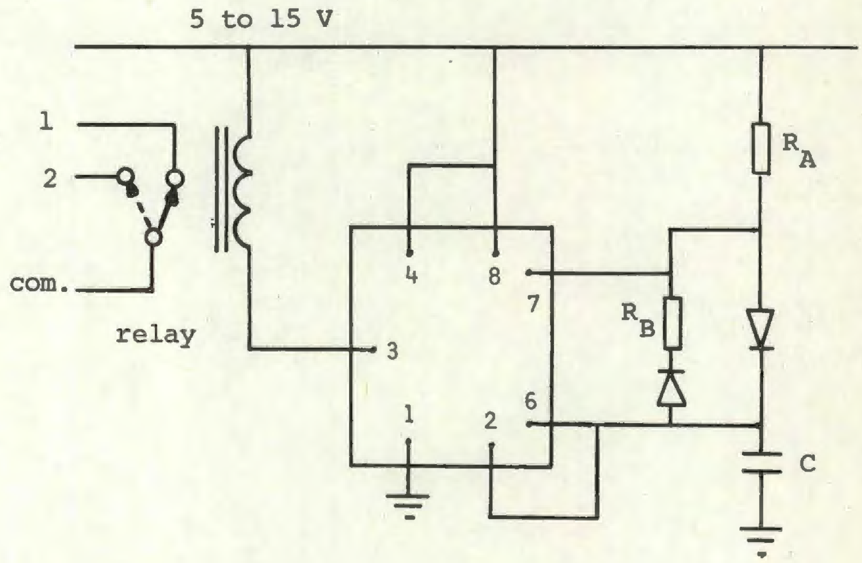



Figure 5.9 Electronic switch - variations in this basic circuit are shown in the individual circuit diagrams.

general texts on meteorology, (see e.g. BERRY, BOLLAY and BEERS, 1945). Two more recent additions to the range of anemometers are the aerovane type of MAZZARELLA (1954), and the hot wire type of GJESSING, LANES and TANGERUD (1969).

None of the instruments mentioned above meet all the requirements of the present work and consequently the instrument described here was developed. It is based on a rotating cup device for measuring wind speed and a wind vane to give direction indications. Since it was desired to measure the wind velocity close to the ground (because the potential gradient was being determined at ground level) the overall height of the anemometer was restricted to 0.5 m. This restriction also meant that the anemometer could be placed fairly closely to the field mill without distorting the field. In addition it was considered necessary that the anemometer be powered by either a.c. mains power or a d.c. power supply and be capable of operating in a harsh atmospheric environment with a minimum of attention.

### 5.3.2 Wind speed measurements

The wind speed is measured by a set of three anemometer cups attached to a shaft running in a bearing. Fixed to the other end of the shaft is a metal disk set parallel to the plane in which the cups rotate. The cups and disk are caused to rotate by the wind. Twelve evenly spaced holes are drilled around the circumference of the disk, which has a small light source above it and a photo-transitor below it. The photo-transistor is thus illuminated whenever a hole in the disk is situated between it and the light source. The rate of interruption of the light beam falling on the photo-transistor depends on the rate of rotation of the disk and anemometer cup assembly, which inturn depends on the wind speed. The photo-transistor delivers a series of pulses to the Schmitt trigger (see the circuit diagram in Figure 5.10) which provides output pulses of uniform height to trigger the monostable multivibrator. The output from the multivibrator is a series of pulses of uniform height and uniform width, the number of such pulses

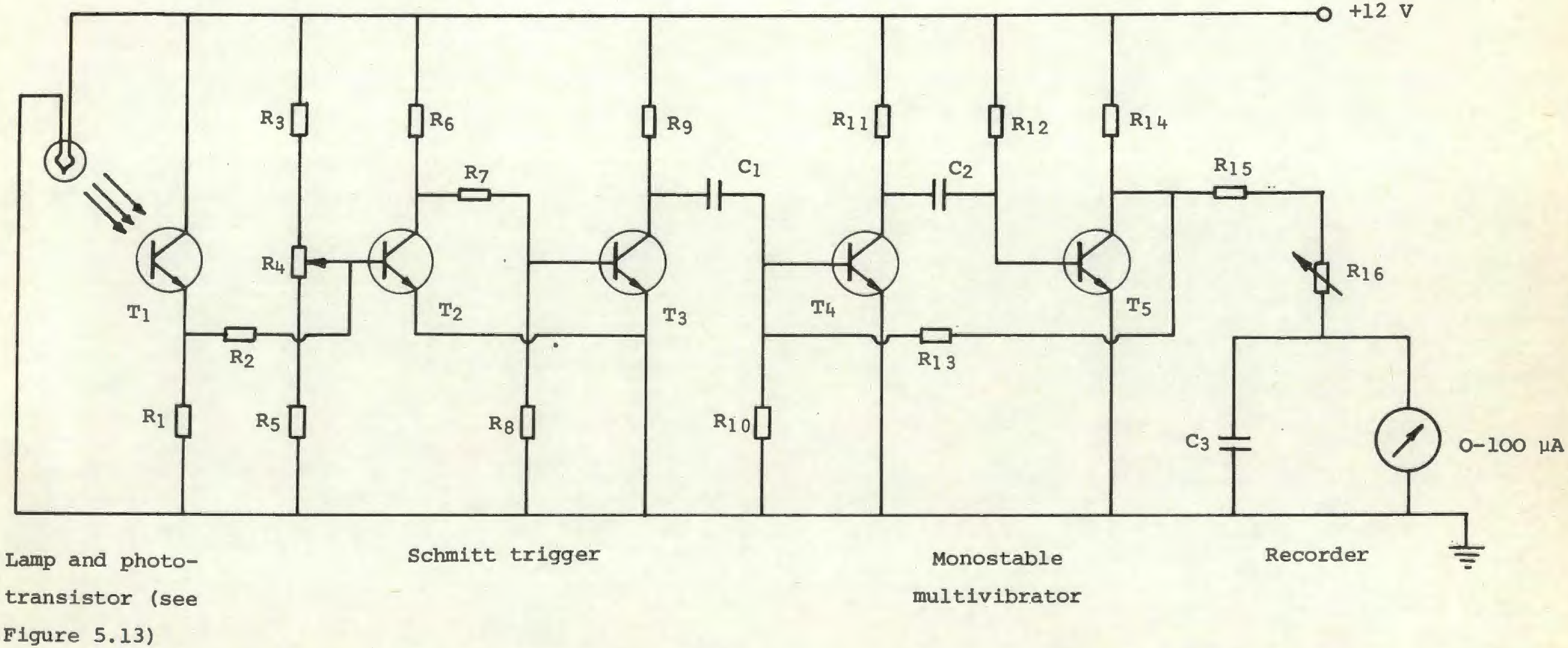



Figure 5.10 Recording anemometer circuit diagram.

per unit time being proportional to the wind speed. The meter and capacitor form an integrator which effectively 'counts' the number of pulses and thus the current flowing through the meter is proportional to the wind speed.

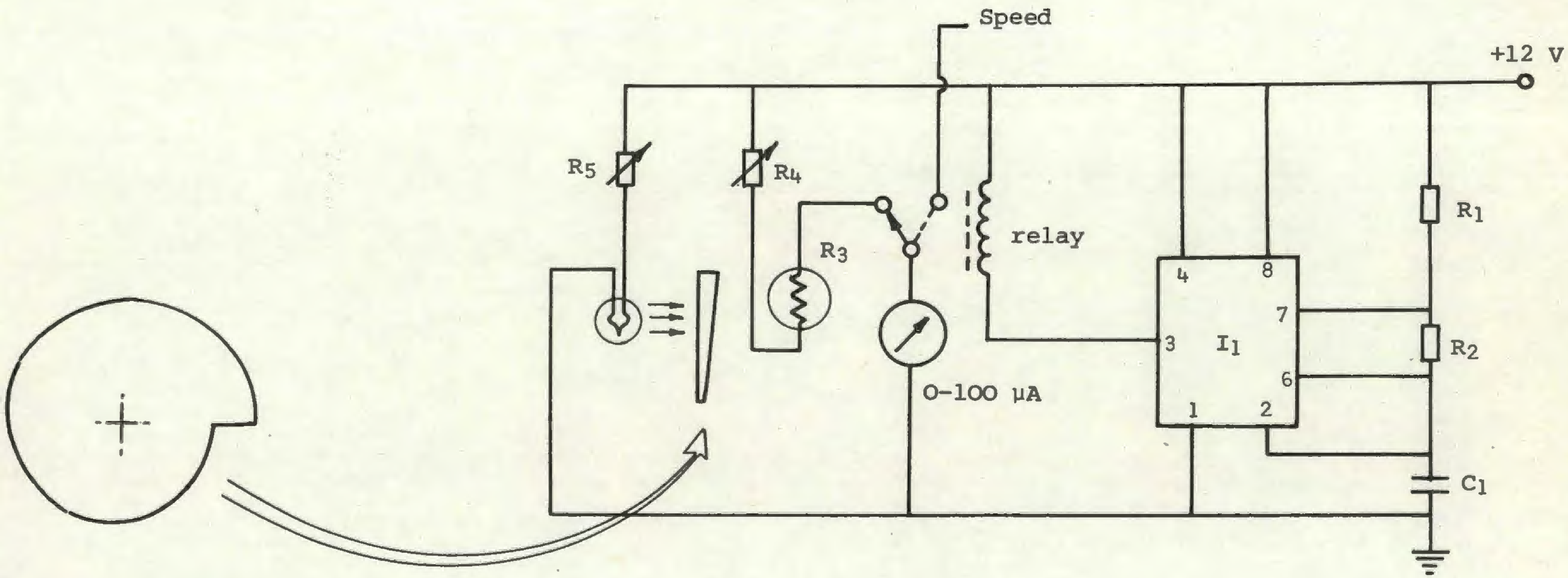
### 5.3.3 Wind direction measurements

The wind vane shaft is attached to a disk whose rim is cut with a varying radius, as shown in Figure 5.11(a). A small lamp is mounted on one side of the disk and a light dependant resistor (LDR) on the other. The amount of illumination falling on the LDR is controlled by the edge of the disk which acts rather like a slit of variable width. The current through the lamp may be controlled by a potentiometer and the current in the LDR and meter circuit may be controlled by a second potentiometer. These two controls enable the range and minimum current reading of the direction finder circuit to be adjusted to suitable values. Normally, the adjustments are made so that the direction readings lie between about 30 and 100 µA on the recording meter. In this way the direction indications are generally fairly well separated from the speed indications, which will not often exceed 30 µA. The circuit diagram of the wind vane circuit is shown in Figure 5.11(b).

### 5.3.4 Electronic switch, power supply and wiring diagram

In order to obviate the use of two recorders, an electronic switch is used which connects the speed circuit to the meter for about 4 minutes and the direction circuit for about 1 minute. The circuit of the switch is shown in Figure 5.11(b), and it is of the same type as dealt with in Section 5.2.

Like the field mills, the anemometer was designed to be powered by a battery (12 V in this case) for field work. However, for occasions when a.c. mains power is available a suitable power supply is incorporated in the anemometer. This uses two integrated circuit voltage regulators as




(a) Shape of light control disk (variable aperture).

(b) Wind direction indicator circuit diagram (with electronic switch).

Figure 5.11 Wind direction indicator.

shown in Figure 5.12. The wiring diagram of the anemometer is shown in Figure 5.13.

### 5.3.5 Calibration and performance

The wind speed calibration was carried out by comparing the readings of the recording pulse-count anemometer with those of a portable cup-anemometer. The cup-anemometer was calibrated against the Dines pressue-tube anemometer of the S.A. Weather Bureau installed at Louis Botha Airport in Durban. The two relevant calibration curves are shown in Figure 5.14 and Figure 5.15.

The direction readings are obtained by lining the anemometer and wind vane along a N-S line using a compass. The wind vane is then rotated to give a minimum reading on the meter, which is then adjusted to be about 30 μA. The vane is then moved slightly to give a maximum current which is set at about 100 μA. These settings are then checked and further adjustments made until values of 30 μA and 100 μA are obtained. The relation between recorder current and wind direction is shown graphically in Figure 5.16, while a section of typical anemometer record is reproduced in Figure 5.17.

## 5.4 ASPIRATION PSYCHROMETER

Knowledge of the air temperature and the moisture content of the atmosphere was required for some of the work described in this thesis, particularly for the studies of the sunrise effect. For this purpose a recording aspiration psychorometer was developed. Both wet-bulb and dry-bulb temperature probes were NTC resistors (thermistors) of the glass covered type. The first unit developed used thermistors made by Standard Telephone and Cables with a nominal resistance of 120 kΩ at 25°C. Both of these thermistors failed eventually because of mechanical failure of the rather long leads inside the glass tubes, probably caused by the continual slight vibration to which the apparatus was subject. (It was mounted on the same stand as the inverted field mill and the vibration was caused by

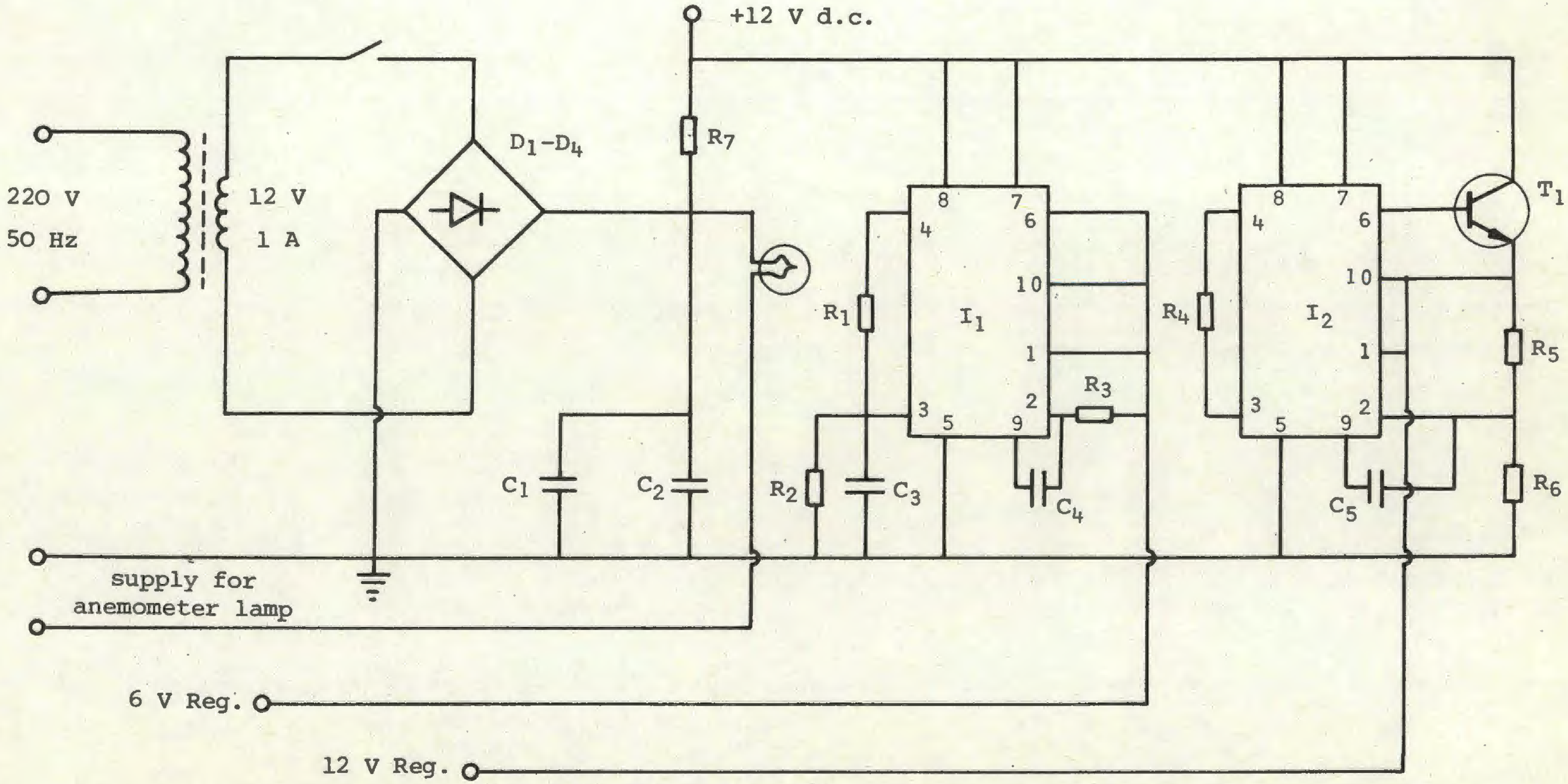



Figure 5.12 Anemometer power supply.

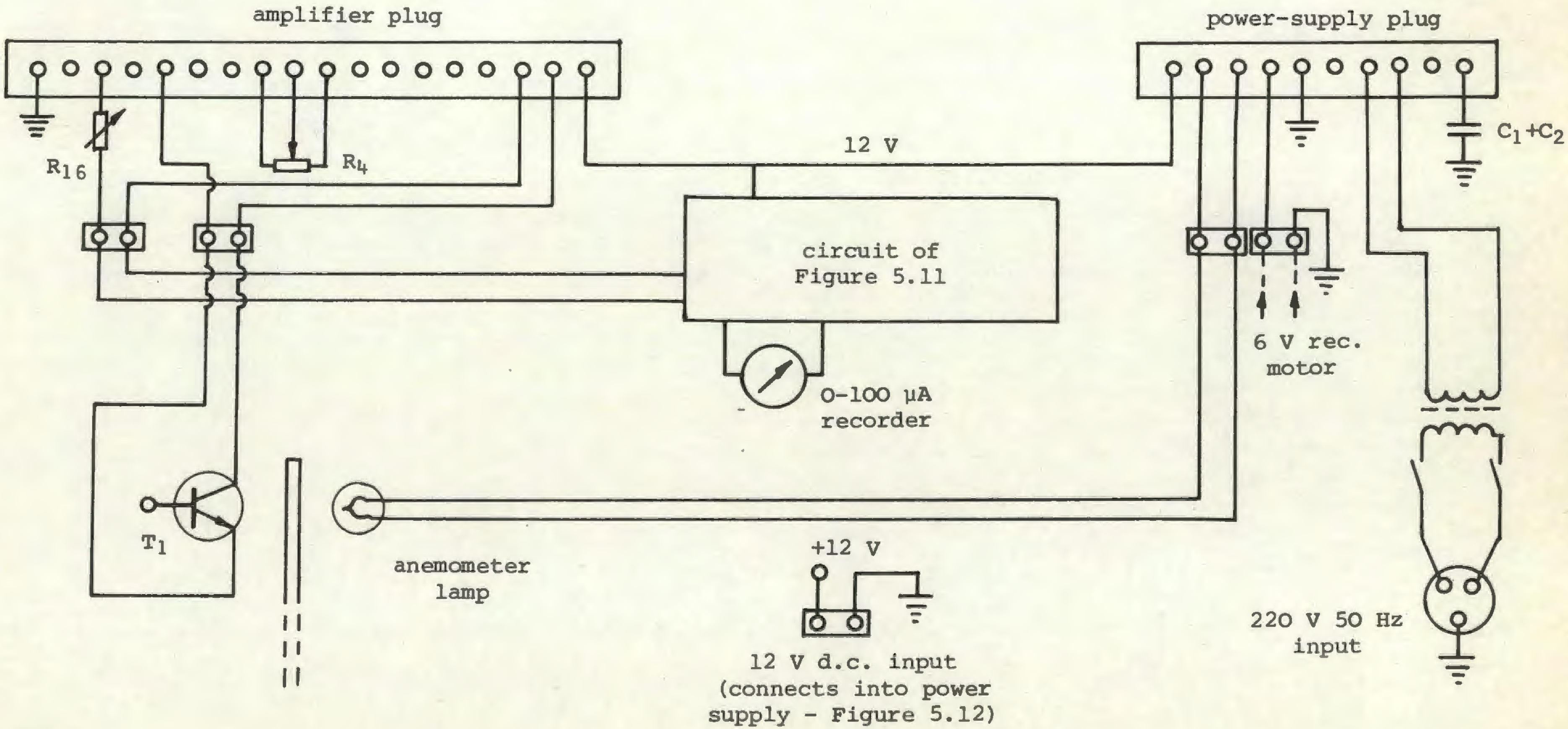
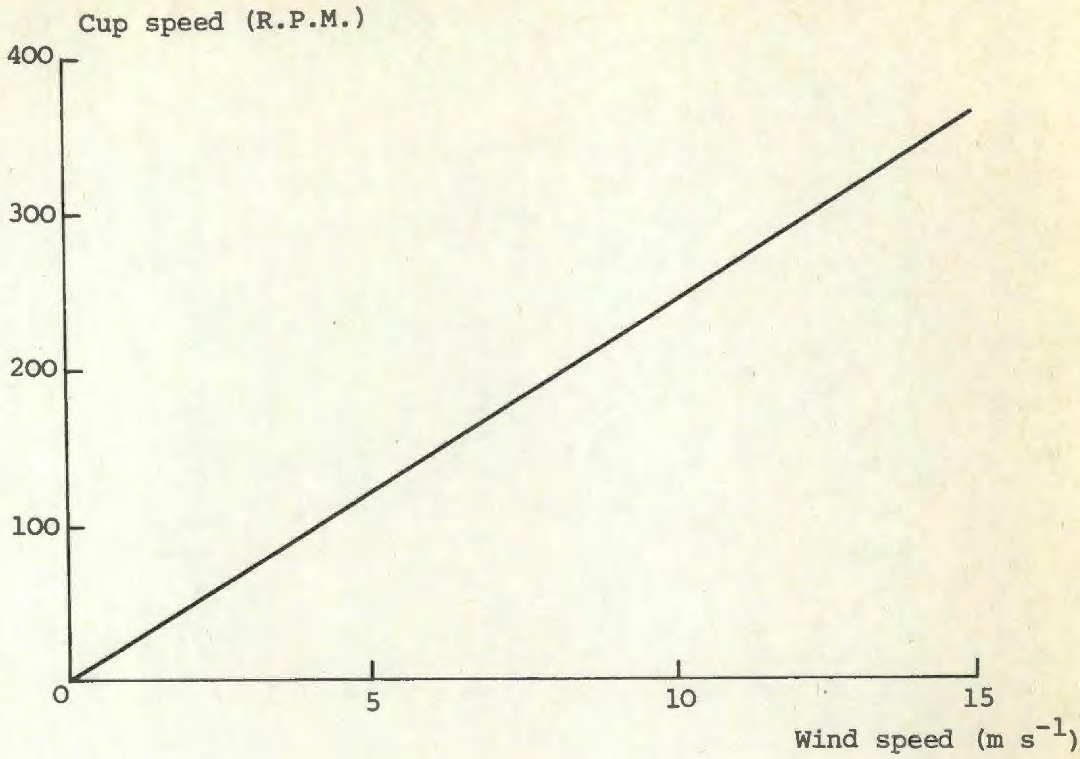
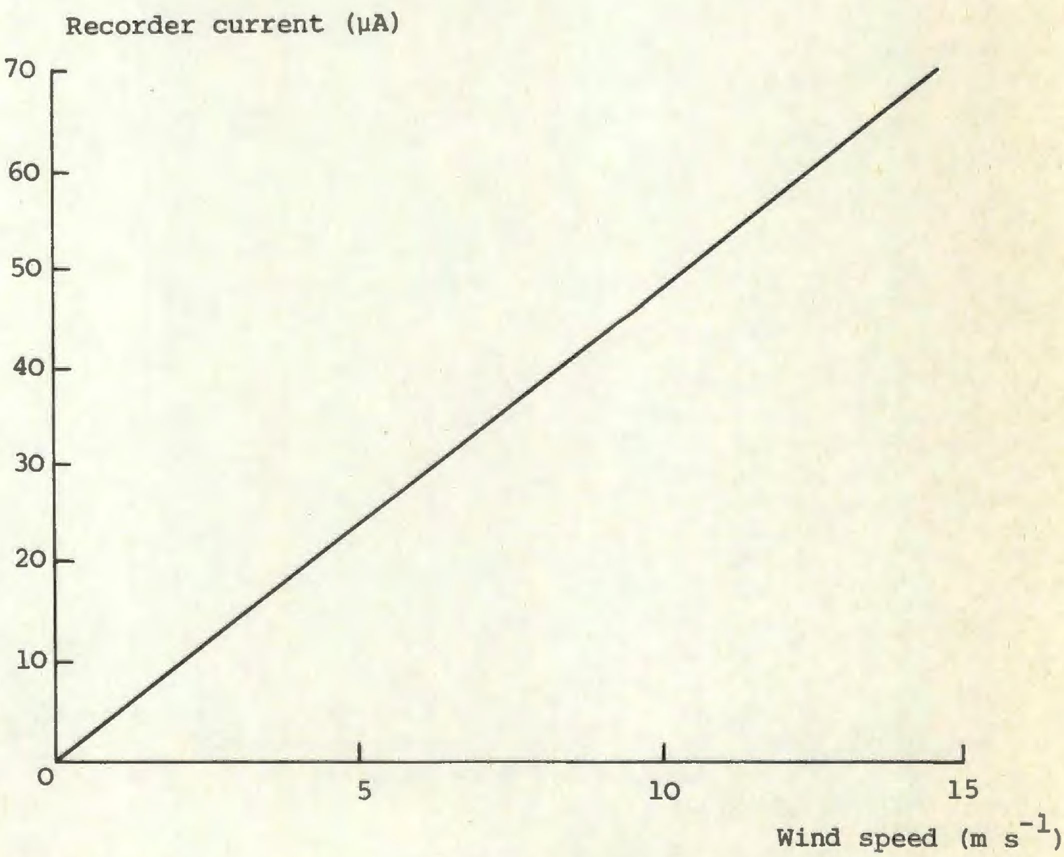



Figure 5.13 Anemometer wiring diagram. Note that when the 12 V d.c. plug is inserted, the a.c. line is interrupted. To operate on a.c., the d.c. plug must be removed.




<u>Figure 5.14</u> Calibration of the portable cup-anemometer.




<u>Figure 5.15</u> Calibration of the recording pulse-count anemometers.

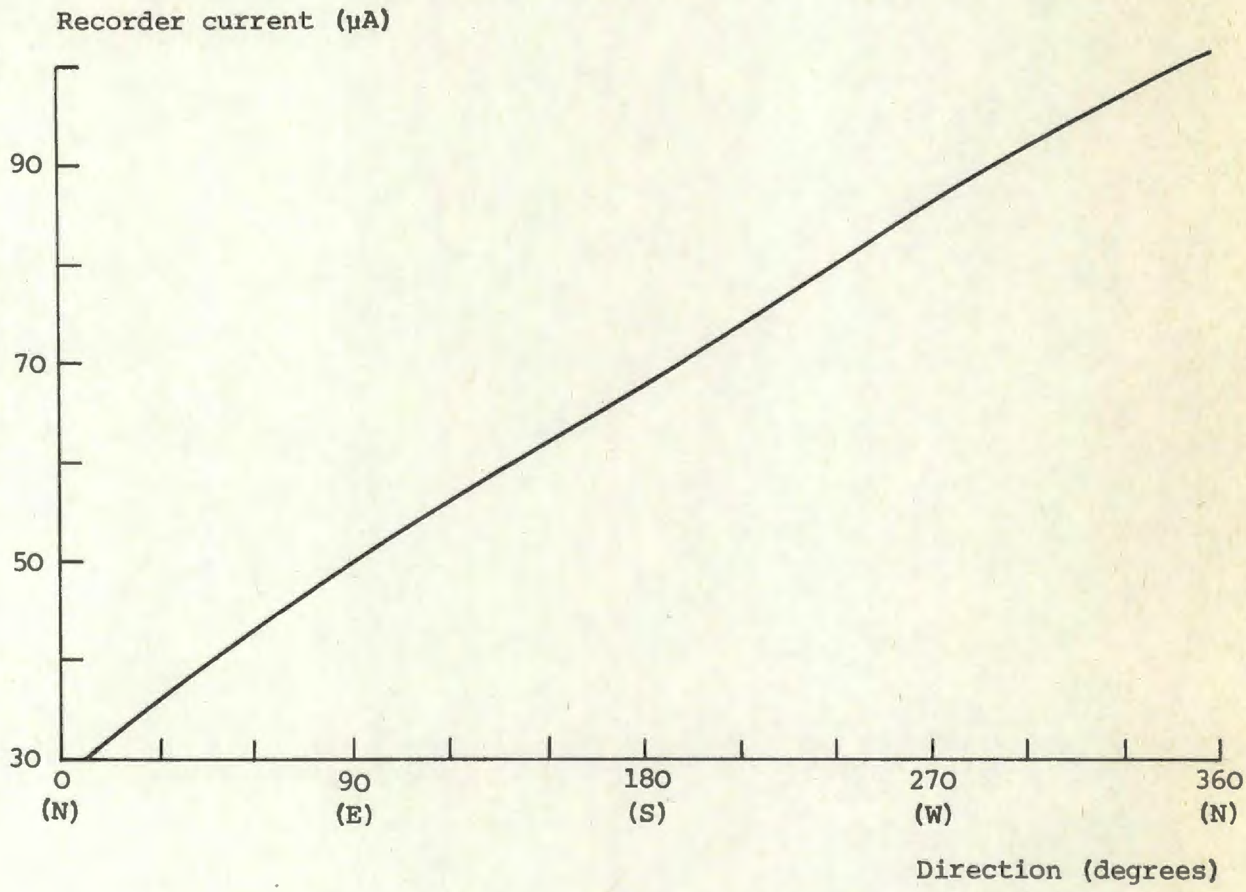



Figure 5.16 Anemometer direction calibration curve.

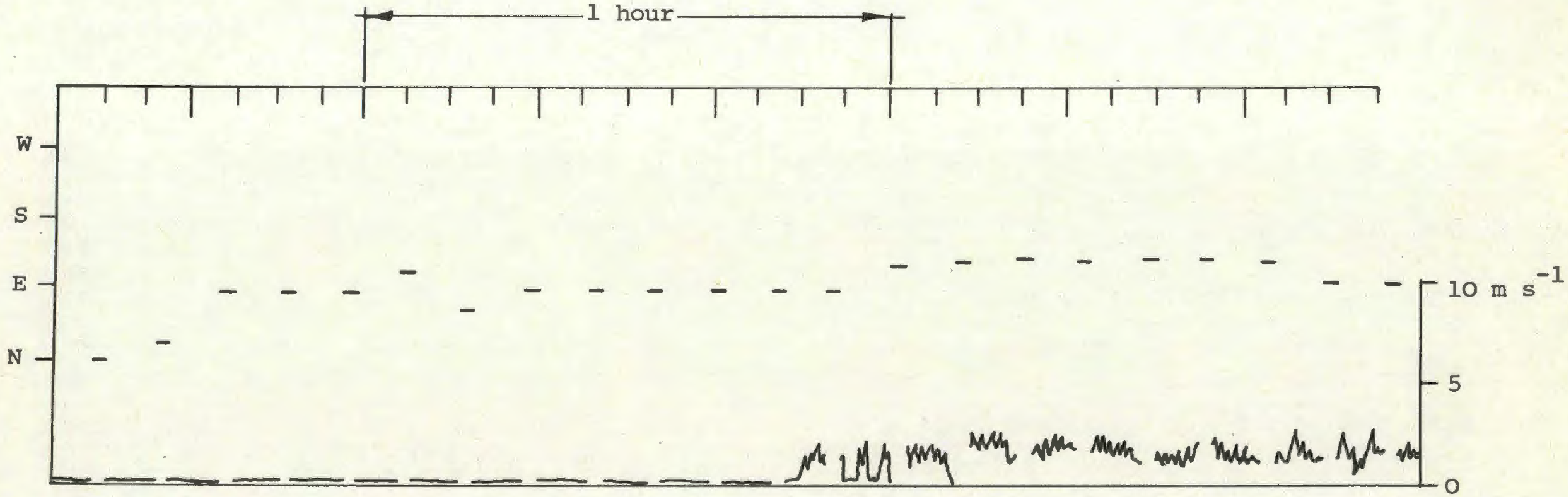


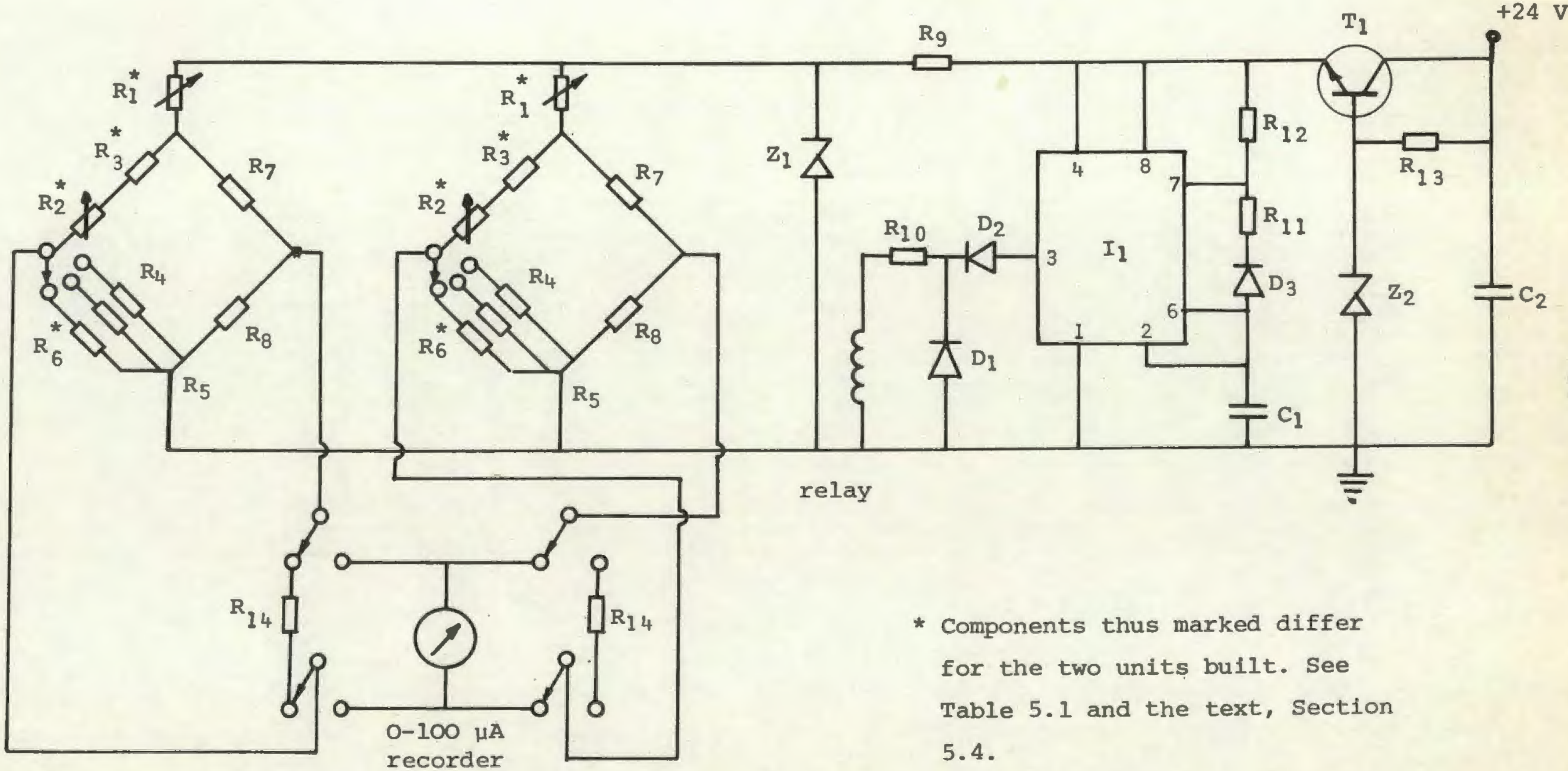

Figure 5.17 Reproduction of a section of anemometer chart record

the field mill motor). A second unit was developed using Philips thermistors of the glass bead type which were much smaller than the STC type and consequently used much shorter leads. These had a nominal resistance of 4.7 kΩ at 25$^{o}$C and several components in the measuring circuit had to be altered to deal with the different thermistor resistance.

The electrical measuring circuit consists of two identical Wheatstone bridge circuits, one element of each bridge being a thermistor. The potentiometer labelled $R_2$ in each circuit is used to set the zero, while that labelled $R_1$ is used to set the range of the instrument; in this case 0$^{o}$C to 40$^{o}$C was used. The fixed resistors $R_4$ and $R_5$ could then be switched into the bridge circuit to check certain pre-determined temperature readings and thus ensure that the calibration of the instrument did not alter. The values used here corresponded to temperatures of 0$^{o}$C and 38$^{o}$C.

To allow a single recording meter to be used for both bridge circuits an electronic sampling switch was again used here, following the basic circuit of Figure 5.9. The specific circuit used is shown in Figure 5.18 while the component values are listed in Table 5.1. These components are such that the switch occupies each of its two states for roughly equal periods of about 2.5 minutes. When the meter is switched into the one bridge circuit, a dummy load equivalent to the meter resistance is switched into the other so that the current flowing in the thermistor remains approximately constant whether the thermistor is being used to give the recorded temperature or not. This arrangement prevents the thermistor taking time to reach a stable temperature each time the meter is switched into the circuit.

To provide suitable ventilation of the thermistors they were mounted in such a way that they protruded into a wooden tunnel through which air was drawn at something in excess of 3 m $s^{-1}$. The one thermistor was surrounded by a wick which dipped into a reservoir of clean water. Thus the temperature recorded on the meter by the two bridge circuits corresponded to the wet - and dry - bulb temperatures. The calibration curves for the two units are




* Components thus marked differ for the two units built. See Table 5.1 and the text, Section 5.4.

Figure 5.18 Aspiration psychrometer circuit diagram.

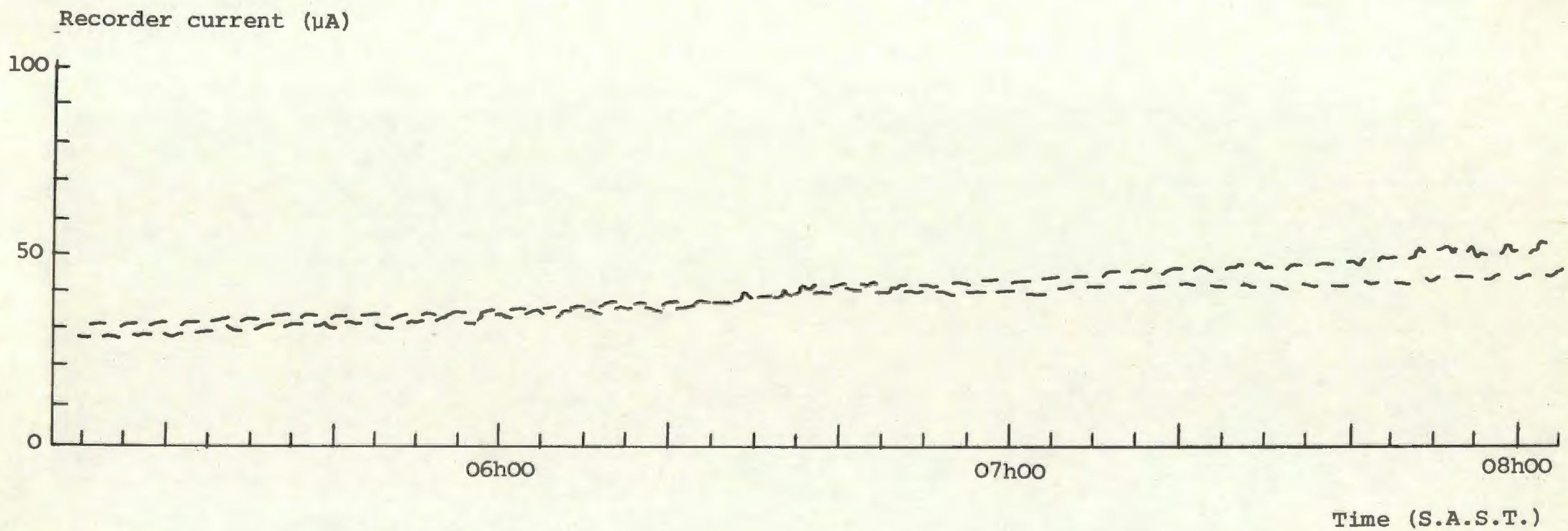



Figure 5.19 Reproduction of a section of an aspiration psychrometer recorder chart showing the air temperature changing from 16.5°C at 05h15 to 25.5°C at 08h10, while the relative humidity was 70% at 05h15, 100% at 06h30 and 74% at 08h10.

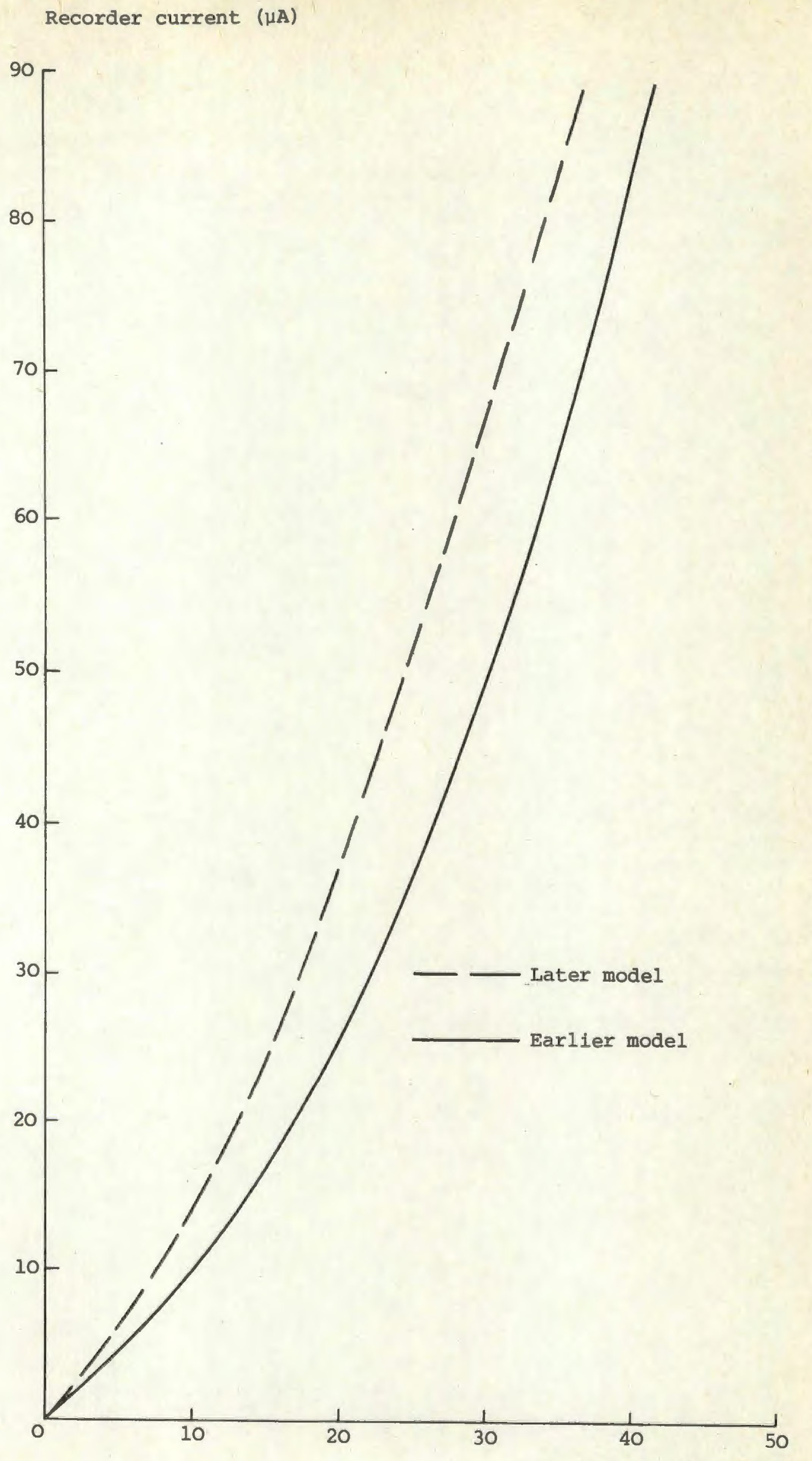



Figure 5.20 Aspiration psychrometer calibration curves.

shown in Figure 5.20 and a typical section of chart is reproduced in Figure 5.19. This section of chart shows the air temperature increasing from 16.5$^{o}$C to 25.5$^{o}$C while the relative humidity changes from 70% to 100% and back to 74%. Values of relative humidity were obtained from the dry- and wet-bulb temperatures using tables given in the Handbook of Chemistry and Physics (WEAST 1973).

| CIRCUIT COMPONENT VALUES |
|---|
| R = resistor (0.25W), C = capacitor, D = diode<br>Z = zener diode, T = transistor, I = integrated circuit. |

1. Field mill amplifier.

| | | | | |
|---|---|---|---|---|
| $R_1$ 100k | $R_2$ 100k | $R_3$ 68k | $R_4$ 68k | $R_5$ 33k |
| $R_6$ 100k | $R_7$ 330 | $R_8$ 180 | $R_9$ 220k | $R_{10}$ 1k |
| $R_{11}$ 1k | $R_{12}$ 2k2 | $R_{13}$ 15 | $R_{14}$ 2k2 | $R_{15}$ 1M |
| $R_{16}$ 10M | $R_{17}$ 2M7 | $C_1$ 0.01 | $C_2$ 47p | $C_3$ 0.02 |
| $C_4$ 0.047 | $C_5$ 0.047 | $C_6$ 0.1 | $C_7$ 47p | $C_8$ 1 |
| $C_9$ 47p | $C_{10}$ 1 | $C_{11}$ 47p | $C_{12}$ 0.22 | $C_{13}$ 0.01 |
| $C_{14}$ 33 | $D_1, D_2$ 1N4001 | $D_3-D_7$ 1N914 | $I_1-I_4$ LM301 | $I_5$ NE555 |

2. Field mill power supply.

| | | | | |
|---|---|---|---|---|
| $R_1$ 270 | $R_2$ 4.7 | $R_3$ 15 | $R_4$ 680 | $R_5$ 680 |
| $C_1$ 1000 | $C_2$ 2200 | $C_3$ 400 | $C_4$ 1000 | $C_5$ 1000 |
| $C_6$ 50 | $C_7$ 50 | $D_1-D_8$ 2N4002 | $D_9-D_{12}$ 40 V 600 mA bridge | |
| $Z_1$ 2 × 9V | $Z_2, Z_3$ 10V | $Z_4, Z_5$ 3.6V | $T_1$ 2N3055 | $T_2$ TIP3055 |
| $T_3$ TIP5503 | | | | |

3. Anemometer wiring diagram.

| | | |
|---|---|---|
| $R_1$ 220k | $R_2$ 1M bias adjust | |

4. Anemometer pulse count circuit.

| | | | | |
|---|---|---|---|---|
| $R_1$ 100k | $R_2$ 10k | $R_3$ 47k | $R_4$ 2k | $R_5$ 2k7 |
| $R_6$ 3k3 | $R_7$ 1k8 | $R_8$ 6k8 | $R_9$ 2k2 | $R_{10}$ 2k2 |
| $R_{11}$ 2k2 | $R_{12}$ 10k | $R_{13}$ 10k | $R_{14}$ 1k | $R_{15}$ 27k |
| $R_{16}$ 10k | $C_1$ 0.1 | $C_2$ 0.32 | $C_3$ 250 | $T_1$ MRD100 |
| $T_2-T_5$ 2N3704 | | | | |

5. Anemometer wind vane and electronic switch.

| | | | | |
|---|---|---|---|---|
| $R_1$ 10M | $R_2$ 2M7 | $R_3$ LDR | $R_4$ 10k | $R_5$ 250 |
| $C_1$ 33 | $I_1$ NE555 | | | |

6. Anemometer power supply

| | | | | |
|---|---|---|---|---|
| $R_1$ 1k15 | $R_2$ 6k04 | $R_3$ 965 | $R_4$ 2k90 | $R_5$ 4k87 |
| $R_6$ 7k15 | $R_7$ 1 | $C_1$ 1000 | $C_2$ 1000 | $C_3$ 100p |
| $C_4$ 100p | $C_5$ 100p | $D_1-D_4$ 60V 1.4 A bridge | | $T_1$ TIP3055 |
| $I_1, I_2$ LM723 | | | | |

7. Aspiration psychrometer.

Where components have two values, the second refers to the second unit constructed - see text.

| | | | | |
|---|---|---|---|---|
| $R_1$ 1k(5k) | $R_2$ 10k(1k) | $R_3$ 27k(1k) | $R_4$ 240k | $R_5$ 39k |
| $R_6$ STC NTC (Philips NTC) | | $R_7$ 390 | $R_8$ 3k9 | $R_9$ 680 |
| $R_{10}$ 180 | $R_{11}$ 2M2 | $R_{12}$ 2M2 | $R_{13}$ 470 | $R_{14}$ 4k7 |
| $C_1$ 56 | $C_2$ 100 | $D_1-D_3$ 1N914 | $Z_1$ 5.6V | $Z_2$ 12V |
| $T_1$ 2N2219A | $I_1$ NE555 | | | |

Table 5.1 Circuit component values.

# Chapter Six

# FAIR WEATHER POTENTIAL GRADIENTS IN THE ATMOSPHERE

*About nature consult nature herself.*

F. Bacon (1561-1626)
De Augmentis Scientiarum

## 6.1 INTRODUCTION

Three separate experiments are described in this chapter. In the first, potential gradient measurements were made in Durham, England during December 1970 and early in 1971. In the second, measurements of potential gradients were made under fair weather conditions in a coastal environment in South Africa. In the third experiment, continuous potential gradient measurements were made at a site some 20 km inland from the coast. This experiment extended over a period of several months during 1974.

The preliminary work on the measurement of potential gradients using vertically separated field mills was carried out in Durham. This work was suggested by Dr. W.C.A. Hutchinson and was done while the author was a Visiting Research Fellow at Durham University. The Observatory site in Durham was used as a field station for this work and this experiment formed the basis for the development of the technique of determining space charge density, which is discussed in the next chapter.

The second experiment consisted of three independent parts. A basic requirement of this work was that field stations should be situated in areas which were as free as possible of atmospheric pollution, and yet be readily accessible from Durban. The first two parts of the experiment were carried out at Ballito Bay on the shore of the Indian Ocean about 45 km north of Durban. This area was relatively free of atmospheric pollution but was close enough to Durban to permit twice weekly visits during August and September 1972 and during May 1973. In fact, even visiting the sites twice a week was not often enough to ensure complete reliability of the results, particularly with the field mills which were in use in 1972 and 1973. Since it also transpired that the rapid growth of the settlement at Ballito Bay was causing increased atmospheric pollution, it was decided to extend the same type of observations in an area more remote from human habitation. This part of the work was carried out during the University vacation in July 1975 on a farm some 150 km north along the coast from Durban. The redesigned field mills described in Chapter Five were used for this part of the experiment and, because the work was done during the vacation period, it was possible for the apparatus to be attended to continuously during recording periods, thereby ensuring reliability of the results.

The third experiment was conducted at the author's home in Kloof. This site is some 20 km inland from the coast at an altitude of about 530 m above sea level. Like the two coastal stations this site also had a relatively unpolluted atmosphere. The instruments at this site could obviously be attended to daily; the experiment described here commenced towards the middle of June 1974.

## 6.2 THE DURHAM EXPERIMENT

### 6.2.1 Experimental arrangements and data handling

Measurements of potential gradient were made using the four-sector vane field mills with bias plates similar to those described in Chapter Five, but without the self-contained recorders. The electronic circuitry used was designed by SHARPLESS (1968). This circuitry is not described here, but the improved circuitry developed by the author for the South African work is described in Chapter Five.

Two inverted mills were mounted at different heights on a 21 m steel lattice tower. A third mill was placed in a pit with its measuring plate flush with the ground. The pit was sufficiently far from the tower for this mill to record the magnitude of the undistorted field. The output of each mill was taken via cable to the Observatory building where a four-channel chart recorder was housed. Continuous automatic recording of potential gradients was not possible in this experiment for two reasons. Firstly, on account of the weather, the lowest mill could not be left in position unattended; and secondly, this work was done during the time of the 1970 strike by the British Power Workers, which meant that there were frequent and irregular interruptions of the power supply. In this chapter only the results obtained by the lowest mill are presented, since these represent the values of the undistorted field. The results provided by the other two mills were used for determinations of space charge densities, which work is discussed in the next chapter.

Each field mill gave a d.c. output signal which was recorded on one track of the four-track chart recorder, each track being the output of a 0-1 mA meter. A constant negative potential was applied to the bias plate to off-set the zero reading to 0.2 mA and the field mill was adjusted to a sensitivity of 1000 V $m^{-1}$ for a meter deflection of 1 mA. This meant that a meter reading of 0 corresponded to a field of -200 V $m^{-1}$; a meter reading of about 0.2 mA resulted with zero field and a reading of 1 mA resulted with a field of about +800 V $m^{-1}$. The amplifier response was only approximately linear. The chart could be read to an accuracy of 0.01 mA which set the limit of accuracy of the field mill readings at 10 V $m^{-1}$.

The field mill was placed in position in its pit when the weather was suitable. A continuous chart record was obtained during these periods and, since this was done only while the author was present at the Observatory, the time marks were known to be reliable in spite of power cuts. Values of the output current were determined at hourly intervals and these were converted into potential gradient readings by means of a calibration curve drawn for this particular mill. These values of potential gradient are listed in Table 6.1. Information concerning wind, humidity and temperature were obtained from recording instruments maintained at the Observatory by the Department of Geography at Durham University. These readings were also upset by interruptions to the power supply causing unreliable time scales on the records. For this reason there are several values missing from Table 6.1.

### 6.2.2 Results

The most striking feature of these results is the large magnitude of the potential gradient. The average of 100 hourly values listed in Table 6.1 is 328 V $m^{-1}$. This is considerably in excess of the value of between 80 and 150 V $m^{-1}$ found at the same site by HIGAZI and CHALMERS (1966). It is also much greater than the value of about 120 V $m^{-1}$ normally assumed for a non-industrial (more correctly, rural) area under fair weather conditions. Apart from a few occasions when rain or snow showers fell, and one day when snow was lying on the ground, the weather conditions listed would have been described as fair weather conditions. It must therefore be concluded that, during the period of these observations at least, the atmosphere in Durham did not correspond to a non-industrial, unpolluted atmosphere. This is particularly interesting since SHARPLESS, ASPINALL and HUTCHINSON (1971) found that at Lanehead, only about 50 km from Durham, the atmosphere was typically that of a globally representative station. (The term globally representative station is defined in Section 3.2.1 of Chapter Three).

Table 6.2 represents an attempt to relate potential gradients to certain prevailing weather conditions. It also includes a list of average hourly potential gradient values obtained for Durham. It is apparent from the table that temperature, wind direction and time of day do not have a significant effect on the potential gradient as judged from this set of 100 readings. The relative humidity does appear to have a more noticeable effect, with the potential gradient being significantly higher when the

| Date | Time hours Z | Potl. Grad. V m$^{-1}$ | Summary of prevailing weather conditions | | | | |
|---|---|---|---|---|---|---|---|
| | | | Wind | | R.H. | Temp. | |
| | | | dir. | knots | % | °C | Remarks |
| 3/12/70 | 15h00 | 250 | Calm | | 41 | 6.1 | O/cast haze |
| | 16h00 | -10 | SSE | 3 | 45 | 5.6 | |
| 4/12/70 | 09h00 | 250 | SSW | 8 | 49 | 6.1 | 2/8 Cloud light breeze |
| | 10h00 | 175 | SSW | 7 | 52 | 5.6 | |
| | 11h00 | 175 | SSW | 7 | 46 | 7.2 | |
| | 12h00 | 105 | SSW | 12 | 38 | 8.3 | |
| | 13h00 | 55 | SSW | 11 | 37 | 8.9 | |
| | 14h00 | 55 | SW | 13 | 35 | 9.4 | |
| | 15h00 | 150 | SW | 11 | 35 | 8.9 | Light rain 15h00-16h00 |
| | 16h00 | 125 | SW | 9 | 50 | 7.8 | |
| 6/12/70 | 11h00 | 500 | W | 15 | 36 | 7.2 | 2/8 - 3/8 Cloud |
| | 12h00 | 0 | WSW | 15 | 34 | 7.8 | Ground drying |
| | 13h00 | -30 | WSW | 7 | 35 | 7.8 | |
| | 14h00 | -15 | WSW | 10 | 35 | 7.8 | |
| | 15h00 | -15 | W | 17 | 36 | 8.3 | |
| 7/12/70 | 11h00 | 125 | NW | 11 | 39 | 6.1 | 4/8 Cloud increasing |
| | 12h00 | 150 | NNW | 14 | 38 | 6.1 | Light haze |
| | 13h00 | 140 | N | 15 | 38 | 6.1 | |
| 12/12/70 | 09h00 | 225 | NW | 10 | 34 | 3.3 | 4/8 Cloud increasing |
| | 10h00 | 90 | NW | 13 | 36 | 2.8 | |
| | 11h00 | 205 | NW | 11 | 36 | 2.8 | Light snow fell at about 11h30 |
| | 12h00 | 140 | NW | 7 | 33 | 3.3 | |
| | 13h00 | 175 | NW | 12 | 32 | 3.3 | |
| | 14h00 | 205 | NW | 12 | 31 | 3.3 | Clearing |
| | 15h00 | 225 | NW | 10 | 28 | 3.9 | |
| | 16h00 | 300 | WNW | 7 | 25 | 3.9 | |
| 22/12/70 | 14h00 | 225 | NW | 13 | 42 | 4.4 | O/cast snow showers |
| | 15h00 | 190 | WNW | 11 | 39 | 4.4 | |
| 29/12/70 | 10h00 | 50 | NE | 15 | 65 | 4.4 | O/cast sleet showers |
| 9/1/ 71 | 14h00 | -400 | SSW | 20 | 56 | 12.8 | O/cast clearing partially |
| | 15h00 | -275 | SSW | 26 | 40 | 13.3 | |
| 19/1/71 | 09h00 | 500 | SW | 12 | 43 | 6.7 | 3/8 Cloud |
| | 10h00 | 250 | WSW | 15 | 40 | 7.2 | Drizzle 10h00-11h00 |

Table 6.1 Potential gradient measurements made in Durham 3/12/70 - 9/3/71. Continued overleaf.

| Date | Time hours Z | Potl. Grad. V m⁻¹ | Summary of prevailing weather conditions | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Wind | | R.H. | Temp. | | |
| | | | dir. | knots | % | °C | Remarks | |
| 19/1/71 | 11h00 | 185 | WSW | 15 | 34 | 7.8 | | |
| | 12h00 | 225 | WSW | 16 | 33 | 8.9 | | |
| | 13h00 | 255 | WSW | 17 | 32 | 8.9 | | |
| | 14h00 | 320 | WSW | 15 | 32 | 8.9 | | |
| 20/1/71 | 09h00 | 435 | SW | 6 | 34 | 3.9 | 2/8 Cloud | some frost |
| | 10h00 | 500 | SW | 8 | 32 | 4.4 | | |
| | 11h00 | 435 | SW | 8 | 30 | 6.1 | | |
| | 12h00 | 350 | SW | 11 | 32 | 6.7 | | |
| | 13h00 | 350 | SW | 11 | 31 | 7.8 | | |
| | 14h00 | 255 | SW | 11 | 31 | 7.8 | | |
| | 15h00 | 380 | SW | 11 | 28 | 7.8 | | |
| 25/1/71 | 09h00 | 225 | SSW | 12 | 47 | 7.8 | 2/8 Cloud | |
| | 10h00 | 190 | SSW | 11 | - | - | | |
| 3/2/71 | 12h00 | 310 | WNW | 5 | - | 12.2 | 4/8 Cloud | clearing |
| | 13h00 | 335 | WNW | 20 | - | - | | |
| | 14h00 | 335 | WNW | 7 | - | - | | |
| | 15h00 | 365 | WNW | 14 | - | - | | |
| | 16h00 | 265 | WNW | 12 | - | - | | |
| 9/2/71 | 10h00 | 625 | SW | 2 | - | 6.7 | 7/8 Cloud | clearing slightly |
| | 11h00 | 505 | SW | 2 | - | 7.8 | Hazy | |
| | 12h00 | 555 | SW | 8 | - | 9.4 | | |
| 11/2/71 | 09h00 | 795 | S | 4 | - | 3.9 | 2/8 Cloud | ground mist |
| | 10h00 | 265 | SW | 6 | - | - | Noticeable smell of smoke | |
| | 11h00 | 455 | SW | 1 | - | 7.2 | | |
| | 12h00 | 725 | SSW | 7 | 38 | 8.9 | 12h00 Clear | |
| | 13h00 | 530 | S | 7 | 38 | 8.9 | | |
| | 14h00 | 960 | ESE | 3 | 39 | 8.9 | | |
| | 15h00 | 675 | SSW | 12 | 31 | 9.4 | | |
| | 16h00 | 650 | SW | 13 | 35 | 9.4 | | |
| 14/2/71 | 16h00 | 770 | SW | 15 | 21 | 8.9 | 4/8 Cloud | increasing |
| | 17h00 | 480 | SSW | 16 | 27 | 7.8 | | |
| | 18h00 | 570 | SSW | 13 | 30 | 6.7 | | |
| | 19h00 | 410 | S | 15 | 31 | 6.7 | | |

Table 6.1 (continued) Potential gradient measurements made in Durham 3/12/70 - 9/3/71. Continued overleaf.

| Date | Time hours Z | Potl. Grad. V $m^{-1}$ | Summary of prevailing weather conditions | | | | |
|---|---|---|---|---|---|---|---|
| | | | Wind | | R.H. | Temp. | |
| | | | dir. | knots | % | °C | Remarks |
| 15/2/71 | 09h00 | 770 | SSW | 7 | - | 2.8 | 3/8 Cloud increasing |
| | 10h00 | 505 | SSW | 9 | - | 3.9 | Frost |
| | 11h00 | 555 | SW | 8 | - | 4.4 | |
| | 12h00 | 505 | SW | 8 | - | 4.4 | |
| | 13h00 | 600 | SW | 4 | - | 5.6 | |
| | 14h00 | 530 | SSW | 5 | - | 5.6 | |
| | 15h00 | 675 | SSW | 8 | 27 | 6.1 | |
| | 16h00 | 530 | SSW | 7 | 29 | 5.6 | |
| | 17h00 | 725 | SSW | 5 | 36 | 4.4 | |
| 21/2/71 | 12h00 | 280 | WNW | 22 | 33 | 10.0 | 3/8 Cloud clearing |
| | 13h00 | 355 | WNW | 22 | 30 | 10.6 | |
| | 14h00 | 355 | WNW | 15 | 27 | 11.1 | |
| | 15h00 | 380 | WNW | 17 | 25 | 11.1 | |
| | 16h00 | 305 | WNW | 17 | 23 | 11.1 | |
| | 17h00 | 355 | WNW | 15 | 27 | 10.0 | |
| 2/3/71 | 10h00 | 550 | WNW | 11 | 23 | 5.0 | 1/8 Cloud snow lying |
| | 11h00 | 500 | NW | 14 | 21 | 6.7 | |
| | 12h00 | 430 | NW | 13 | 22 | 7.8 | |
| | 13h00 | 380 | NW | 16 | 23 | 7.8 | |
| | 14h00 | 430 | NNW | 17 | 23 | 8.3 | Some snow still lying 14h00 |
| | 15h00 | 575 | NNW | 13 | 23 | 8.9 | |
| | 16h00 | 475 | NNW | 12 | 23 | 8.3 | |
| | 17h00 | 305 | NNW | 13 | 23 | 7.8 | |
| 5/3/71 | 10h00 | 165 | SW | 4 | - | 1.7 | O/cast dense haze |
| | 11h00 | 265 | SSW | 2 | - | 2.2 | Snow lying |
| | 12h00 | 215 | SSW | 5 | - | 2.2 | |
| | 13h00 | 0 | S | 3 | - | 2.8 | |
| 8/3/71 | 10h00 | 550 | N | 3 | - | 7.8 | O/cast some drizzle |
| | 11h00 | 380 | NNW | 5 | - | 7.8 | |
| | 12h00 | 190 | NNW | 6 | - | 8.3 | |
| | 13h00 | 260 | NNW | 11 | - | 10.0 | |
| | 14h00 | 340 | NNW | 10 | - | 10.0 | |
| 9/3/71 | 13h00 | 165 | WNW | 19 | - | 11.7 | 5/8 Cloud |
| | 14h00 | 190 | WNW | 15 | - | 11.7 | |

Table 6.1 (continued) Potential gradient measurements made in Durham 3/12/70 - 9/3/71.

| Prevailing weather conditions | | | Average hourly potential gradient ($V\ m^{-1}$) | Standard deviation ($V\ m^{-1}$) | No. of records |
|---|---|---|---|---|---|
| Relative humidity | ⩾ | 45% | 74 | 210 | 8 |
| | ⩽ | 25% | 450 | 137 | 12 |
| Temperature | ⩾ | 9°C | 268 | 278 | 17 |
| | ⩽ | 4°C | 295 | 225 | 16 |
| Wind direction within 22½° of: | | N | 319 | 153 | 13 |
| | | NE | 50 | – | 1 |
| | | E | 960 | – | 1 |
| | | SE | 475 | 686 | 2 |
| | | S | 339 | 325 | 25 |
| | | SW | 344 | 259 | 51 |
| | | W | 262 | 161 | 24 |
| | | NW | 299 | 119 | 37 |
| Hourly averages of potential gradient | | 09h00 | 457 | 247 | 7 |
| | | 10h00 | 326 | 205 | 12 |
| | | 11h00 | 357 | 156 | 12 |
| | | 12h00 | 299 | 198 | 14 |
| | | 13h00 | 234 | 158 | 14 |
| | | 14h00 | 270 | 300 | 14 |
| | | 15h00 | 298 | 277 | 12 |
| | | 16h00 | 379 | 250 | 9 |
| | | 17h00 | 466 | 187 | 4 |
| | | 18h00 | 570 | – | 1 |
| | | 19h00 | 410 | – | 1 |

Table 6.2 Analysis of the Durham results

relative humidity was < 25% than when it was > 45%. The relation between wind direction and potential gradient is completely undefined, the only conclusion which can be reached is that the prevailing wind direction was from the SW, W and NW for 73% of the total time during which records were obtained.

The most important finding from these results remains the finding concerning the magnitude of the average potential gradient at Durham. The records discussed here were all obtained during the winter when the level of nuclei in the atmosphere due to domestic heating fires would be large. In view of the finding concerning relative humidity, another factor which may have affected the result was the general dryness of the atmosphere. Of the 71 records for which relative humidity values were obtained, 44 or 62% of the total were for 35% relative humidity or less.

It must be concluded that, during the winter months in question, the atmosphere at Durham was not that of a rural area. This in itself is not surprising since the Observatory, although situated on a small farm, is within the city environs. What is surprising is the big difference between these results and those quoted earlier by HIGAZI and CHALMERS (1966). Clearly this is an aspect which should be investigated further as it is possible that there has been a long term trend towards increasing potential gradients, possibly indicative of increasing levels of pollution.

## 6.3 THE COASTAL ENVIRONMENT EXPERIMENTS

### 6.3.1 Experimental arrangements and data handling

The details of the apparatus used and the layouts adopted for these three experiments differed, although the basic arrangements of each were similar. The primary function of the coastal environmental experiment was an investigation of the generation of space charge (discussed in the next chapter), but the values of the potential gradients measured in the undistorted field during the course of this work are not without interest.

Two recording sites were used for each experiment. The one was close to the surf and the other further inland. At each site two field mills were used, one with its measuring plate flush with the ground and the other mounted in an inverted position on a stand about 2 m above the ground and some 3 to 4 m away from the lower mill. In this chapter the absolute values of potential gradients, obtained from the lower mills only, are pertinent to the discussion.

At Ballito Bay the measuring apparatus at each site was located on private property. The field mills used here had the fixed potential bias-plate method of off-setting the zero to indicate the polarity of the field. The apparatus was powered by 220 V 50 Hz mains power derived from private houses on each of the two sites. Figure 6.1 shows the relative positions of the two sites and of the coast line at Ballito Bay. The beach site was about 20 m from the high-water mark and about 1.5 m above this mark. The inland site was some 0.5 km from the beach site and about 70 m above mean sea level. In addition to the field mills, a recording anemometer was installed at each site for the 1973 experiment to provide information concerning wind speed and direction in the vertical space between upper and lower mills.

The third coastal experiment was set up on a farm near the small Zululand settlement of Mtunzini some 150 km north of Durban. The positions of these sites relative to the coast are shown in Figure 6.2. The field mills used in this experiment were just as described in Chapter Five, with the relevant connections suited for battery operation. In this case the beach site was situated on the inland side of a high sand dune about 90 m from the high-water mark at an elevation of about 5 m above mean sea level. The inland site was some 0.6 km away at an elevation of about 30 m. These two sites were connected only by a foot-path through coastal dune forest and it took about 15 minutes to walk from one site to the other. Long periods of observation were not possible because batteries had to be used for all power supplies. The technique adopted here was to switch on and

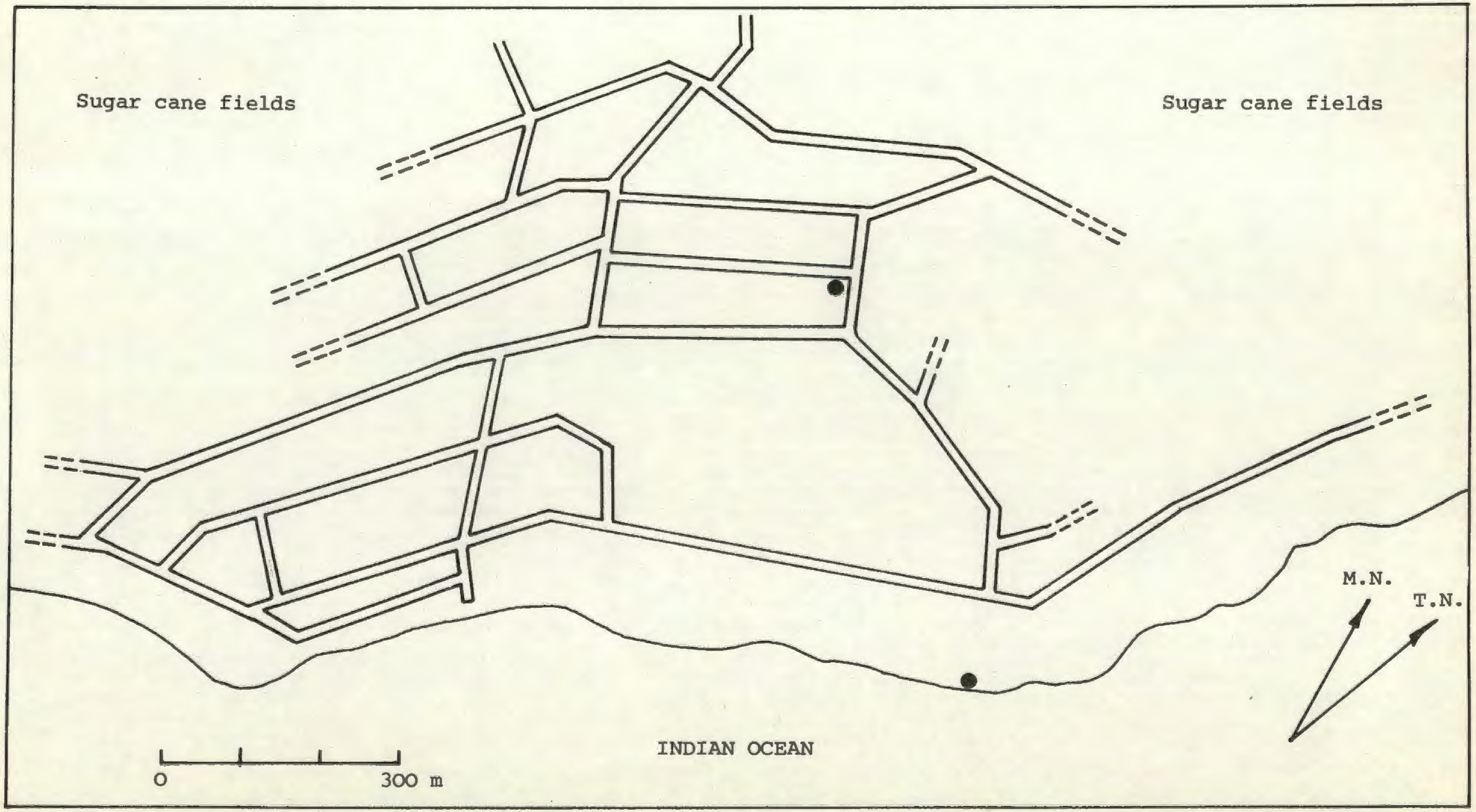



Figure 6.1 Map of the field station at Ballito Bay showing the two recording sites.

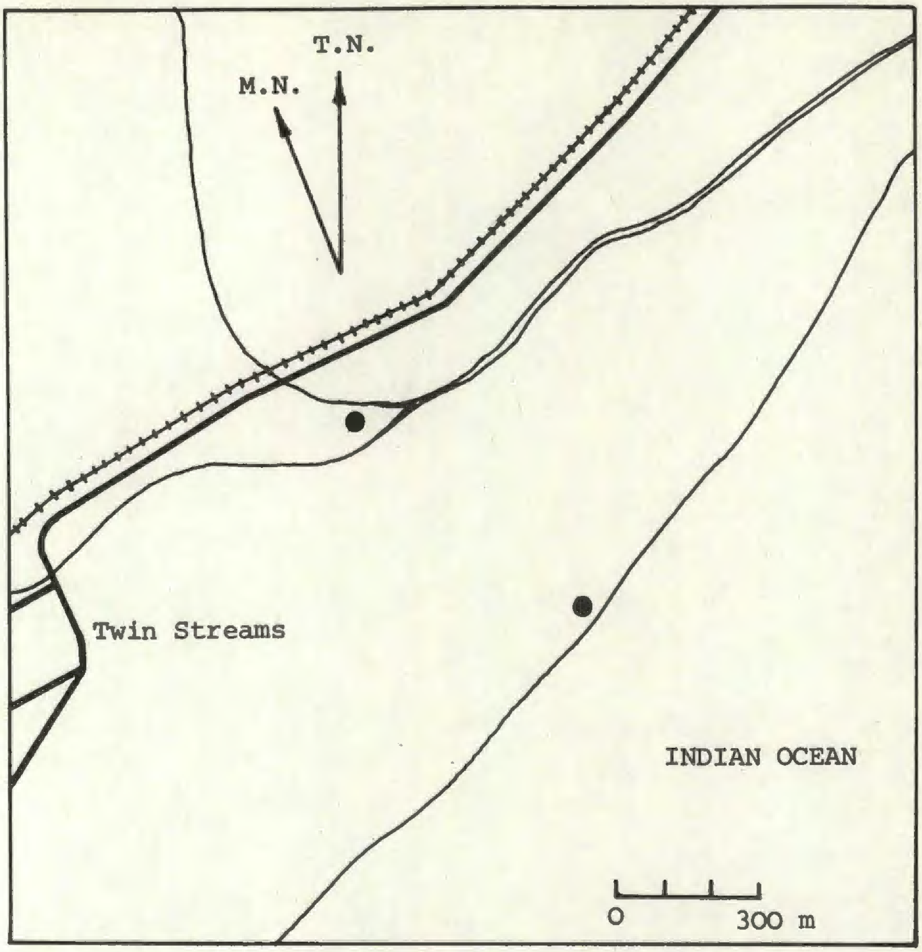



Figure 6.2 Map of the farm "Twin Streams" (Mr I.F.Garland) near Mtunzini, showing the two recording sites.

calibrate the field mills at the inland site first. Those at the beach were then switched on and calibrated some 15 minutes later. After a period of 45 to 60 minutes the beach instruments were recalibrated and then switched off. The same operation was then carried out 15 minutes or so later at the inland site. In this way about 45 to 60 minutes of simultaneous recording was obtained at both sites, and since the instruments at the inland site ran for longer periods of time than did those at the beach, the recharging of batteries at the beach site - where access with the portable petrol driven battery charger was difficult - was reduced to a minimum. In this experiment, since the instruments were calibrated at the beginning and end of each set of observations, very reliable results were obtained.

Each field mill used in the three sets of experiments gave an output in the form of a direct current signal which was recorded on a self-contained miniature recorder with a 0-100 μA movement. The amplifiers developed for these field mills gave a linear response and the different sensitivities used in the three sets of experiments meant that at Ballito Bay potential gradients could be determined to within ±10 V $m^{-1}$, while at Mtunzini the accuracy was ±10 V $m^{-1}$ at worst and ±5 V $m^{-1}$ when maximum sensitivity was used. The technique of constant off-set of the zero used for sign discrimination at Ballito Bay was not very reliable on account of the high salt and moisture content of the atmosphere (see the relevant section of Chapter Five). Consequently the accuracy of the Ballito Bay results was not regarded as being better than ±20 V $m^{-1}$.

The anemometer records obtained at each site at Ballito Bay in 1973 were, like those of the field mills, in the form of a chart output of a self-contained 0-100 μA d.c. recorder. As described in Chapter Five, a system of time sharing was used so that each chart provided information of wind speed for about 4 minutes in every 5, with the fifth minute being devoted to direction information. An example of a typical record is shown in Figure 5.17, while the actual directions and wind speeds were determined from calibration curves similar to Figures 5.15 and 5.16.

### 6.3.2 Results

#### 6.3.2.1 Ballito Bay - August and September 1972 and May 1973

During August and the early part of September 1972 the preliminary coastal environment experiment was carried out at Ballito Bay. The results obtained on 6 days during this period are reproduced in Table 6.3. The meteorological data included in the table refer to the South African Weather Bureau at Louis Botha Airport in Durban, but the conditions at Ballito Bay would be very similar. The average potential gradient at the inland site was 187 V $m^{-1}$ (standard deviation 87 V $m^{-1}$) which makes this value not very different from the generally accepted value of about 120 V $m^{-1}$ for a globally representative recording site. The average potential gradient recorded at the beach was 342 V $m^{-1}$ (standard deviation 133 V $m^{-1}$). The fact that this value was consistently higher than the value recorded inland, by an average factor of about 1.9, is consistent with the theories of the generation of space charge in the surf zone which will be discussed in the next chapter. It will be noticed from Table 6.3 that the results were in general obtained at a few isolated times and over short periods of about 1 hour or so. The exceptions to this are the first two entries in the table where long continuous periods of reliable observations were obtained. These results are discussed more fully in the next chapter.

Because of the zero drift of the field mills, mentioned earlier in this chapter and discussed in Chapter Five, results were found to be reliable only for periods of about 1 hour immediately after the calibration of the instruments, except for a few occasions when it was possible to attend to the instruments continuously.

In an attempt to increase the number of records obtained at Ballito Bay, the experiment was repeated in May 1973, additional information being provided for this experiment by the recording anemometers, described in Chapter Five. Once again, results were only taken for periods of about 1

| Date | Period of observation (S.A.S.T.) | Average potential gradient ($V\ m^{-1}$) | | | Durban weather summary | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Air temp. ($^{o}C$) | | Rel. humidity (%) Times (S.A.S.T.) | | | Hours sun-shine |
| | | Beach | Inland | Beach / Inland | max. | min. | 08h00 | 14h00 | 18h00 | |
| 8/8/72 | 04h15 - 11h45 | 256 | 148 | 1.73 | 21.3 | 14.0 | 79 | 63 | 67 | 3.9 |
| 9/8/72 | 00h15 - 22h15 | 278 | 127 | 2.19 | 22.6 | 8.6 | 69 | 49 | 67 | 9.4 |
| 10/8/72 | 04h45 - 05h30<br>06h15 - 07h00<br>+ 10 values | 358 | 209 | 1.71 | 22.8 | 8.5 | 81 | 56 | 81 | 8.9 |
| 11/8/72 | 06h00 - 06h15<br>08h30 - 09h30<br>+ 5 values | 191 | 100 | 1.91 | 22.4 | 8.2 | 88 | 61 | 50 | 8.6 |
| 22/8/72 | 12h30 - 13h15 | 411 | 346 | 1.19 | 23.3 | 12.4 | 93 | 75 | 78 | 7.9 |
| 7/9/72 | 14h30 - 15h15 | 563 | 193 | 2.92 | 27.2 | 8.0 | 79 | 52 | 74 | 9.6 |
| | Average | 342 | 187 | 1.94 | | | | | | |
| | Standard deviation | 133 | 87 | 0.58 | | | | | | |

Table 6.3 Potential gradient measurements at Ballito Bay in 1972.

hour immediately following the calibration of the instruments. Absolute values of potential gradients obtained during these periods are recorded in Table 6.4. The values shown are averages taken over the 1 hour period and they are accurate to within ±20 V $m^{-1}$. The weather on all occasions except the first was fine and sunny. The first entry, for 2/5/73, indicates that conditions were overcast with a fairly strong wind. As with the 1972 experiment, the meteorological data refer to Durban, but generally conditions at Durban and at Ballito Bay are very similar.

It is apparent from these results that the potential gradients were generally considerably higher than those normally associated with fair weather conditions in a clean atmosphere. Here the average values were 226 V $m^{-1}$ (standard deviation 48 V $m^{-1}$) at the inland site and 369 V $m^{-1}$ (standard deviation 104 V $m^{-1}$) at the beach. It should be noted that the potential gradient at the beach was consistently higher (by an average factor of about 1.7) than the value inland. These findings are again consistent with the theory of space charge generation by surf action, as will be seen in the next chapter. The one exception to the statement that the potential gradient at the beach was consistently higher than that inland is the entry for 11/5/73, where the value at the beach was 256 V $m^{-1}$, while that inland was 230 V $m^{-1}$. Since these values should be expressed as 256 ± 20 V $m^{-1}$ and 230 ± 20 V $m^{-1}$, respectively, it is probable that the two values are not significantly different. There is no obvious reason as to why this set of readings should differ from the others, although it will be seen in the next chapter that, at least some of the time, the atmosphere at Ballito Bay was not as unpolluted as had been hoped.

<u>6.3.2.2 Mtunzini - July 1975</u>

The results obtained in the two Ballito Bay experiments, as well as the obvious rapid development of the settlement at Ballito Bay (known as Ballitoville), indicated a possible increase in the pollution at this site. (One possible indication of this is given by the inland average potential

| Date | Approx. time of start (S.A.S.T) | Average potential gradient $(V\ m^{-1})$ | | | Wind $(m\ s^{-1})$ | | Durban weather summary | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Air temp. (°C) | | Rel. humidity (%) Times (S.A.S.T.) | | | Hours Sun-Shine |
| | | Beach | Inland | Beach/Inland | Beach | Inland | max. | min. | 08h00 | 14h00 | 18h00 | |
| 2/5/73 | 12h00 | 309 | 205 | 1.51 | SW 5 | SW 4 | 18.5 | 16.2 | 50 | 49 | 70 | 0 |
| 4/5/73 | 16h00 | 367 | 151 | 2.43 | SW 5 | SW 3 | 23.5 | 15.9 | 67 | 43 | 48 | 9.2 |
| 9/5/73 | 12h00 | 480 | 252 | 1.90 | E 3 | E 2 | 25.7 | 13.0 | 89 | 62 | 81 | 8.4 |
| 11/5/73 | 14h00 | 230 | 256 | 0.90 | E 4 | E 3 | 25.6 | 15.8 | 81 | 69 | 86 | 4.6 |
| 16/5/73 | 09h00 | 457 | 268 | 1.71 | W 2 | W 2 | 25.5 | 13.9 | 70 | 51 | 75 | 8.5 |
| | Average | 369 | 226 | 1.69 | | | | | | | | |
| Standard deviation | | 104 | 48 | 0.56 | | | | | | | | |

Table 6.4 Potential gradient measurements at Ballito Bay in 1973.

gradient of 187 ± 87 V $m^{-1}$ in August 1972 rising to 226 ± 48 V $m^{-1}$ in May 1973. Clearly, allowing for the standard deviations, these values overlap, but they may be indicative of an increasing potential gradient although too much significance must not be attached to these figures). As a result, the same type of experiment was repeated in a region more remote from human habitation.

The results obtained in this experiment are reproduced in Table 6.5. The most significant findings are firstly, that the average inland potential gradient of 152 V $m^{-1}$ (standard deviation 76 V $m^{-1}$) is very much what would be expected of a globally representative recording site, while secondly, the ratio of beach to inland values is somewhat higher than those obtained at Ballito Bay. The average ratio is 2.5 (standard deviation 1.5) in this case compared with average values for Ballito Bay of 1.7 (standard deviation 0.6) in 1973 and 1.9 (standard deviation 0.6) in 1972. Even if the one particularly high value of the ratio of potential gradients shown in Table 6.5 is excluded from the average, the value at Mtunzini still remains quite high at 1.9 (standard deviation 0.2).

Although there are insufficient results here from which to draw definite conclusions, it is interesting to note that the value of the ratio of beach potential gradient to inland potential gradient appears highest when the atmosphere is cleanest and has its lowest value under the most polluted atmospheric conditions. The change in this ratio between 1972 and 1973 may be an indication of the increasing atmospheric pollution at Ballito Bay. It is interesting to speculate on one possible consequence of this suggestion. If the ratio decreases to unity, or even less, then it would suggest that the generation of positive charge in the surf zone is controlled by the prevailing potential gradient, which in turn depends on the degree of pollution in the atmosphere.

Reference to Table 6.5 will show that the lowest values of both potential gradients and the highest value of the ratio of beach to inland potential

| Date | Period of observation (S.A.S.T.) | Average potential gradient (V $m^{-1}$) | | | Summary of observed weather conditions. |
|---|---|---|---|---|---|
| | | Beach | Inland | Beach/Inland | |
| 15/7/75 | 16h40 - 17h00 | 189 | 359 | 1.90 | No cloud. Light breeze on shore |
| 16/7/75 | 15h35 - 16h10 | 260 | 412 | 1.58 | No cloud. Some haze. Breeze parallel to shore. Spray-haze visible to about 3m over surf - apparently not being blown inland. |
| 17/7/75 | 17h15 - 17h40 | 30 | 164 | 5.47 | $^7/_8$ cloud, overnight rain,. Moderate breeze blowing off-shore. Visibility good. |
| 19/7/75 | 09h20 - 10h10 | 160 | 356 | 2.23 | $^1/8$ high cloud. Calm. Moderate visibility. |
| 20/7/75 | 09h30 - 10h10 | 151 | 291 | 1.93 | $^2/8$ cloud. Light haze. Very light on-shore breeze. |
| 21/7/75 | 10h00 - 10h35 | 120 | 216 | 1.80 | $^1/8$ cloud. Visibility good. Breeze changed from off-to on-shore at 10h05. Spray-haze starting to become visible over land. |
| | Average | 152 | 300 | 2.49 | |
| | Standard deviation | 76 | 95 | 1.48 | |

Table 6.5 Potential gradient measurments made at Mtunzini in 1975.

gradient were obtained on the 17/7/75. On this occasion there had been some overnight rain and the atmosphere appeared particularly clean. The highest values of the two potential gradients and the lowest value of the ratio resulted on the day preceding the rain when a fair amount of haze was present in the atmosphere.

During the observation made on the 21/7/75 the wind changed in direction from being off-shore to being on-shore. The potential gradient reflected this change, going from a value of about 190 to about 330 V $m^{-1}$ at the beach. The value inland rose from about 50 to about 85 V $m^{-1}$ roughly 7 minutes after the change occurred at the beach. This would imply a wind velocity component directly on-shore of about 5 km $hour^{-1}$, which is reasonable. This change in potential gradient is obviously due to wind borne space charge, and this aspect is discussed in the next chapter.

## 6.4 THE KLOOF EXPERIMENT

### 6.4.1 Experimental arrangement and data handling

The site at Kloof was on the front lawn of the author's home. The area is a suburban one lying between 450 and 550 m above sea level in wooded and hilly countryside some 20 km inland from the coast. The actual recording site used here was at an elevation of about 530 m on a fairly open sloping site. The nearest industries were situated about 8 km away at a lower elevation (about 300 m).

The field mills developed for use at Kloof have been described in Chapter Five. Two mills were used, one with its measuring plate flush with the ground and the other inverted on a stand about 2 m above the ground. (Like the other experiments described in this chapter, this configuration was used to yield information on space charge density).

The anemometer and aspiration psychrometer described in Chapter Five were also used in Kloof. Both of these instruments, like the field mills, could be powered by battery. However, since 220 V 50 Hz mains power was available, d.c. power supplies as described in Chapter Five were used.

All of the instruments used gave outputs in the form of direct currents recorded on 0-100 µA chart recorders. These data were reduced to the values of the particular parameters being measured by use of the relevant calibration curves.

The results obtained from the aspiration psychrometer were required for the sunrise effect dealt with in Chapter Eight, although some use has been made of them here. The anemometer results were not used at all in the Kloof experiment because of the nature of the site which tended to cause both the direction and speed of the wind at the position of the anemometer to differ quite markedly from the generally prevailing wind direction and speed. Particular attention was paid to diurnal variations in potential gradient. Records were selected only for those days when clear and cloudless, or nearly cloudless, conditions prevailed. The records for all such days in any one calendar month were averaged on an hourly basis and, for each hour, the results were then expressed as a percentage of the mean of all the hourly values for that month.

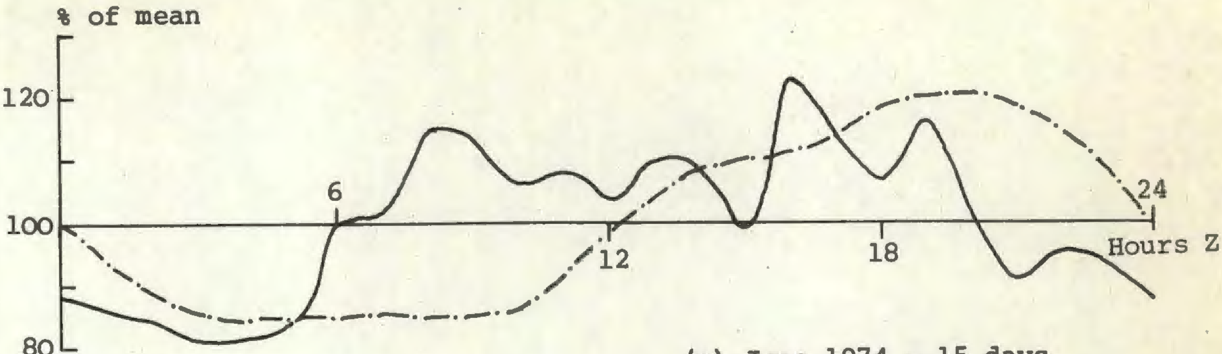
### 6.4.2 Results

Suitable fine and clear weather conditions were experienced on 15 days in June, 16 days in July, 14 days in August and 6 days in September during 1974. The average of the hourly values of potential gradient recorded at Kloof for all of these 51 days was 106 V $m^{-1}$; with the monthly averages being June 104 V $m^{-1}$, July 110 V $m^{-1}$, August 96 V $m^{-1}$ and September 119 V $m^{-1}$. The values of the hourly averages are listed in Table 6.6 and these are represented graphically in Figure 6.3.

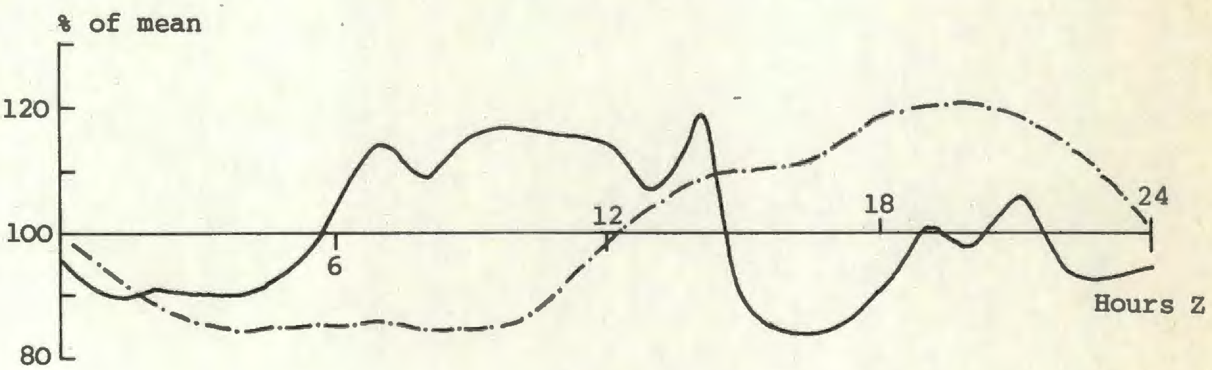
Figure 6.3 shows the monthly averages of the hourly values of potential

| Time hours Z | June 15 days μA | % | July 16 days μA | % | August 14 days μA | % | September 6 days μA | % | June 51 days μA | % |
|---|---|---|---|---|---|---|---|---|---|---|
| 00h00 | 23.87 | 88 | 27.17 | 95 | 25.65 | 102 | 26.83 | 88 | 25.79 | 94 |
| 01h00 | 23.40 | 86 | 25.69 | 90 | 28.07 | 112 | 25.00 | 82 | 25.59 | 93 |
| 02h00 | 23.13 | 85 | 26.00 | 91 | 26.93 | 107 | 24.83 | 81 | 25.27 | 92 |
| 03h00 | 22.13 | 81 | 25.69 | 90 | 23.50 | 93 | 28.83 | 94 | 24.41 | 89 |
| 04h00 | 22.33 | 82 | 25.88 | 90 | 23.50 | 93 | 32.33 | 106 | 24.94 | 91 |
| 05h00 | 22.73 | 83 | 26.75 | 93 | 26.07 | 104 | 32.17 | 105 | 26.02 | 94 |
| 06h00 | 27.47 | 100 | 29.75 | 104 | 28.43 | 113 | 30.83 | 101 | 28.84 | 105 |
| 07h00 | 27.73 | 101 | 32.81 | 114 | 25.14 | 100 | 26.17 | 85 | 28.43 | 103 |
| 08h00 | 31.47 | 115 | 31.19 | 109 | 25.86 | 103 | 24.50 | 80 | 29.02 | 105 |
| 09h00 | 30.73 | 112 | 33.19 | 116 | 26.64 | 106 | 25.83 | 84 | 29.80 | 108 |
| 10h00 | 28.93 | 106 | 33.50 | 117 | 25.57 | 102 | 28.83 | 94 | 29.20 | 106 |
| 11h00 | 29.60 | 108 | 33.25 | 116 | 25.21 | 100 | 26.83 | 88 | 29.22 | 106 |
| 12h00 | 28.47 | 104 | 32.94 | 115 | 26.79 | 107 | 29.00 | 95 | 29.47 | 107 |
| 13h00 | 30.20 | 110 | 30.25 | 106 | 24.29 | 97 | 31.50 | 103 | 28.75 | 104 |
| 14h00 | 29.73 | 109 | 34.19 | 119 | 24.21 | 96 | 32.33 | 106 | 29.92 | 109 |
| 15h00 | 27.13 | 99 | 25.81 | 90 | 24.07 | 96 | 33.00 | 108 | 26.57 | 96 |
| 16h00 | 33.60 | 123 | 24.25 | 85 | 22.64 | 90 | 34.67 | 113 | 27.78 | 101 |
| 17h00 | 31.20 | 114 | 24.44 | 85 | 21.93 | 87 | 40.33 | 132 | 27.61 | 100 |
| 18h00 | 29.33 | 107 | 26.19 | 91 | 23.50 | 93 | 35.67 | 116 | 27.49 | 100 |
| 19h00 | 31.73 | 116 | 28.88 | 101 | 25.36 | 101 | 33.17 | 108 | 29.25 | 106 |
| 20h00 | 27.73 | 101 | 28.19 | 98 | 24.50 | 97 | 34.33 | 112 | 27.76 | 101 |
| 21h00 | 25.13 | 92 | 30.50 | 106 | 24.71 | 98 | 32.67 | 107 | 27.59 | 100 |
| 22h00 | 26.27 | 96 | 26.81 | 94 | 26.64 | 106 | 38.33 | 125 | 27.96 | 102 |
| 23h00 | 25.67 | 94 | 26.63 | 93 | 23.93 | 95 | 31.17 | 102 | 26.14 | 95 |
| 24h00 | 23.87 | 88 | 27.17 | 95 | 25.65 | 102 | 26.83 | 88 | 25.79 | 94 |
| Mean (μA) | 27.24 | | 28.66 | | 25.15 | | 30.64 | | 27.54 | |
| Mean (V $m^{-1}$) | 104 | | 110 | | 96 | | 119 | | 106 | |

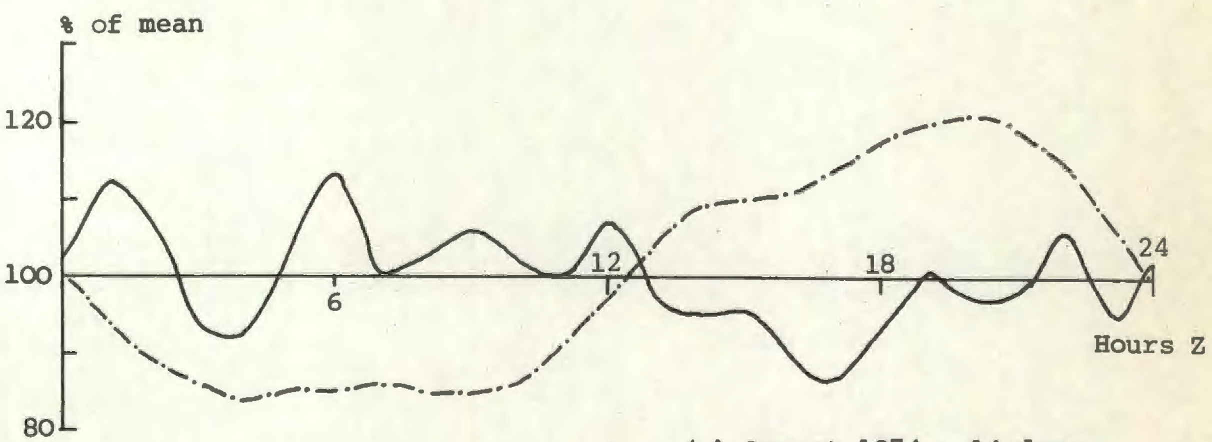
Table 6.6 Average hourly values of potential gradient (entered as field mill reading in μA)obtained at Kloof during 1974. These values are also expressed




(a) June 1974 - 15 days

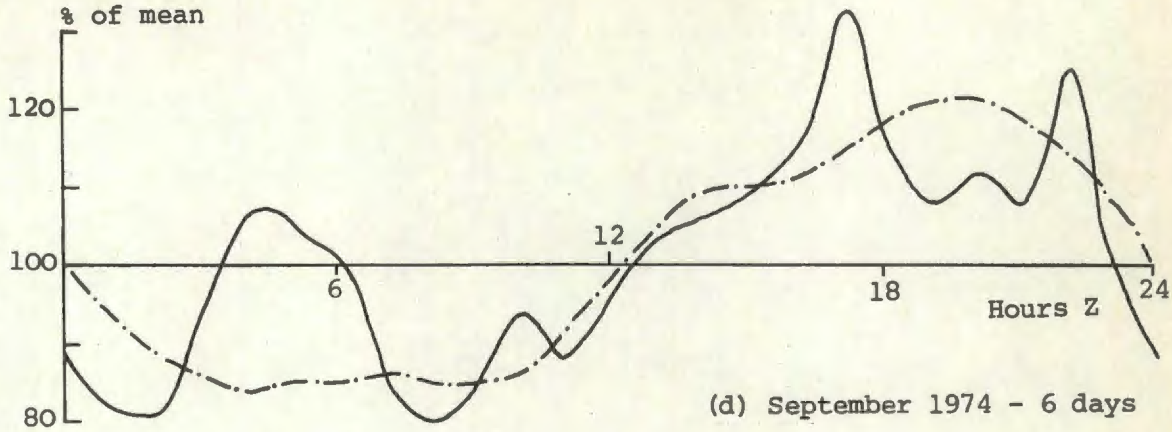



(b) July 1974 - 16 days

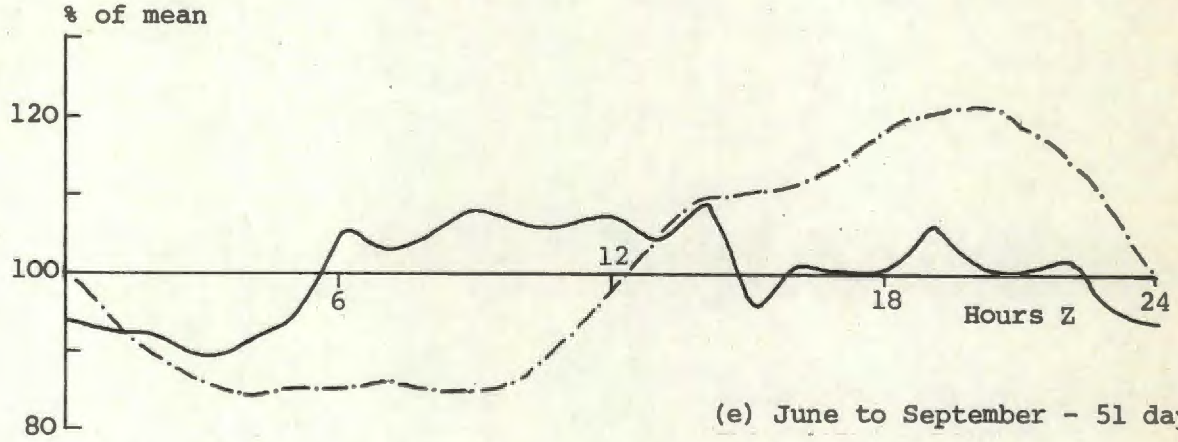



(c) August 1974 - 14 days

Figure 6.3 Comparison of the diurnal variation in potential gradient (solid line), measured at Kloof, with global thunderstorm activity (broken line). (Continued overleaf).




(d) September 1974 - 6 days




(e) June to September - 51 days

Figure 6.3 (Contd.) Comparison of the diurnal variation in potential gradient (solid line), measured at Kloof, with global thunderstorm activity (broken line).

gradient recorded at Kloof plotted against the modified global thunderstorm activity curve which was described in Chapter Three (Section 3.2.1). This indication of the thunderstorm activity was used, rather than that given by DOLEZALEK (1972), because the amplitude of the modified Whipple-Scrase curve was more nearly the same as the amplitude of the potential gradient variations. (The difference between the amplitude of the Dolezalek curve and that of the modified Whipple-Scrase curve is discussed in Section 3.2.1).

It is immediately apparent from Figure 6.3 that there is virtually no correlation between the potential gradient variation at Kloof and the global thunderstorm activity. This is despite the facts that the potential gradient values refer to selected fair weather days (when correlation might be expected to be at its highest level) and that, from the average potential gradient of 106 V $m^{-1}$, it might be expected that the site should exhibit the properties of a globally representative site. The best correlation was obtained in September for a sample of only 6 days, and even here there is a marked divergence between the two curves during the period 03h00 to 07h00 Z. For the other months, and indeed for the entire period, one may conclude that there is no correlation at all. This conclusion can mean one of two things: Either, there is in fact no correlation between potential gradient variations and the global incidence of thunderstorms as measured by the modified Whipple-Scrase curve or the Dolezalek curve; or, for some reason, the Kloof field station is not a suitable site to show global variations in potential gradient.

If the first of these alternatives is the correct one, as has been suggested by DOLEZALEK (1972), then no correlation should be expected. An attempt was made in this experiment to exclude all results which might show local effects on the potential gradient, such as cloud cover.

If the Kloof site was not suitable for showing the global variation, assuming this variation to exist (an assumption which is supported by the findings of SHARPLESS, ASPINALL and HUTCHINSON (1971) and of KASEMIR (1972)) then reasons must be sought to explain the unsuitability of the Kloof site. The most obvious possible reason is the pollution of the atmosphere by human activities. The emissions from motor vehicle exhausts and domestic heating fires would seem to be the main sources of such pollution, although factory effluent discharged into the atmosphere from the industrial area about 8 km away must also be regarded as a possible source. A less obvious, but none-the-less possible, source of electrical perturbation of the atmosphere is the generation of positive space charge along the coast line and the subsequent movement of this space charge over the land. This aspect of the electrical behaviour of the atmosphere is discussed more fully in the next chapter.

Whatever the reason for the fact that the Kloof results do not show a diurnal variation it must be regared as significant that this is in spite of the fact that the average potential gradient on 51 fair weather days was 106 $V\ m^{-1}$, a value very much the same as that generally regarded as applying to globally representative stations.

# Chapter Seven

## ELECTRIC SPACE CHARGE IN THE ATMOSPHERE

*Fair is foul, and foul is fair:*
*Hover through the fog and filthy air.*

W. Shakespeare (1564-1616)
Macbeth

### 7.1 INTRODUCTION

Earlier in this thesis it was stated that any normal sample of the atmosphere contains ions of various sorts. These are usually classified as being either large or small ions, and of course they may be either positively or negatively charged. Under most conditions a given sample of atmospheric air might be expected to contain roughly equal quantities of both types of charge and the sample as such will have no net charge. If, however, conditions are such that charge of one type is predominant in a sample of air, then the sample has a net charge, called space charge.

Various agencies may be responsible for space charge in the atmosphere; for example, artificial space charge generators such as the internal combustion engine, or natural agencies such as the electrode effect. Space charge may have a bearing on atmospheric pollution, it may play a role in cloud electrification, it is a useful tracer of atmospheric movement and it has been stated, by LATHAM and MIKSAD (1974), that the extent to which a given meteorological event can produce anomalies in the electric field often depends on the extent to which changes in space charge can be produced. Consequently a knowledge of both the concentration and type of space charge is often desirable.

The two most widely used methods for the measurement of space charge in the lower atmosphere involve either filtration of the air and direct measurement of any charge trapped by the filter, or measurement of potential gradients in the atmosphere at different levels and use of Poisson's equation to obtain values of the space charge. Resumés of space charge measuring techniques have been given by VONNEGUT and MOORE (1958b) and by ANDERSON (1966). Filtration methods, such as that described by BENT (1964), have the disadvantage that results can only be obtained under fair weather conditions.

The use of field mills to measure potential gradients, and hence space charge concentrations, may be divided broadly into two categories; the use of special devices such as the double field mill of SMIDDY and CHALMERS (1960), or the siting of conventional field mills at different fixed levels above the ground. One of the problems associated with the use of either category of field mill is the calibration of the instrument, particularly when situated on some field distorting structure. The procedure generally adopted involves comparing the readings of a mill on the structure with one placed in the plane of the ground some distance from any field distorting objects. The major disadvantage of this method is the necessary assumption that zero space charge exists in the region between the levels of the two mills. The following approach to the problem was suggested by the author (MUIR, 1971) and has proved successful.

## 7.2 THEORY

Consider two field mills placed as shown in Figure 7.1. The one mill is well clear of any field distorting object, in the plane of the ground, and it indicates a potential gradient $M_1$ at the same instant that the other, at a height h above the ground, indicates a potential gradient $M_2$. If $\rho$ is the average space charge density within the region h, then by Poisson's equation the difference in potential gradient between the levels of the two mills due to this space charge will be given by

$$dE/dh = -\rho/\varepsilon_0$$

where $\varepsilon_0$ is the electric space constant. Integrating this equation between

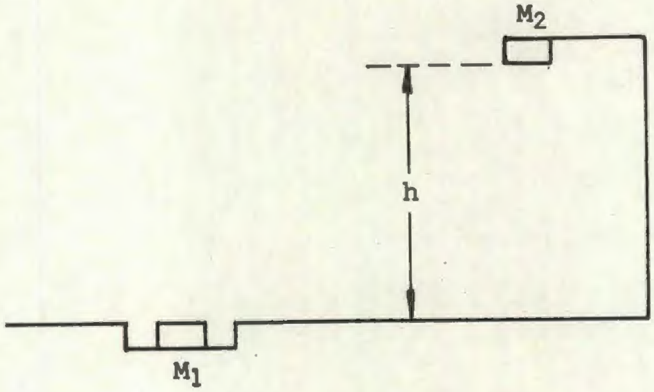



Figure 7.1 The arrangement of the two field mills.

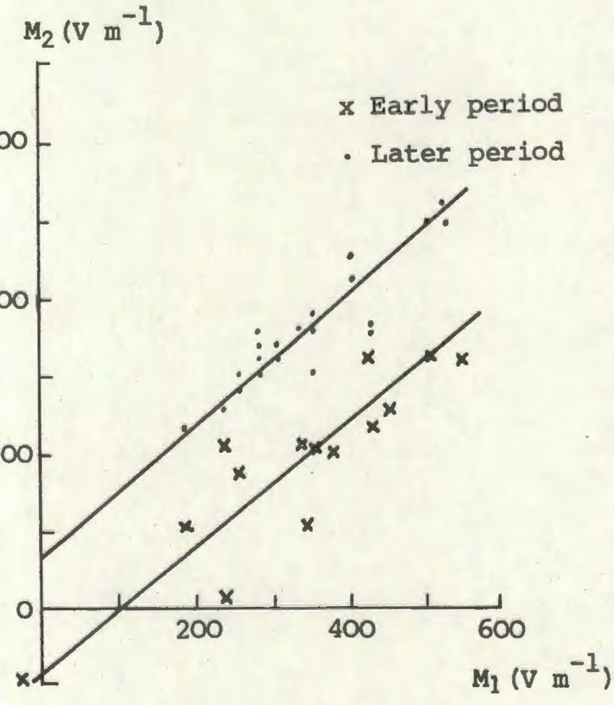



Figure 7.2 Graphs of the calculated best straight lines for the first two entries in Table 7.1, plotted according to equation (7.1).

the mill in the ground plane (height 0) and the upper mill (height h) with $\rho$ assumed constant, yields a difference in potential gradient between the two mills of $-\rho h/\varepsilon_0$. Thus the potential gradient at the level of the upper mill, in the absence of the field distorting structure, will be

$$M_1 - \rho h/\varepsilon_0 .$$

If now this value of potential gradient is modified by a factor A due to the presence of the structure, then

$$M_2 = A(M_1 - \rho h/\varepsilon_0)$$

$$\text{or} \quad M_2 = AM_1 + B \qquad (7.1)$$

where $B = - A\rho h/\varepsilon_0$. The factor A is often called the form factor or exposure factor of the second mill.

If A and B are constants, then a linear relationship exists between $M_1$ and $M_2$. If simultaneous pairs of values, $M_1$ and $M_2$, recorded during a period when the space charge remains constant, are plotted and the resultant straight line drawn, the slope (A) and the intercept (B) of this line will yield an average value of $\rho$ over the period considered. It was shown by MUIR (1971) that reasonable agreement was obtained between results yielded by the above procedure and results obtained with a conventional space charge collector, such as that described by BENT (1964).

Additonal experimental evidence which tends to confirm equation (7.1) is provided by COLLIN, RAISBECK and CHALMERS (1963) who derived a purely empirical relationship of exactly the same form as this equation.

## 7.3 THE DURHAM EXPERIMENT

### 7.3.1 Experimental arrangement and data handling

The experimental work at Durham was conducted at the Observatory field station. A 21 m high steel lattice tower of the type used to carry overhead high-voltage electricity lines had been erected in the field at the Observatory. This was used to mount two field mills on, both in the inverted position, one at a height h = 2.2 m above the ground ($M_2$) and the other 12.6 m above the ground ($M_3$). The reference mill ($M_1$) was placed upright in a pit (with its measuring plate flush with the ground) about 25 m from the base of the tower. The output of each mill was taken by cable to the Observatory building where they were recorded on three channels of a four channel 0 - 1 mA chart recorder. In each case a constant bias voltage was used to off-set the zero to provide sign discrimination.

The recorded direct current output of each mill was converted to potential gradient values using suitable calibration curves. Simultaneous values of the potential gradients $M_1$, $M_2$ and $M_3$ could then be obtained. The readings $M_1$ and $M_2$ are related by equation (7.1); readings $M_2$ and $M_3$ may be similarly related by

$$M_3 = A'M_2 + B' \tag{7.2}$$

where A' may be regarded as the form factor, or exposure factor, of the third mill in terms of the second, while $B' = -A'h'\rho/\varepsilon_0$. Values of the average space charge densities over each of the two regions, h and h', obtained in this way are given in Table 7.1.

Fluctuations in space charge density, due for example to wind borne pockets of space charge, will obviously cause a scatter in the points plotted for equations (7.1) and (7.2). In order to draw the best straight line to the experimental points, the least squares method proposed by MORGAN (1960) was used. This method allows for errors in both variables and it was adapted for use with a Hewlett-Packard HP9100B calculator. This procedure enabled the equation of the best straight line to be calculated for any given set of points ($M_1$,$M_2$) or ($M_2$,$M_3$).

If the sensitivities of the mills remain unchanged and their positions remain fixed, then A and A' in equations (7.1) and (7.2) should each be constant. Variations in space charge will then show by shifting the line parallel to itself to give a different intercept and hence space charge value. Figure 7.2 shows this effect quite clearly in the case of the lower two mills on an occasion when two distinct periods showing different space charge occurred. These are the first two entries in Table 7.1 and they are more fully discussed later.

### 7.3.2 Results

In calculating the values of space charge density, the sensitivity of the field mill was the factor which limited accuracy. This limit was about 20 pC $m^{-3}$ in the Durham experiment and consequently all values are expressed to the nearest 20 pC $m^{-3}$. Where a value in Table 7.1 is recorded as zero followed by a number in parentheses, this is the number actually calculated using the procedure outlined above. It is included here as possibly showing a trend in the results. These results may now be discussed in three groups as follows:

#### 7.3.2.1 Positive space charge near the ground

Record number 5 in Table 7.1 shows a space charge density of +180 pC $m^{-3}$ in the region up to 2.2 m and zero space charge between 2.2 m and 12.6 m, the weather conditions on this day being reasonably calm and settled. Record number 6 shows that the space charge in the region up to 2.2 m was +260 pC $m^{-3}$ and there was some indication that the layer extended above 2.2 m. The weather conditions of record 6 were more conducive to convection and mixing taking place (higher air temperature and higher wind speeds) than were those of record 5. Thus the layer of positive charge might be expected to extend over a greater height in the case of record 6.

These values of space charge density are easily obtainable in an urban area such as Durham where many artificial sources of space charge (domestic fires, motor-car engines etc.) are active in addition to the natural sources of ionization (radioactivity in the soil, cosmic rays) and to natural sources of space charge (point discharge currents). In fact, filtration measurements

| Record no. | Date and time (Z) | Average potential gradient (V $m^{-1}$) | Average space charge density ($pC\ m^{-3}$) h = 0 to 2.2 | h' = 2.2 to 12.6 | Summary of prevailing weather conditions: Wind (m $s^{-1}$) | Air temp. (°C) | Remarks |
|---|---|---|---|---|---|---|---|
| 1. | 23/2/71 09h15 - 10h20 | 335 | +400 | -20 | SW 3-4 | 5-9 | 7/8 Cloud, light haze |
| 2. | 23/2/71 10h25 - 16h25 | 350 | -300 | +20 | WSW 6-7 | 11-12 | Cloud clearing, light haze |
| 3. | 2/3/71 10h00 - 17h00 | 430 | 0(-2) | -20 | NW 7-8 | 3-9 | Overnight snow melting rapidly |
| 4. | 5/3/71 10h00 - 13h00 | 220 | 0(+8) | +20 | Calm | 2 | Overcast, snow lying, dense haze |
| 5. | 8/3/71 10h00 - 14h30 | 295 | +180 | 0 | N 2-5 | 7-10 | Overcast |
| 6. | 9/3/71 13h00 - 15h00 | 245 | +260 | 0(+5) | WNW 8-11 | 11-12 | 5/8 Cloud |

Table 7.1 Results of some interesting space charge measurements made at Durham in 1971.

of space charge produced by natural sources alone, made by CROZIER (1963) under conditions of low wind at night, when convection may be assumed to be at a minimum, have shown values of up to +640 pC $m^{-3}$ (4000 elementary charges $cm^{-3}$) extending up to some 0.5 m.

### 7.3.2.2 The melting snow effect

Laboratory and field experiments carried out with melting snow, such as the experiment reported by BENT and HUTCHINSON (1965), have indicated that in the melting process the snow acquires a positive charge while liberating a negative charge to the air. Since the melting snow remains on the ground, only the negative charge should be detected by the field mills. Bent and Hutchinson found negative space charge up to about 1.5 m with positive space charge above this level over melting snow. The positive charge they attributed to wind borne space charge from distant blowing snow.

Record 3 is considered to be an example of the melting snow effect. Rapidly melting snow generates negative charge at the surface. To explain the low density of space charge recorded in the region up to 2.2 m, it is postulated that an artificial source of positive space charge existed nearby, and that a thin layer of this charge existed near the surface. Under the action of the prevailing field the positive ions move downward and the negative ions move upward away from the surface. Within 2.2 m of the surface it is assumed that the number densities of positive and negative ions were roughly equal. If the negative charge generated at the surface was in the form of small ions of high mobility, then most of this negative charge would penetrate the thin layer of positive charge and thus be detected as a net negative space charge in the region above the positive layer. The negative charge lost from the lowest layers in this way is continually being replaced by further melting of the snow on the ground. It is of interest to note that this situation persists in spite of the fairly high wind speed which is often taken as indicative of good mixing conditions.

Record 4 shows a modification of the melting snow effect. On this day there was a dense haze which extended to above the 12.6 m level. It is suggested that this haze carried positive charge which was thus evenly distributed throughout the region in which measurements were made. The snow on the ground was melting only slowly (air temperature about $2^{o}C$) and the slow but persistent generation of negative charge caused the resultant zero of space charge in the region near the ground. If most of this negative charge was lost by attachment and recombination in the lower regions of the haze, then a region of positive space charge would be detected above the region of zero charge. It must be noted that the upper positive charge in this case cannot be ascribed to any effect such as that suggested by BENT and HUTCHINSON (1965), but is due to the charge in the haze which most probably resulted from artificial sources such as domestic fires.

7.3.2.3 Space charge sign reversal

Records 1 and 2 fall into a third category. These records were made as a continuous record on a single day. It was found that the potential gradient record showed a marked change in appearance and on the basis of the appearance it was divided into two parts. The early period lasted from 09h15 Z to 10h20 Z on the 23rd of February 1971. During this period 14 points were obtained and the best straight line calculated for these gave A = 0.78 and $\rho = +400$ pC $m^{-3}$ with a correlation coefficient of 0.90. The later period yielded 25 points between 10h25 Z and 16h25 Z and the best straight line to these gave A = 0.85, $\rho = -300$ pC $m^{-3}$, with a correlation coefficient of 0.95.

Figure 7.2 shows the large scatter in the points of record 1. The later period, the commencement of which coincided with a slight change in wind direction, shows a very different and rather more consistent value of space charge density. The greater consistency is shown by the smaller scatter in the points. The most interesting feature of these records is the reversal in sign of the space charge of both regions. The following mechanism is suggested as a possible explanation of these records.

During the early period, when the wind speed was low, fairly large pockets of positive space charge from a stationary artificial source, such as a domestic fire, were carried by the wind into the lower region. The existence of this charge in the form of discrete pockets would account for the large scatter in the results. Such pockets of space charge could well be a source of the space charge pulses reported by OGDEN and HUTCHINSON (1970), although their amplitude would appear to be about twice as large as the 50 pC $m^{-3}$ reported by these workers.

In order to explain all the observed results, it would appear to be necessary to postulate the existence of artificial sources of both positive and negative charge. These sources would be situated in such positions relative to the field mill positions that the effect detected by the mills depended on wind direction and speed. These sources could be as far as several hundred metres from the field mills, since easily discernible effects have been found at such distances from an artificial source of charge by VONNEGUT et al (1962). It is of interest to note the long persistence of these values of space charge, often lasting for several hours.

## 7.4 APPLICATION OF THE SPACE CHARGE THEORY TO SOME EARLIER RESULTS

PAGE-SHIPP (1968) made measurements of the potential gradients at heights of 0.2 and 0.7 m above the ground. He found that a linear relationship existed between the readings of the two field mills; a similar conclusion to that reached by COLLIN, RAISBECK and CHALMERS (1963). The data obtained by Page-Shipp are reproduced in Table 7.2 and the two graphs are plotted as Figure 7.3. It will be seen that there are two clearly distinct periods involved.

Page-Shipp obtained the best straight line to each set of data (by regression on $M_1$, where $M_1$ represents the potential gradient at 0.2 m and $M_2$ that at 0.7 m) and hence arrived at the following equations:

| Potential gradients ($V\ m^{-1}$) | | | |
|---|---|---|---|
| Group 1 | clear skies | Group 2 | passing clouds |
| 0.7 m | 0.2 m | 0.7 m | 0.2 m |
| 95 | 80 | 170 | 130 |
| 85 | 70 | 450 | 265 |
| 85 | 70 | 145 | 120 |
| 85 | 60 | 360 | 215 |
| 80 | 50 | 205 | 150 |
| 105 | 70 | 310 | 205 |
| 195 | 110 | 380 | 240 |
| 385 | 190 | | |
| 530 | 245 | | |
| 420 | 195 | | |
| 500 | 225 | | |
| 100 | 60 | | |
| 235 | 135 | | |
| 255 | 130 | | |
| 165 | 100 | | |
| 220 | 125 | | |
| 185 | 110 | | |
| 220 | 125 | | |
| 185 | 110 | | |
| 120 | 75 | | |
| 120 | 70 | | |
| 150 | 90 | | |
| 110 | 75 | | |
| 145 | 90 | | |
| 115 | 90 | | |
| 105 | 85 | | |
| 410 | 195 | | |
| 355 | 175 | | |
| 480 | 220 | | |
| 515 | 235 | | |
| 480 | 215 | | |
| 210 | 125 | | |
| 430 | 190 | | |
| 135 | 75 | | |
| 535 | 250 | | |

Table 7.2 Potential gradient measurements at two levels above the ground obtained by PAGE-SHIPP (1968).

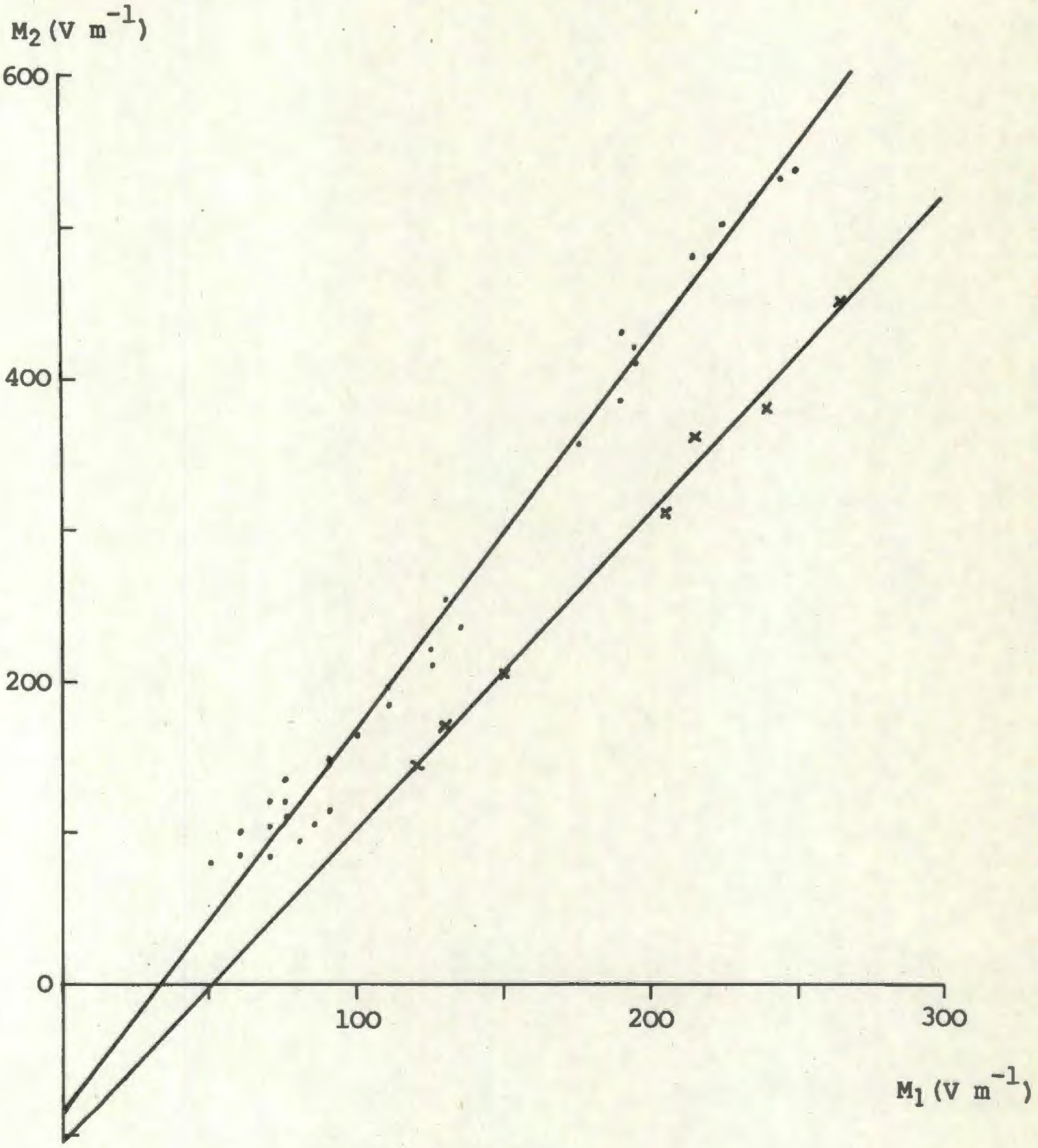



Figure 7.3 Graphical representation of the data of Table 7.2. ( · clear skies, x passing clouds).

$$M_2 = 2.48M_1 - 75 \quad \text{for the clear skies}$$

and $$M_2 = 2.06M_1 - 100 \quad \text{for the passing cloud.}$$

He did not attempt to interpret the significance of these equations.

Application of the theory of Section 7.2 to the data of Table 7.2 yields the equations

$$M_2 = 2.53M_1 - 83$$

and $$M_2 = 2.07M_1 - 104 \text{ respectively.}$$

(The difference in the numbers in these equations and those obtained by Page-Shipp result from the fact that the method used here, due to MORGAN (1960), is effectively an average of regression on $M_1$ and regression on $M_2$). From these equations it was found that the space charge density was +580 pC $m^{-3}$ when the skies were clear and +890 pC $m^{-3}$ with passing clouds.

These results are interesting as they indicate the high value of space charge density (890 pC $m^{-3}$ or about 5600 elementary charges $cm^{-3}$) which can result in an urban and industrialized environment. Unfortunately Page-Shipp does not state whether the data were obtained on a single day or not, nor are the prevailing weather conditions given, so that the significance of the clouds cannot be assessed.

## 7.5 GENERATION OF SPACE CHARGE BY THE SURF ACTION

### 7.5.1 Introduction

It is generally accepted that the processes of bubbling and splashing in the oceans act as sources of positive space charge. BLANCHARD (1966) made measurements of potential gradients and space charge densities on the shore of the island of Hawaii. He commonly found values of positive space charge of the order of 320 pC $m^{-3}$ (2000 elementary charges $cm^{-3}$) generated by a region of the sea where intense bubbling took place. GATHMAN and

TRENT (1968) found that, over the open ocean, positive space charge was only produced where there were whitecaps in the vicinity of the vessel on board which measurements were made.

If bubbling and whitecaps in the sea are sources of positive space charge, then it is likely that the breaker action in the surf zone should also generate positive charge. This may well be an important generator which should be included in estimates of the global charge 'balance sheet' (see for example ISRAEL, 1973 p 555) since there are many thousands of kilometres of active surf line in the world. GATHMAN and HOPPEL (1970) found definite evidence that positive space charge was generated in the surf zone.

To investigate the space charge generated by the surf the space charge density was measured close to the surf zone and at a point further inland from the beach. Two vertically separated field mills were used at each site in a manner similar to the Durham experiment described earlier in this chapter. The theory described in Section 7.5.4 was developed in an attempt to obtain some quantitative idea of the space charge density due to the surf action, and also the thickness of an assumed layer of space charge resulting from the surf action.

### 7.5.2 Experimental arrangements and data handling

The experimental work referred to here was carried out at Ballito Bay in August and September 1972 and in May 1973 and at Mtunzini in July 1975. The sites used for the experiments have been described in Chapter Six. Briefly, two recording sites were used at each field station, one close to the surf and the other further inland. At each site two vertically separated field mills were used.

At Ballito Bay the beach site was about 20 m from the high-water mark and about 1.5 m above this mark. The inland site was about 0.5 km from the beach site at an elevation of about 70 m above mean sea level. The vertical separation between the field mills was $h = 2.31$ m inland and

$h' = 2.11$ m at the beach. The field mills used the bias voltage method to off-set the zero of the recorder and so provide sign discrimination. The field mills were equipped with self-contained chart recorders and suitable calibration curves were used to convert the value of current recorded on the chart into a value of potential gradient.

At Mtunzini the improved model field mills described in Chapter Five were used, in this case connected for operation from batteries as mains power was not obtainable. Here the instruments at the beach were about 90 m from the high-water mark and the lower mill was about 5 m above mean sea level. At this site the vertical separation was $h' = 2.00$ m. The inland site was about 0.6 km away at an elevation of about 30 m with a vertical separation of $h = 1.47$ m between the mills. Once again, suitable calibration curves were used to convert the values of current recorded on the chart into values of potential gradient.

### 7.5.3 Results

#### 7.5.3.1 Ballito Bay - August and September 1972 and May 1973

Values of the space charge density in the vertical space between the two field mills at the beach site were obtained on 10 days during the 1972 experiment. These results are listed in Table 7.3. It will be noticed that the average space charge, taken over prolonged periods, was positive on 6 days, negative on 4. The mean value of space charge density over the 10 days was about +200 pC $m^{-3}$. However, when only those values which were included in the analysis of Chapter Six were used, the average charge was positive on each occasion with a mean value for the 6 days concerned of about +1330 pC $m^{-3}$. It will be seen later in this chapter that there is some evidence for the existence of a bipolar space charge layer under certain conditions. However, if it is assumed that potential gradient values not included in the analysis of Chapter Six were totally unreliable, then it must be concluded that only positive space charge was detected at this site.

| Date | Period of observation (S.A.S.T.) | Average potential gradient (V $m^{-1}$) upper | lower | Space charge density (pC $m^{-3}$) | Space charge for restricted period of Chapter Six | Durham surf temp. ($^{o}$C) |
|---|---|---|---|---|---|---|
| 8/8/72 | 04h15-11h45 | -5 | 278 | +1240 | +1240 | 20.0 |
| 9/8/72 | 00h15-22h15 | 51 | 332 | +650 | +650 | 19.4 |
| 10/8/72 | 00h15-23h45 | 116 | 272 | -240 | +50 | 18.8 |
| 11/8/72 | 02h30-09h30 | 79 | 141 | -230 | +800 | 19.4 |
| 22/8/72 | 12h30-19h30 | 166 | 466 | +220 | +1700 | 21.0 |
| 31/8/72 | 12h00-23h45 | 170 | 323 | -290 | - | 18.8 |
| 1/9/72 | 04h30-23h00 | 130 | 368 | +230 | - | 19.4 |
| 2/9/72 | 00h30-21h00 | 99 | 423 | +840 | - | 20.1 |
| 7/9/72 | 14h15-16h45 | 383 | 470 | -560 | +3560 | 18.3 |
| 18/9/72 | 02h00-10h30 | 183 | 447 | +90 | - | 19.4 |

Table 7.3 Space charge densities at the beach site at Ballito Bay, measured in 1972. Some of the observations which feature in this table were not included in Chapter Six because of malfunction of the inland site field mills.

It is probably more realistic to treat those results excluded from Chapter Six with extreme caution, and to conclude that while the space charge at the beach site was generally positive, there may have been indications of negative charge on occasions.

For the 1973 experiment, values of space charge density were calculated for the 5 days dealt with in Chapter Six. These results are listed in Table 7.4. The averages were obtained over periods of about 1 hour, in accordance with the discussion of the reliability of the results given in Section 6.3.2.1 of the previous chapter. In every case the space charge near the surf zone was positive, with a mean value of about +380 pC $m^{-3}$ and a smallest value of +200 pC $m^{-3}$. It is interesting to note that the two lowest values were obtained on days when the wind was blowing strongly from the south-west. On these days whitecaps were clearly visible at sea. Reference to Figure 6.1 will show that a south-westerly wind is an on-shore wind and, in fact, wind from this direction approached the field mill site over an area of fairly quiet surf. The next two values in Table 7.4 resulted when an east wind was blowing. The space charge density was greater on the occasion of higher wind speed and higher humidity. The east wind approached the field mills over a much rougher surf zone than did the south-west wind (because of rocks in the surf zone) and also the field mills were much closer to the sea along this line than they were along the south-west line. The final reading in Table 7.4 resulted on a day when a fairly gentle westerly wind was blowing. This was an off-shore wind and consequently should have resulted in the lowest value of space charge if the surf generator was regarded as the major source of positive charge. However, this wind with its overland fetch blew over much of the township of Ballitoville and the sugar-cane fields lying inland of the township. It is postulated that this wind carried positive space charge from its fetch into the field mill area in order to account for the high positive space charge density recorded on this occasion.

| Date | Approx. time of start of observation (S.A.S.T.) | Average potential gradient (V $m^{-1}$) | | Wind ($m\ s^{-1}$) | Average space charge density (pC $m^{-3}$) | Durban surf temp. ($^{o}C$) |
|---|---|---|---|---|---|---|
| | | Upper | Lower | | | |
| 2/5/73 | 12h00 | 110 | 309 | SW 5 | + 200 | 20.5 |
| 4/5/73 | 16h00 | 91 | 367 | SW 5 | + 250 | 21.1 |
| 9/5/73 | 12h00 | 160 | 480 | E 3 | + 350 | 23.8 |
| 11/5/73 | 14h00 | 22 | 230 | E 4 | + 600 | 22.7 |
| 16/5/73 | 09h00 | 142 | 457 | W 2 | + 500 | 22.2 |

Table 7.4 Space charge densities at the beach site at Ballito Bay. Measured in 1974.

Another technique of investigating the generation of positive space charge in the surf zone would be to examine the potential gradient records at times when the wind direction changed from being on-shore to off-shore, or vice-versa. If the atmosphere over the land was a truly rural one, and if positive space charge was generated in the surf zone, then a change in wind direction from off- to on-shore should be accompanied by an increase in space charge density and similarly a decrease in density would accompany an on- to off-shore change. This investigation could be carried out quite easily in the case of the 1973 experiment (in 1972 the anemometers were not in use) since relative values of the potential gradient could be used. The major limitation imposed was that only when the wind was at a reasonable strength could the readings be used. At very low wind speeds the direction indication was not reliable - in the limiting case of zero wind speed, direction indications were still given by the instrument. Table 7.5 contains the results of this investigation. In each case the average value of the potential gradient over about 30 minutes before the change in wind direction was ascribed a value of 1.00. Changes in potential gradient were only recognized as such if the difference between the average potential gradients before and after the change in wind direction amounted to at least 5% of the value which pertained before the change in wind direction.

In general, the results recorded in Table 7.5 support the theory of the generation of positive space charge in the surf zone. Only the last entry in the table is apparently not compatible with this theory. Once again, however, this could be explained in terms of positive space charge being generated further inland and being carried over the field mills by the off-shore wind.

#### 7.5.3.2 Mtunzini - July 1975

Values of the space charge density in the vertical space between the field mills were obtained for 8 occasions, on 7 days, at the Mtunzini beach site. These values are given in Table 7.6. Here 6 of the 8 results are negative and the mean space charge density for all 8 results

| Wind direction change | Date | Average relative potential gradient | | | | | |
|---|---|---|---|---|---|---|---|
| | | Beach | | | Inland | | |
| | | before | after | % change | before | after | % change |
| Off to on-shore | 7/5/73 | 1.00 | 1.02 | - | 1.00 | 1.00 | - |
| | 16/5/73 | 1.00 | 0.99 | - | 1.00 | 0.98 | - |
| | 19/5/73 | 1.00 | 1.00 | - | 1.00 | 1.23 | + 23 |
| | 28/5/73 | 1.00 | 2.44 | +144 | 1.00 | 2.30 | +130 |
| On to off-shore | 6/5/73 | 1.00 | 0.32 | - 68 | 1.00 | 0.81 | - 19 |
| | 9/5/73 | 1.00 | 0.52 | - 48 | 1.00 | 0.33 | - 67 |
| | 18/5/73 | 1.00 | 2.59 | +159 | 1.00 | 1.37 | + 37 |

Table 7.5 The effect of changes in wind direction on the relative potential gradient.

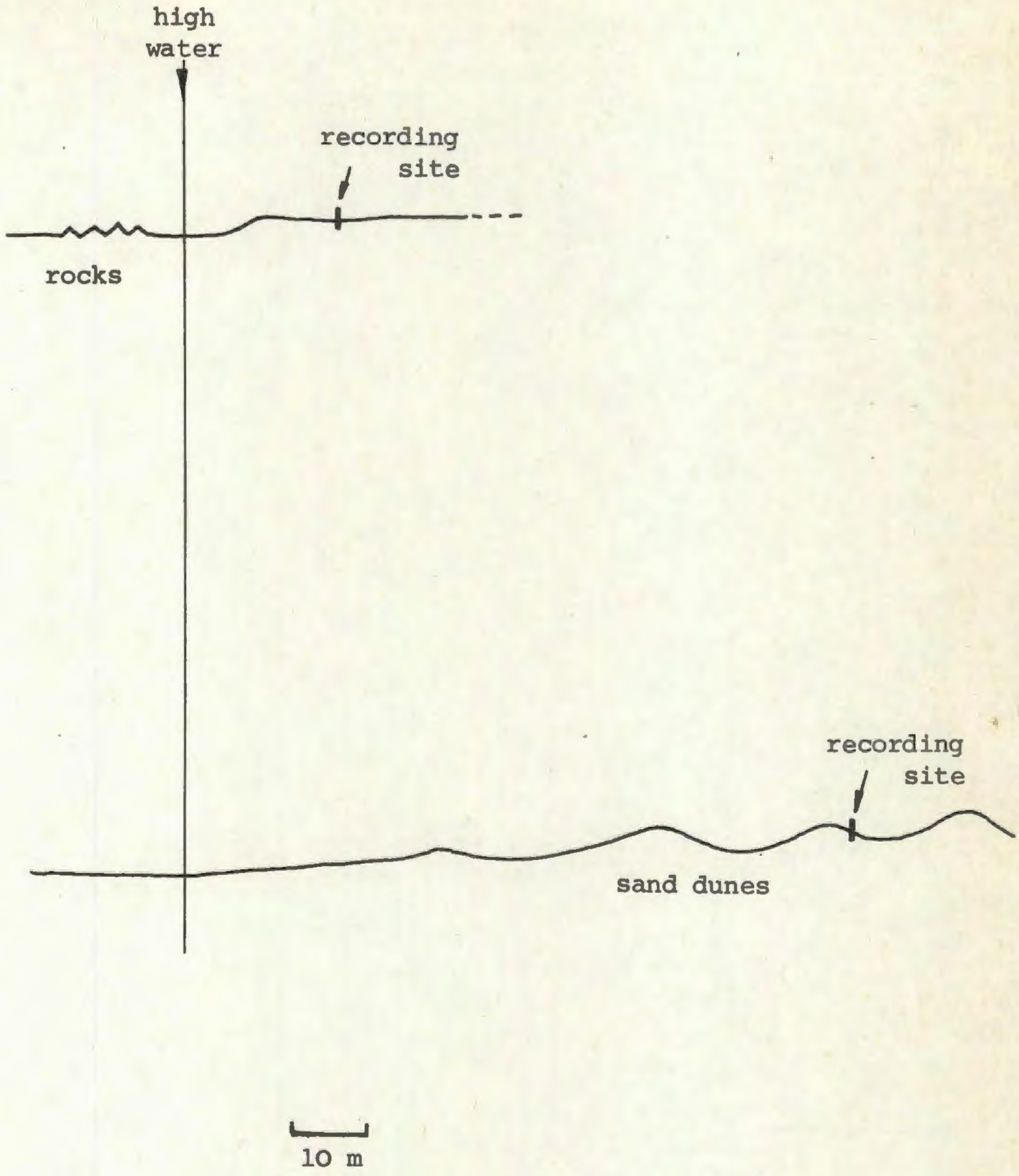
| Date | Period of observation (S.A.S.T) | Average potential gradient (V m$^{-1}$) upper | lower | Space charge density (pC m$^{-3}$) | Summary of observed weather conditions |
|---|---|---|---|---|---|
| 15/7/75 | 16h40-17h00 | 447 | 359 | -1170 | No cloud. Light breeze on-shore |
| 16/7/75 | 08h35-09h20 | 308 | 315 | +60 | No cloud. Calm. Light haze. |
| 16/7/75 | 15h35-16h10 | 360 | 412 | -220 | No cloud. Some haze. Breeze parallel to shore. Spray-haze visible to about 3 m over surf. Apparently not being blown inland |
| 17/7/75 | 17h15-17h40 | 101 | 164 | -330 | 7/8 Cloud. Overnight rain. Moderate breeze off-shore. Visibility good. |
| 18/7/75 | 07h50-08h15 | 223 | 220 | -180 | Fine and clear. No wind. Spray haze over surf mainly. |
| 19/7/75 | 09h20-10h10 | 367 | 356 | -560 | 1/8 High cloud. Calm. Moderate visibility. |
| 20/7/75 | 09h30-10h10 | 326 | 291 | -420 | 2/8 Cloud. Light haze. Very light on-shore breeze. |
| 21/7/75 | 10h00-10h35 | 301 | 216 | +280 | 1/8 Cloud. Visibility good. Breeze changed from off- to on-shore at 10h05. Spray-haze starting to become visible over land. |

Table 7.6 Values of space charge density obtained at the beach site at Mtunzini in 1975.

is about -320 pC $m^{-3}$. These results are particularly interesting in view of the results obtained at Ballito Bay which indicate that the space charge near the surf is predominantly positive. What makes these results even more interesting is the fact (which will be shown later, in Section 7.5.5) that positive space charge was being produced by the surf at the time that the negative charge was detected at this site, some 90 m from the surf zone.

In investigating the basic difference between the Ballito Bay and the Mtunzini results it is helpful to consider the approximate profile of the land at the two measuring sites. These profiles are sketched in Figure 7.4. It will be seen that the instruments at Mtunzini were considerably further from the surf than those at Ballito Bay. They were also situated on the inland slope of a sand dune, with the lower instrument being about 1 m below the highest ridge of the dune. One other immediately apparent difference between the two sites is the gently sloping sand beach at Mtunzini as opposed to the steeper beach with large outcrops of rock in the surf zone found at Ballito Bay. Evidence will be produced in Section 7.5.5 to show that positive space charge was being generated by the surf on all occasions. Positive space charge was measured at the beach at Ballito Bay, with possibly a slight suggestion of negative charge on occasions, although, as has already been seen, this cannot be regarded as more than a suggestion. The reason for the doubt associated with these instances of negative space charge was shown earlier to be the lack of reliability of the readings obtained when the apparatus was unattended for extended periods. The Mtunzini results, on the other hand, must be regarded as reliable and thus there is very definite evidence for a region of negative charge associated with the surf generated positive charge. The picture which emerges is then one of a bipolar layer of space charge.

The suggestion of a bipolar layer resulting from a charge generating mechanism is not a new one. There have been various suggestions made in




<u>Figure 7.4</u> Profiles of the beach measuring sites at Ballito Bay (upper) and at Mtunzini (lower).

the literature, for instance HARRIS (1971) suggested a bipolar layer in connection with the Harmattan wind in Nigeria, while BENT and HUTCHINSON (1965) found a bipolar layer resulting from negative charge generated by melting snow being overlaid with positive charge resulting from distant blown snow.

It will be seen later that the space charge generated by the surf action was positive on all occasions. Thus it would seem to be necessary to find some mechanism to account for the generation, or accumulation, of negative charge fairly near to the ground. There are many instances cited whereby negative charge is associated with dust storms (see, for example KAMRA, 1972). It is difficult, however, to imagine the sand on the dune surface moving sufficiently under calm, or very light wind, conditions to generate the required density of charge. Even if the vibration of the sand due to the seismic action of the waves breaking nearby is considered, the effect would be very small and, furthermore, any mechanism involving movement of the sand would result in negative charge beneath the positive layer, which would not explain the observations. Neither would such a mechanism account for the instances of negative charge recorded at the inland site, which was not on sand dune but on grassland.

On one occasion during the course of an observation in the Mtunzini experiment the wind changed direction from off- to on-shore. This occurred at about 10h05 S.A.S.T. on 21/7/75. The field mills at the beach responded almost immediately, the lower going from about 190 to about 330 V $m^{-1}$ on average, in a time of the order of 2 minutes. At the same time the upper mill reading increased from an average of about 120 to about 280 V $m^{-1}$. The two potential gradient records also changed in nature from being smooth traces with slow variations to fairly jagged traces characterised by rapid, large amplitude variations. The effect of this change in wind direction became evident at the inland site some 7 to 10 minutes later, which indicates that the wind had a direct on-shore component with velocity of 1.0 to 1.4 m $s^{-1}$ (3.6 to 5.1 km $hour^{-1}$). The average reading of the lower mill at the inland site increased from about 50 to about 85 V $m^{-1}$, while the upper mill went from about 40 to about 90 V $m^{-1}$. Values of the space charge density for each site were calculated by applying equation (7.1) to the field mill readings at various times during this period. The results obtained are illustrated in Figure 7.5.

Reference to Figure 7.5 reveals several interesting features. The space charge density between upper and lower mills at the beach site is very clearly related to the potential gradient measured at this site. The increase in potential gradient at the inland site is not as well defined as that at the beach, and it occurs, as has already been seen, somewhat later than did the change at the beach. Perhaps the most interesting feature, however, is the negative charge which occurs in the region between the field mills at the inland site. This negative charge appears to occur only during the period associated with the increase in potential gradient caused by the wind, since the average space charge over the whole period of the observation at the inland site was +75 pC $m^{-3}$. In this case, since the potential gradient at both levels increased, while the negative charge between the field mills also increased in density, it must be concluded that the positive charge lay above the negative charge. Once again there is evidently a bipolar space charge layer, although inverted relative to that mentioned earlier. The mechanism suggested to explain this observation is the following: The wind borne positive charge from the surf was carried inland and over the field mills at a height in excess of 2 m. Reference to Figure 6.2 will show that the inland site was situated on a headland between two streams. Both of these streams contained several rapids and very small waterfalls which resulted in splashing and hence in the generation of negative charge (see, for example PIERCE and WHITSON, 1965; or ISRAEL, 1971 p 5). This negative charge was detected by the mills in the space between them, while both mills indicated increased potential gradients due to the surf generated positive charge at a height somewhere above the upper mill.

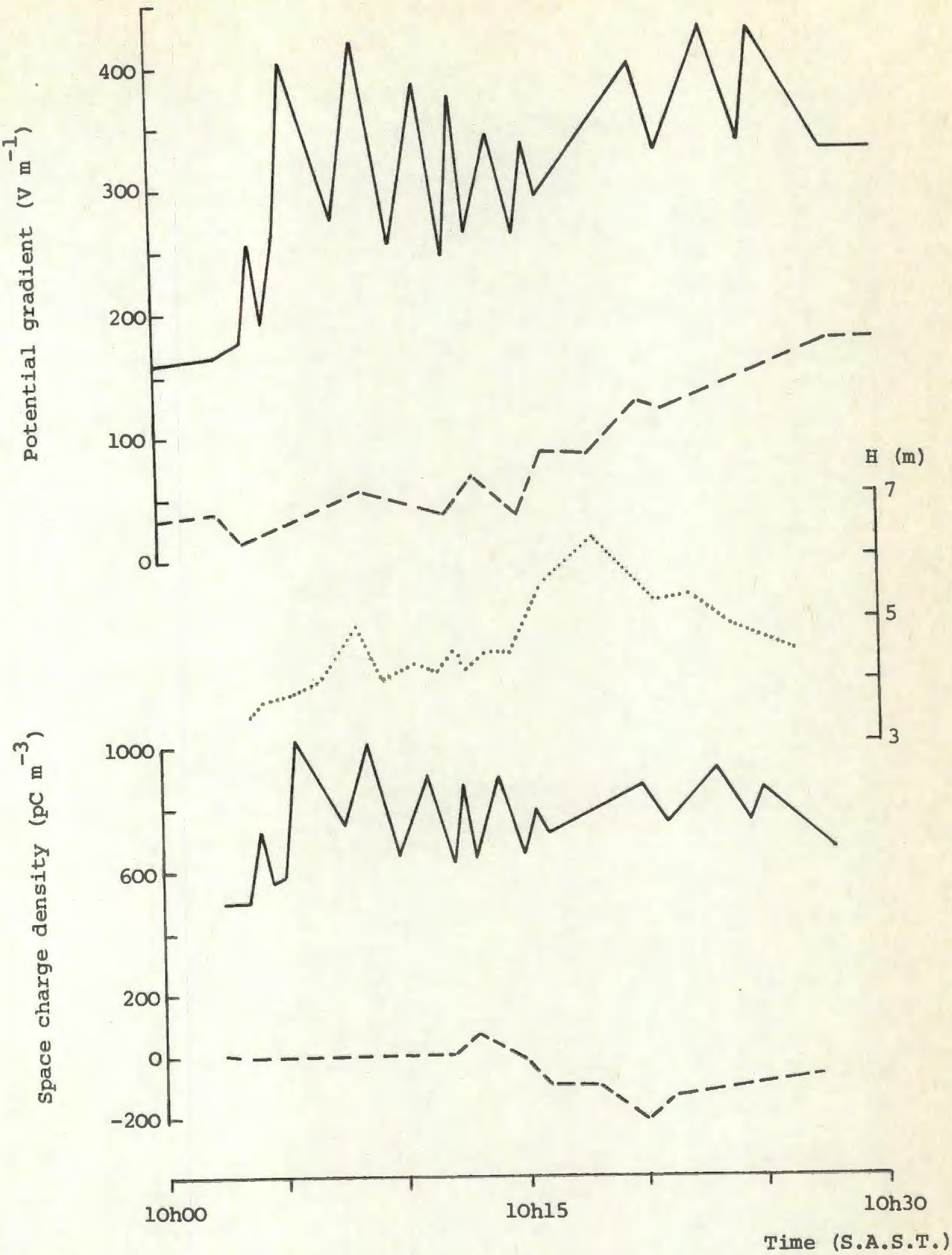



Figure 7.5 Potential gradient and space charge density records which accompanied a change in wind direction from off- to on-shore. The solid lines refer to the beach site, the dashed lines to the inland site. The dotted curve with the vertical scale on the right represents the thickness (H) of the space charge layer.

It is possible to estimate the height at the beach site of the layer of positive space charge borne by the wind on this occasion. In order to do this it is assumed that, at the beach site, this space charge forms a layer of constant height H and constant density $\rho$. If the potential gradient at the top of the layer H is called P.G. (also assumed constant), then the mill in the ground will record a value of potential gradient M, where

$$M = P.G. + H\rho/\varepsilon_0.$$

If the space charge density changes to a new value $\rho + \Delta\rho$, then the potential gradient at the ground becomes $M + \Delta M$ where

$$M + \Delta M = P.G. + H(\rho + \Delta\rho)/\varepsilon_0.$$

Subtracting yields, after rearranging terms,

$$H = \varepsilon_0 \Delta M/\Delta\rho.$$

Values of $\Delta M$ and $\Delta\rho$ were calculated for neighbouring points on the respective graphs for the beach site, as illustrated in Figure 7.5. The resulting values of H are shown in the figure as a dotted curve. The average value of H is 4.6 m (standard deviation 0.7 m) and it will be seen that the thickness of the layer increases between 10h05 and 10h17 S.A.S.T. and then decreases again. This value of H agrees fairly well with the typical height of the layer of surf generated space charge arrived at in Section 7.5.5.

### 7.5.4 Theory applying to the behaviour of the surf generated space charge layer.

As was mentioned earlier, in Section 7.5.1, a theory was developed in order to obtain a quantitative idea of the density of space charge generated by the surf and of the height of such a layer of space charge above the ground.

Figure 7.6. represents the two recording sites, the primed values referring to the beach site, the unprimed to the inland site. The symbols used are in accordance with the theory developed in Section 7.2. The space

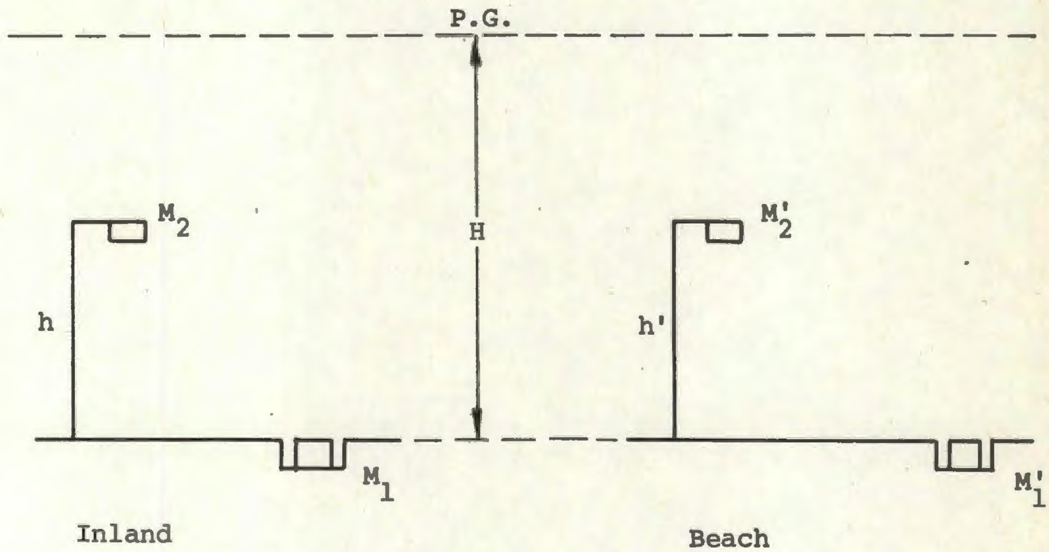



Figure 7.6 A sketch of the experimental arrangement involving two recording sites.

charge at both sites is assumed to be restricted to a layer of thickness H and to be uniformly distributed in this layer, although the density may differ at each site. By means of equation (7.1) one may write, for the inland site,

$$M_2 = AM_1 + B, \text{ with } B = -A\rho h/\varepsilon_0 \tag{7.3}$$

At the beach site

$$M_2' = A'M_1' + B', \text{with } B' = -A'\rho'h'/\varepsilon_0 \tag{7.4}$$

Now assume that $\rho' = \rho + \rho_s$ where $\rho_s$ is the space charge density due to the surf. Further, assume that above the layer H the potential gradient (P.G.) at both sites is the same. Then

$$M_1 = P.G. + H\rho_s/\varepsilon_0 \tag{7.5}$$

and $$M_1' = P.G. + H\rho'/\varepsilon_0 = P.G. + H\rho/\varepsilon_0 + H\rho_s/\varepsilon_0 \tag{7.6}$$

Thus

$$M_1' = M_1 + H\rho_s/\varepsilon_0,$$

or

$$H\rho_s = \varepsilon_0(M_1' - M_1). \tag{7.7}$$

Since it has been assumed that the space charge density within the layer H is uniform at each site, the potential gradient at the level of the upper mill in each case is:

inland $\quad P.G. + (H - h)\rho/\varepsilon_0$

beach $\quad P.G. + (H - h')\rho'/\varepsilon_0,$

which may be written

$$M_2 = C(P.G. + (H - h)\rho/\varepsilon_0)$$

and

$$M_2' = C'(P.G. + (H - h')\rho'/\varepsilon_0) \tag{7.8}$$

where C and C' are reduction factors due to the inversion of the upper mills. C and C' may be shown to be just A and A' as follows: Clearly, from equation (7.5)

$$P.G. = M_1 - H\rho/\varepsilon_o$$

while from equation (7.8)

$$P.G. = M_2/C - H\rho/\varepsilon_o + h\rho/\varepsilon_o,$$

or

$$M_2 = C(M_1 - h\rho/\varepsilon_o).$$

From equation (7.3)

$$M_2 = A(M_1 - h\rho/\varepsilon_o),$$

thus C = A. It follows similarly that C' = A'.

The two equations (7.8) may be used to eliminate P.G. and yield

$$M_2/A - (H - h)\rho/\varepsilon_o = M_2'/A' - (H - h')\rho'/\varepsilon_o.$$

Substituting $\rho' = \rho + \rho_s$,

$$M_2/A - (H - h)\rho/\varepsilon_o = M_2'/A' - (H - h')(\rho + \rho_s)/\varepsilon_o$$

or

$$\varepsilon_o(M_2/A - M_2'/A') = \rho_s(h' - H) + \rho(h' - h).$$

Substituting for $\rho_s$ from equation (7.7),

$$\varepsilon_o(M_2/A - M_2'/A') = \varepsilon_o(M_1' - M_1)(h' - H)/H + \rho(h' - h).$$

Therefore,

$$H(M_2/A - M_2'/A') = (M_1' - M_1)(h' - H) + H\rho(h' - h)/\varepsilon_o$$

or

$$H(M_2/A - M_2'/A' - \rho(h' - h)/\varepsilon_o) = (M_1' - M_1)(h' - H).$$

Hence

$$H = \frac{h'(M_1' - M_1)}{M_2/A - M_2'/A' - \rho(h' - h)/\varepsilon_o + M_1' - M_1} \tag{7.9}$$

Once H has been found using equation (7.9), $\rho_s$ may be found from equation (7.7). Note that H does not have to exceed h or h', and nor does $\rho_s$ have to be positive or non-zero. Essentially the inland site is being used as a control site, and the values of H and $\rho_s$ are being determined at the beach site.

### 7.5.5 Application of the theory

The theory developed in the previous section was applied to the results obtained in the two Ballito Bay experiments and in the Mtunzini experiment. Clearly, in order to apply the theory it is necessary that all four field mills be functioning satisfactorily at the same time and that the readings obtained be considered reliable. The results obtained when these criteria were met, together with the calulated values of H and $\rho_s$ are shown in Table 7.7. From this table it will be seen that the average density of space charge generated by the surf action is about +1040 pC $m^{-3}$ and the thickness of the space charge layer is about 2.4 m on average. It is also worth noting that the ratio of the average potential gradient measured at the beach to that measured inland is about 1.9.

Examination of Table 7.7 indicates that there are some obvious differences between the Ballito Bay and the Mtunzini results. The average values of H and $\rho_s$ taken separately for these two stations are:

Ballito Bay $\quad H = 3.7$ m (standard deviation 1.8 m)

$\rho_s = 437$ pC $m^{-3}$ (standard deviation 117 pC $m^{-3}$)

Mtunzini $\quad H = 0.9$ m (standard deviation 0.3 m)

$\rho_s = 1747$ pC $m^{-3}$ (standard deviation 767 pC $m^{-3}$).

The average values of the lower field mill readings are:

Ballito Bay, $\quad M_1 = 192$ V $m^{-1}$, $M_1' = 346$ V $m^{-1}$, $M_1'/M_1 = 1.8$

Mtunzini, $\quad M_1 = 152$ V $m^{-1}$, $M_1' = 300$ V $m^{-1}$, $M_1'/M_1 = 2.0$.

The average thickness of the space charge layer at Ballito Bay, where $\rho_s$ was measured fairly close to the surf was 3.7 m. Within this 3.7 m the density of space charge due to the surf generator was, subject to the assumptions made in the theory, 437 pC $m^{-3}$ on average. Under the action of the prevailing electric field this positive charge will move downwards, and so it would be expected that, as the space charge drifted further from the surf zone, the layer would decrease in thickness (assuming that no

| Site | Average potential gradients (V $m^{-1}$) | | | | | H | $\rho_s$ |
|---|---|---|---|---|---|---|---|
| | Date | $M_1$ | $M_1'$ | $M_2$ | $M_2'$ | (m) | (pC $m^{-3}$) |
| Ballito Bay | 8/8/72 | 148 | 257 | 14 | -5 | 1.8 | 510 |
| | 9/8/72 | 127 | 278 | 42 | 36 | 3.1 | 580 |
| | 10/8/72 | 209 | 358 | 99 | 118 | 5.4 | 320 |
| | 11/8/72 | 100 | 191 | 95 | 74 | 3.1 | 380 |
| | 22/8/72 | 346 | 411 | 110 | 138 | 1.3 | 460 |
| | 7/9/72 | 193 | 563 | 42 | 367 | 6.2 | 540 |
| | 4/5/73 | 222 | 367 | 71 | 91 | 4.8 | 270 |
| Mtunzini | 15/7/75 | 189 | 359 | 191 | 447 | 0.5 | 2950 |
| | 16/7/75 | 260 | 412 | 215 | 357 | 0.8 | 1620 |
| | 17/7/75 | 30 | 164 | 23 | 101 | 0.8 | 1600 |
| | 19/7/75 | 160 | 356 | 167 | 367 | 0.8 | 2120 |
| | 20/7/75 | 151 | 291 | 127 | 326 | 0.8 | 1580 |
| | 21/7/75 | 120 | 216 | 97 | 301 | 1.4 | 610 |
| Average | | 173 | 325 | 99 | 209 | 2.4 | 1042 |
| Standard deviation | | 78 | 108 | 63 | 154 | 2.0 | 845 |

Table 7.7 The generation of space charge by the action of the surf.

other processes such as convection or wind gusts are active). This is what appears to be happening in the present case where the layer as measured at Mtunzini, at a place considerably further from the surf than the corresponding measuring site at Ballito Bay, was only 0.9 m thick. If the assumption is made that all the charge generated by the surf remains within the layer, with very little loss either to the ground or by recombination, then as the layer thickness decreases so the density must increase. In fact, if all the charge resulting in a density of 437 pC $m^{-3}$ within a layer 3.7 m thick (as measured at Ballito Bay) is confined to a layer only 0.9 m thick (as measured at Mtunzini), then the density becomes 1796 pC $m^{-3}$. The value actually measured at Mtunzini was, on average 1747 pC $m^{-3}$, which allows for a loss of some 50 pC $m^{-3}$ during the time that the layer takes to collapse from 3.7 to 0.9 m. In view of these figures it seems reasonable to suppose that the surf generated space charge layer decreases in thickness, while the density increases as the layer moves inland. Presumably at greater distances from the surf sufficient time has elapsed for the loss of charge to become significant. Clearly, if convection plays an important part in the suggested process (or possibly mixing due to gusty wind conditions) then it should be expected that the layer thickness would increase and the charge density decrease.

The process outlined in the preceding paragraph explains the observations recorded in Table 7.7, in particular the marked difference between the Ballito Bay and Mtunzini results. It remains, however, to explain the negative space charge recorded at the beach site at Mtunzini on all except the last of these occasions. (See Table 7.6. Note that the second entry in this table was not included in the surf generator investigation). This negative space charge was recorded in spite of the generation by the surf of positive charge at the same time. In order that there exist a layer of positive surf generated charge up to about 1 m above the ground at the same time that the field mills detect a net negative charge in the vertical region between them, it is necessary that there exist a region of negative charge above the layer of positive charge.

In Section 3.3.4 of Chapter Three it was shown (following MOORE et al, 1962) that the space charge density $\rho$ may be related to the conductivity $\lambda$ of the atmosphere by

$$\rho = \frac{\varepsilon_o j}{\lambda^2} \frac{d\lambda}{dz}$$

where j was the conduction current density, z the height above the ground. It was shown in Section 2.3 of Chapter Two that the conductivity $\lambda = 1/r$ where r was the resistance of the lowest metre of a column of atmosphere 1 $m^2$ in cross-sectional area stretching between the Earth and the electrosphere. Hence r is the resistivity of the atmosphere and clearly

$$\frac{1}{\lambda^2} \frac{d\lambda}{dz} = - \frac{dr}{dz} ,$$

so that

$$\rho = - \varepsilon_o j \frac{dr}{dz} .$$

If the resistivity increases with altitude then $\rho$ is negative while if the resistivity decreases with altitude (the normal clean atmosphere situation) $\rho$ is positive. As a result, whenever there is a current flowing in the atmosphere, a change in resistivity will produce an accumulation of space charge on each side of the layer of different resistivity. In view of the above, it is suggested that at a level of somewhere between 1 and 2 m above the ground there is a fairly abrupt change in the resistivity of the air, the layer below this region - which contains most of the surf generated space charge - constituting a layer of high resistivity. The upward moving negative charge within this layer will accumulate near the top boundary, which must lie between the two mills in order that the net space charge be recorded as negative. The upper boundary of the high resistivity layer would act in a manner very similar to the top of a layer of haze (see MOORE et al, 1962) and it would be expected that the downward moving positive charge would accumulate at the top of this layer. Clearly this upper positive space charge layer would have to lie largely above the upper mill in order to give the observed results.

Some of the consequences of the mechanism which has been outlined are worth considering more closely. For instance, if the atmosphere is insufficiently stable for the formation of the 1 to 2 m thick high resistivity layer, or if this layer is much thicker than normal, then the negative space charge would not be detected since the downward moving positive charge would not be well stratified near the ground and would extend to greater heights. This would be the sort of situation recorded on the 21/7/75, which was the only occasion at Mtunzini during the surf generator investigation when net positive space charge was recorded at the beach site. Another consequence would be the outcome closer to the surf, in other words at an earlier stage in the life of the surf generated charge. It is suggested that under these conditions the resistivity of the air is lower because the charge carriers have higher mobilities and also the air will have more turbulent motion, being closer to the surf. As a result there is much better mixing of the air, and while the surf generated charge will be moving downward it will still be much higher than at a later time when it is further from the surf. The result would be observations similar to those made at Ballito Bay, where positive net space charge was found in the region between the mills on every occasion, and where the surf layer was, on average, about 4 times as thick as it was at Mtunzini.

On one particular day, 9/8/72, apparently reliable results were obtained over an extended period of more than 21 hours. It is interesting to examine the variation of H and $\rho_s$ during this period. Table 7.8 shows the average values of H and $\rho_s$ for two-hourly periods through this day. In each period 9 values were obtained, with 15 minutes between successive values. It will be seen from the table that there is a clear indication of increasing convection with the thickness of the space charge layer reaching its maximum value at about mid-day when convection is reaching a maximum. The density of space charge attained a maximum in the early morning. The thickness of the space charge layer shows clearly the effect of convection in the atmosphere, which in turn is associated with the air temperature. Temperatures recorded in Durban for this day were 14.9°C at 08h00 S.A.S.T, 22.2°C at 14h00 S.A.S.T. and 19.0°C at

| Period of observation (S.A.S.T.) | Thickness H of layer (m) | | Space charge density $\rho_s$ (pC $m^{-3}$) | |
|---|---|---|---|---|
| | Average | Std. dev. | Average | Std. dev. |
| 00h15 - 02h00 | 0.6 | 0.2 | 730 | 70 |
| 02h00 - 04h00 | 0.9 | 0.2 | 760 | 60 |
| 04h00 - 06h00 | 1.0 | 0.3 | 700 | 30 |
| 06h00 - 08h00 | 1.2 | 0.9 | 1030 | 240 |
| 08h00 - 10h00 | 1.6 | 1.4 | 1010 | 180 |
| 10h00 - 12h00 | 5.8 | 2.6 | 580 | 350 |
| 12h00 - 14h00 | 5.1 | 1.2 | 420 | 100 |
| 14h00 - 16h00 | 4.2 | 1.2 | 440 | 130 |
| 16h00 - 18h00 | 4.2 | 1.9 | 430 | 130 |
| 18h00 - 20h00 | 4.2 | 2.7 | 260 | 120 |
| 20h00 - 22h00 | 2.9 | 2.0 | 260 | 210 |

Table 7.8 Analysis of the surf generation of space charge for 9/8/72 at Ballito Bay.

18h00 S.A.S.T. During the early morning, while the temperature was fairly low and the atmosphere was stable, the thickness increased gradually from 0.6 to 1.6 m. A rapid increase to nearly 6 m then accompanied the rise in temperature to its maximum value of 22.6$^{o}$C and its value at 14h00 S.A.S.T. of 22.2$^{o}$C. During the afternoon the layer remained at about 4 m in thickness until after sunset when it showed a tendency to decrease again. The variation in space charge density cannot be commented upon in detail because the prevailing wind, condition of the surf and local weather conditions, other than those extrapolated from Durban, were all unknown factors. It is obvious, however, from Figure 7.7 (which illustrates graphically the results contained in Table 7.8) that the space charge originating in the surf attained its maximum density at about the time of sunrise and that sunset occurred at about the time of a marked decrease in space charge density. There was no obvious connection with the state of the tide.

### 7.5.6 Conclusion

It was shown in Section 6.3.2 of the last chapter that absolute values of the potential gradient at ground level at the beach site exceeded those at the inland site by factors of 1.9 at Ballito Bay in 1972, of 1.7 at Ballito Bay in 1973 and of 2.5 at Mtunzini in 1975. The average value of this same factor arrived at in the present chapter for all those results included in the surf generation of space charge analysis was 1.9. BLANCHARD (1966), in his Hawaii experiment, made measurements at three sites and found the same sort of local effect near the surf. The actual values of both potential gradients and space charge densities recorded by Blanchard tended to be lower than those recorded in the present set of experiments, but he found that, typically, when the potential gradient near the surf varied from 90 to 175 V $m^{-1}$, that measured further away varied from 65 to 100 V $m^{-1}$. These figures yield factors of 1.4 to 1.8, which are of the same order as the 1.9 found here. Blanchard found that on an occasion when the wind, which had been blowing over the sea, veered and blew over the land the measured space charge density dropped from about 2500 to less than 1500 elementary charges $cm^{-3}$. This would seem to imply that

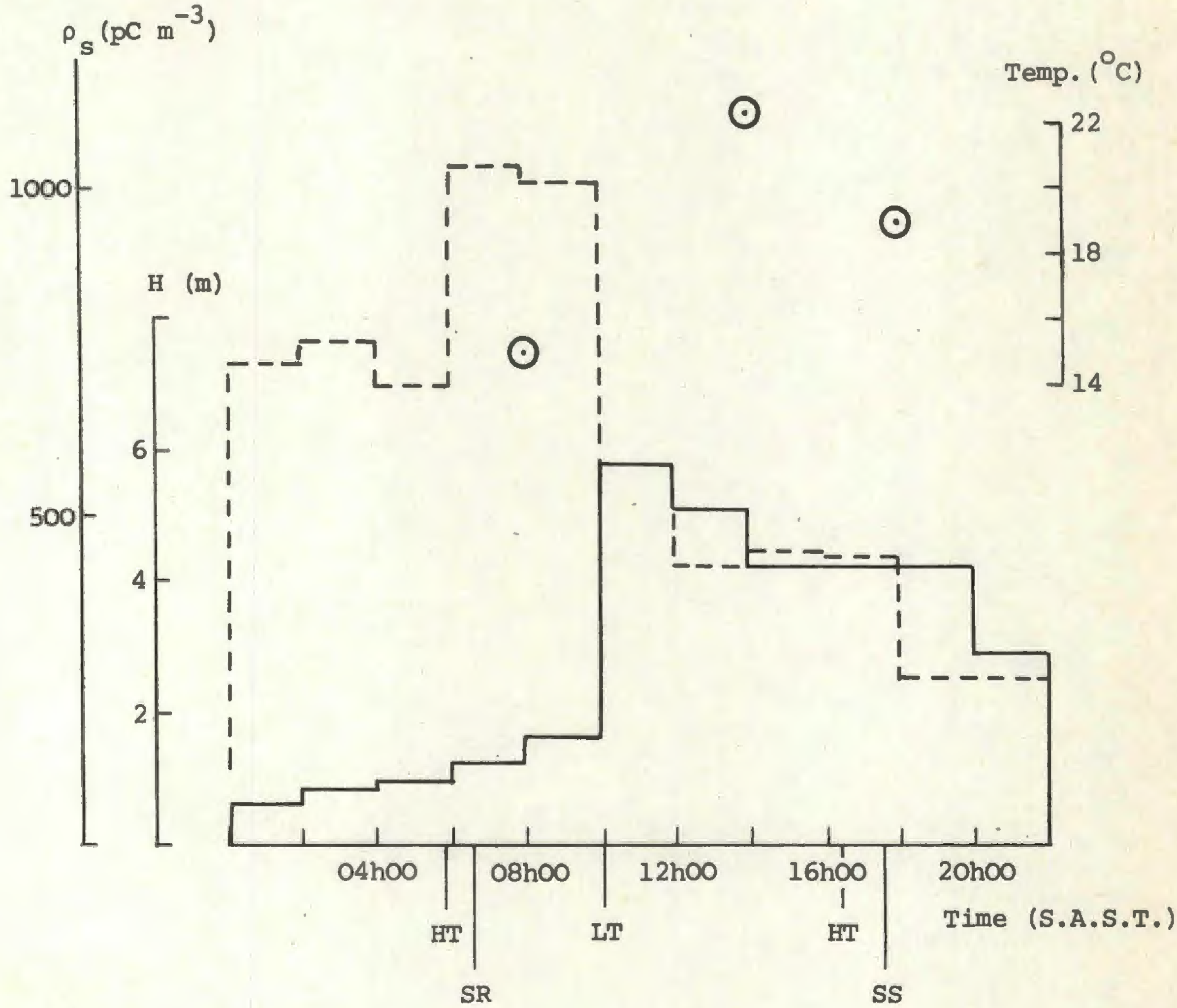



Figure 7.7 The variations of H and $\rho_s$ during the day of 9/8/72. The solid line represents H, the broken line $\rho_s$. The times of sunrise (SR), sunset (SS), low tide (LT) and high tide (HT) are shown. The three encircled points shown represent air temperatures measured in Durban.

the surf zone was responsible for some 160 pC $m^{-3}$ on that occasion. Using a different argument to that developed in Section 7.5.4 here, Blanchard arrived at a figure of about 4 m for the thickness of the surf generated space charge layer. This again is in agreement with the sort of values of H arrived at in this chapter.

It is clear from the results obtained, and from the agreement between these results and those obtained by Blanchard, that positive space charge is generated in the surf zone. According to Blanchard, this space charge is either reduced or removed in overland travel. Once again this general finding has been confirmed in the present work, but in addition evidence has been found which seems to indicate that a layer of low conductivity containing most of the surf generated charge forms within a metre or so of the ground. Upward moving negative space charge accumulates beneath the top surface of this layer. Apparently very little loss occurs of the downward moving surf generated positive charge within the time taken for the space charge to move from a measuring site about 20 m from the surf (as at Ballito Bay) to one about 90 m from the surf (as at Mtunzini). Typically this time could be about 50 to 70 s (for an on-shore wind velocity component of 1.0 to 1.4 m $s^{-1}$ as found in Section 7.5.3.2).

Evidence has also been produced to show that the initial layer of the atmosphere which becomes charged by particles originating in the surf zone is sensitive to the general conditions of atmospheric convection. From the increase in space charge density which is possibly associated with sunrise, and the decrease possibly associated with sunset as shown in Figure 7.7, it may be that solar radiation plays some role in the generation of space charge in the surf zone. The suggestion has also been made that the generation of space charge in the surf zone might be influenced by the prevailing space charge density in the vicinity.

Another factor which presumably must influence the mechanism of space charge generation over the ocean (and this would include the surf action in addition to the BLANCHARD (1961) bubbling mechanism in and outside the surf zone) is the dependence of the potential gradient over the water surface on the choppiness of the sea. VONNEGUT (1974) has found that with waves 1 m high the potential gradient 0.5 m above the crests is at least twice that above the troughs. It is also suggested by the Ballito Bay and Mtunzini results quoted here that the area of the surf zone is probably a more important factor in the generation of space charge than is the roughness of the surf. The reason for this is that it appears that the surf generators are roughly equally effective at each site. The surf zone at Ballito Bay, although not occupying a large area since the sea is reasonably deep here, was often the source of vigorous splashing and bubbling. This rough surf was due largely to the outcrops of rock found in the surf zone. At Mtunzini, with the shallow nature of the sea there, the surf was much quieter than at Ballito Bay, but it extended over a considerably larger area, with waves frequently breaking about 1 km from the shore.

Finally, it is worth noting that the thickness of the surf generated space charge layer of from about 1 m to 4 or 5 m is in reasonable agreement with visual estimates of the height of the layer of particles which may be seen rising from the surf and blowing inland on occasions. This effect is particularly noticeable where the surf may be viewed against a dark background of vegetation.

## 7.6 THE KLOOF EXPERIMENT

### 7.6.1 Experimental arrangement and data handling

Potential gradient records were obtained using two vertically separated field mills of the type described in Chapter Five. The power supplies for the mills were derived from the 220 V 50 Hz mains supply. In addition to the field mills, the aspiration psychrometer described in Chapter Five was also used. Each instrument yielded an output in the form of a direct current in the range 0 - 100 μA which was recorded on a self-contained chart recorder. Suitable calibration curves were then used to convert these readings to potential gradients in the case of the field mills, or wet-bulb and dry-bulb temperatures in the case of the psychrometer. Values of the relative humidity were determined from the wet- and dry-bulb temperatures using psychrometric tables as described in Chapter Five.

From the field mill output charts, simultaneous values of the potential gradients at the two levels, which differed by 1.69 m, were obtained. These values were used in the theory developed in Section 7.2. From this analysis a mean value of the exposure factor A = 0.81 (standard deviation 0.26) was obtained for 25 separate events recorded on 14 days between 1/7/74 and 11/1/75. These results are discussed in the next section.

Diurnal variations in space charge densities were computed by determining simultaneous values of the upper and lower potential gradients at hourly intervals and using the value of A given above in the application of the theory of Section 7.2. The diurnal variation in space charge density was compared with the variation in potential gradient after suitable treatment of the results. This treatment, and the results obtained, are dealt with in Section 7.6.2.2.

## 7.6.2 Results

### 7.6.2.1 Isolated events

On a number of occasions both field mills showed evidence of large variations in the potential gradient. These were generally associated with cloud overhead, but on some occasions no visible cause of the variation in potential gradient was apparent. Since these occasions yielded simultaneous values of field mill readings which covered a wide range in a fairly short time, they were ideally suited to application of the theory in Section 7.2. Of the total number of events recorded, only those which met certain criteria were selected for inclusion in the analysis. These criteria, although established quite arbitrarily, were intended to maximise the reliability of the determination of A and minimise the effects of space charge variations in the region between the two mills. It was felt that these objectives would be achieved if a certain minimum number of pairs of simultaneous readings (taken as 5 pairs) resulted in a calculated best straight line fit with a certain minimum correlation coefficient (taken as $r = 0.95$). The results of the events which met these criteria are given in Table 7.9. From these results it can be seen that the average value of A is 0.81 and the standard deviation 0.26.

A small selection of some of these interesting events has been reproduced as Figures 7.8, 7.9 and 7.10. In each figure the variation of potential gradient, of space charge density, of relative humidity and of air temperature have been plotted. Figure 7.8 shows the results obtained on two separate occasions when warm somewhat hazy weather prevailed at the start of the observation. During the course of the observations the temperature fell fairly quickly and the fall in temperature was accompanied by increasing cloud cover. On both occasions the cloud cover included some cumulus cloud. It is interesting to note that in each case the potential gradient was negative during the period when the temperature decrease was steepest. A tendency of the temperature decrease to level out was then accompanied by a positive potential gradient 'pulse' of some 15 minutes duration on 30/7/74 and 30 minutes on 9/8/74. Following this pulse the potential gradient reverted to a negative value in each case. The event on the 30/7/74 was preceded by a very rapid and large increase in humidity. No such increase occurred on 9/8/74.

Figure 7.9 refers to two occasions when the temperature of the air either increased or remained constant during the event. It will be noticed that apart from this similarity the two events produced very different results. The relative humidity was fairly constant, or constant,

| Date | Slope of best straight line (A) | Correlation coefficient | Number of readings |
|---|---|---|---|
| 1/1/74 | 0.4729 | 0.9902 | 14 |
| | 0.7844 | 0.9981 | 8 |
| 9/7/74 | 0.5032 | 0.9898 | 7 |
| | 1.2821 | 0.9603 | 8 |
| 16/7/74 | 0.4513 | 0.9951 | 7 |
| 28/7/74 | 0.7253 | 0.9793 | 13 |
| 30/7/74 | 0.5352 | 0.9907 | 14 |
| 9/8/74 | 0.8386 | 0.9599 | 5 |
| | 0.5613 | 0.9793 | 9 |
| | 0.5264 | 0.9894 | 20 |
| 23/8/74 | 0.6934 | 0.9986 | 8 |
| | 0.3755 | 0.9896 | 7 |
| | 1.0907 | 0.9556 | 13 |
| 26/8/74 | 0.8028 | 0.9643 | 12 |
| | 0.9303 | 0.9982 | 5 |
| 9/10/74 | 1.0387 | 0.9913 | 31 |
| 8/11/74 | 1.0451 | 0.9912 | 24 |
| | 0.8427 | 0.9617 | 7 |
| 10/11/74 | 0.6116 | 0.9589 | 11 |
| 6/1/75 | 0.8132 | 0.9557 | 9 |
| | 1.0486 | 0.9823 | 9 |
| 10/1/75 | 1.0919 | 0.9786 | 7 |
| | 1.0151 | 0.9975 | 5 |
| 11/1/75 | 0.9134 | 0.9951 | 7 |
| | 1.2427 | 0.9897 | 8 |
| Mean values | 0.8095 | 0.9816 | |
| Standard dev. | 0.2587 | 0.0152 | |

Table 7.9 Results obtained from applying the theory developed in Section 7.2 to selected occasions when large deflections occurred in the potential gradient records.

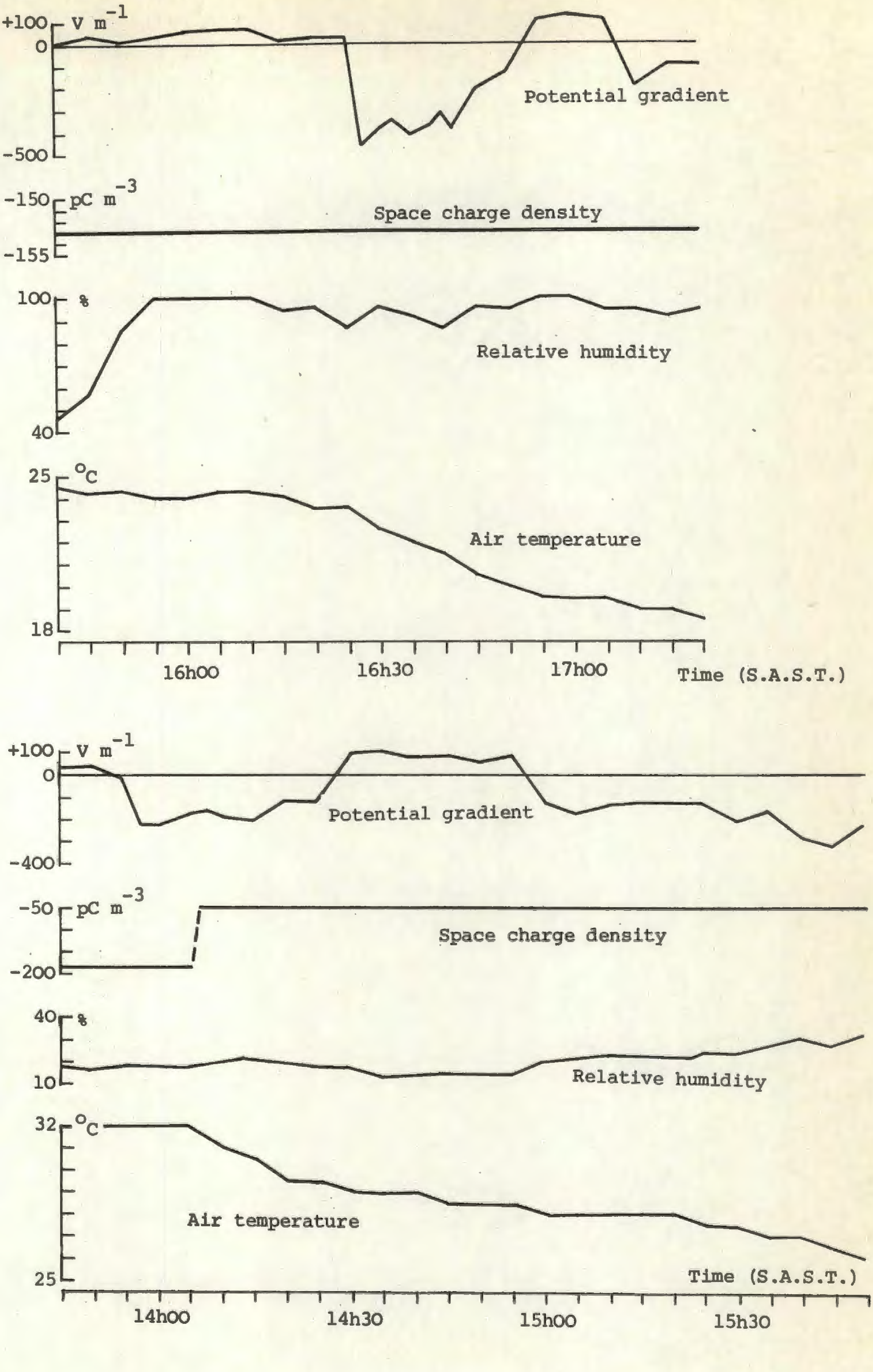



Figure 7.8 Variations of several parameters at Kloof. The top set of curves refers to 30/7/74, the lower set to 9/8/74.

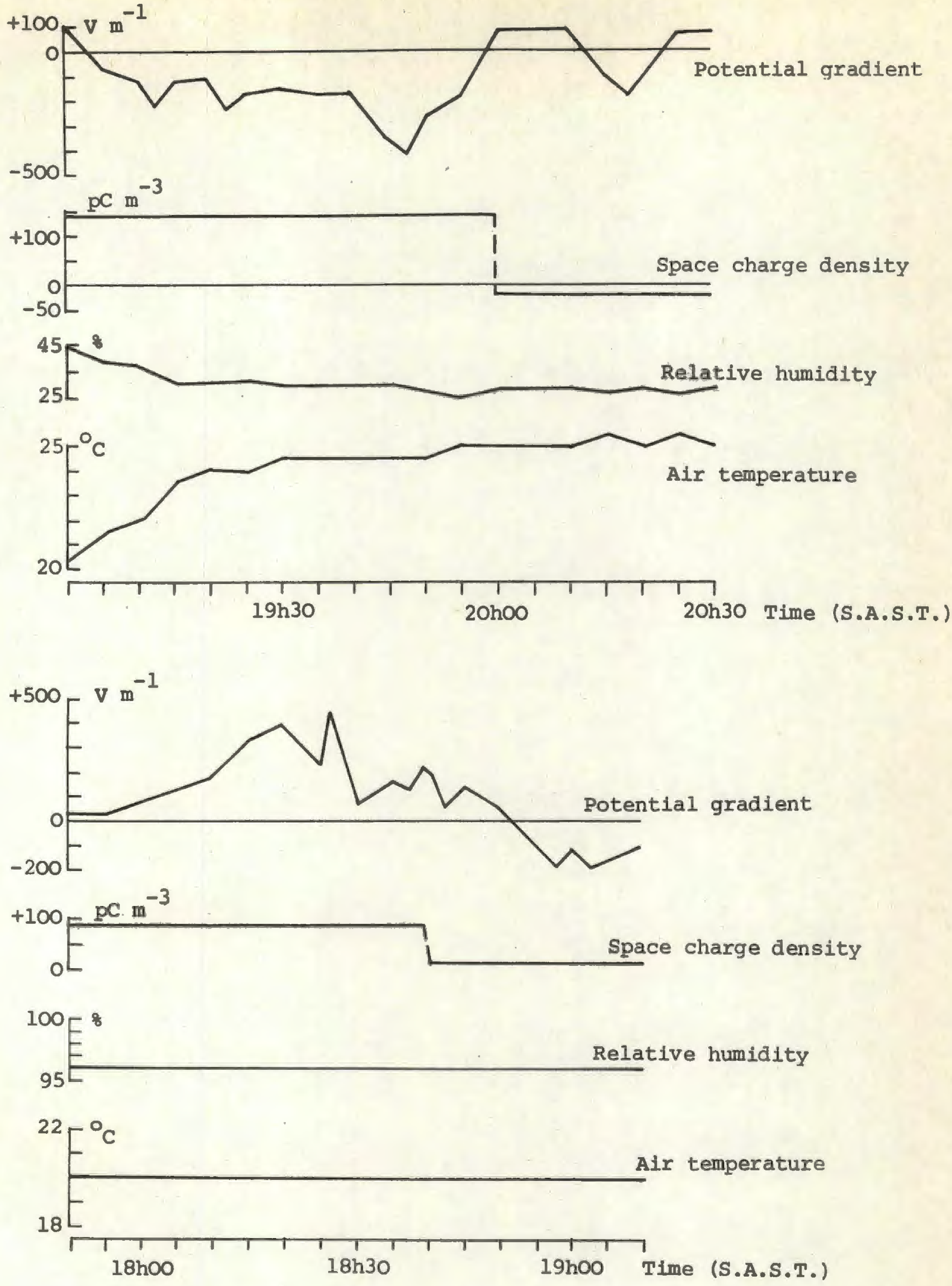
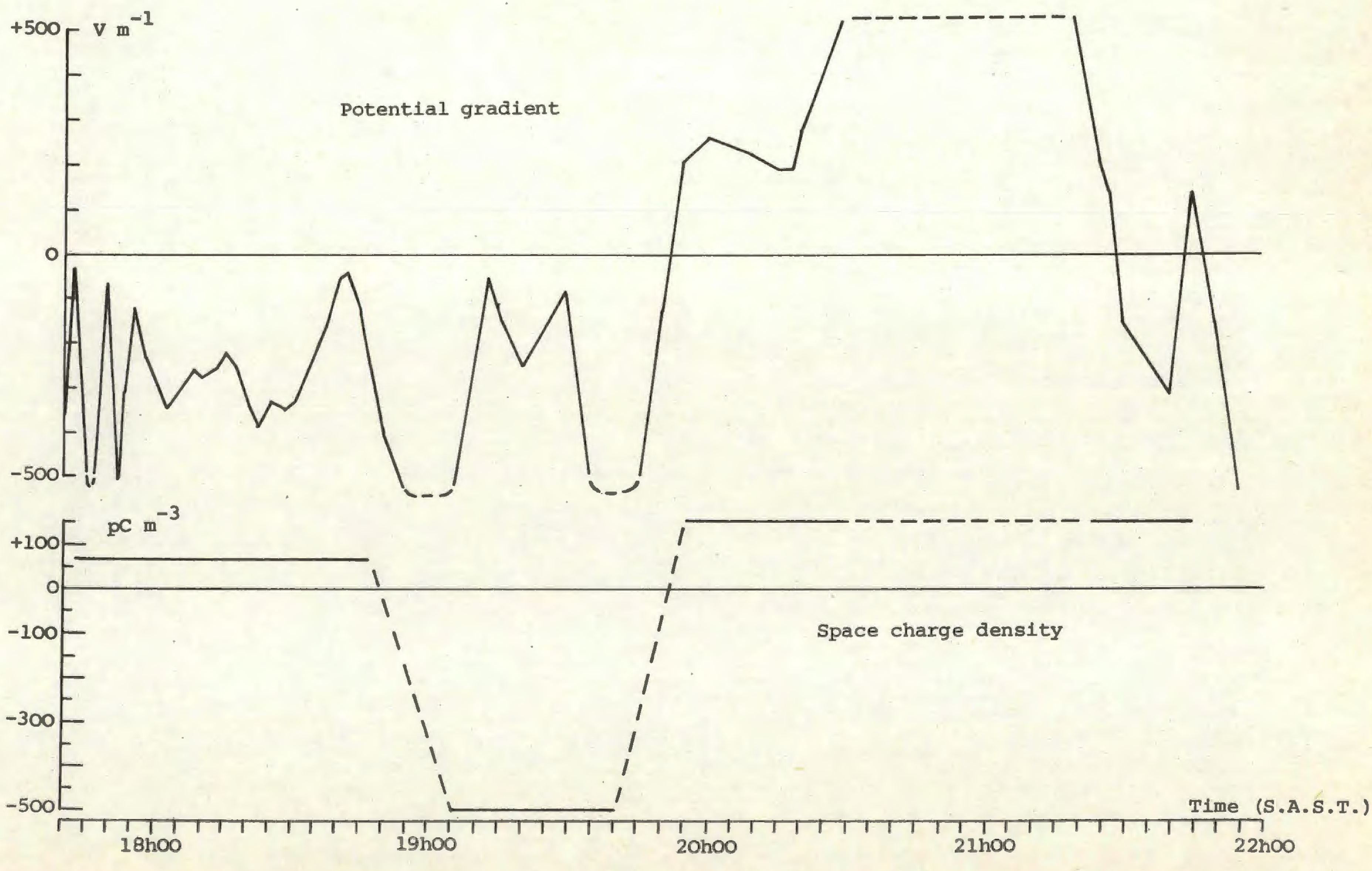



Figure 7.9 Variations of several parameters at Kloof. The top set of curves refers to 26/8/74, the lower set to 9/10/74.

on the two occasions, but at very different values, being about 30% on 26/8/74 and 96% on 9/10/74. On the 26/8/74 the potential gradient was negative while the space charge was positive at the beginning of the record. At a point something over half-way through the period both the potential gradient and the space charge reversed sign. On the 9/10/74 however, when the relative humidity was much higher and the air temperature much lower, the space charge decreased in magnitude during the event, but remained positive throughout, while the potential gradient changed in sign from positive to negative.

Figure 7.10 shows the variation in potential gradient and in space charge density which accompanied the passage overhead of a thundercloud. The broken lines on the potential gradient curve at values whose magnitude exceeded 500 V $m^{-1}$ indicate where the recorder meter was driven off scale. Here it was found that the potential gradient was initially negative and had large, rapid fluctuations which were most probably associated with the movement of charge within the cloud. During this initial period the space charge was positive. A large negative space charge 'pulse', of nearly one hour duration, then preceded a rapid rise in the value of the potential gradient, the potential gradient going positive more or less as the space charge reverted to a positive value. Although the thundercloud cannot really be regarded as part of the realm of fair weather electricity, this discussion has been included here since at no time were there any visual or aural signs of discharges taking place either from or within the cloud. The cloud itself had the typical anvil at the top, and the well known 'mammatus' structure was evident on the underside of the anvil.

It is possible to set up plausible models to explain all of these observed results. In the case of Figures 7.8 and 7.9 the models would be largely concerned with the behaviour of the low atmosphere in the vicinity of the field mills. In the case of Figure 7.10 the model would be mainly concerned with the assumed charge distribution and movements




<u>Figure 7.10</u> Potential gradient and space charge density variations on an occasion when a thundercloud was overhead (8/11/74).

within the thundercloud. However, it is felt that such models would be of limited value - indeed it would be feasible to propose two or more different models each of which would adequately explain a given set of results! The important fact which does emerge from this study is that there is no obvious direct relationship between the meteorological parameters of temperature and humidity and the atmospheric electrical parameters of potential gradient and space charge density.

### 7.6.2.2 Diurnal variation

Diurnal variations in the space charge density were obtained by recording simultaneous values of both field mill readings at hourly intervals and, using the average value of the exposure factor A determined in the foregoing section, determining the space charge density from equation (7.1). The values obtained in this way are listed in Table 7.10. For each month the average hourly value of space charge density is shown both in pC $m^{-3}$ and as a percentage of the mean monthly value.

In order to compare the diurnal space charge density variation with the diurnal potential gradient variation, the hourly values of potential gradients were extracted from the data of Chapter Six for exactly the same days for which there were space charge density results. This information is listed in Table 7.11 and here it will be seen that the data have been expressed in terms of the average hourly potential gradient and each hourly value expressed as a percentage of the monthly mean.

The space charge density was, in general, very much more variable than the potential gradient, the former varying by up to 800% of the mean while a variation of 20% was more typical for the latter. In order to try to compare these results graphically they were treated as follows: The average hourly values of space charge densities and of potential gradients, expressed as percentages of the respective monthly mean values (see Tables 7.10 and 7.11) were designated S and P respectively. The percentage deviation of each value from the monthly mean was then determined by calculating $s = S - 100$ and $p = P - 100$. The resulting values of s and p are given in Table 7.12. The deviation of space charge density from the mean value (s) was then reversed in sign, since for each month

| Time Hours Z | June 6 days pC m$^{-3}$ | % | July 15 days pC m$^{-3}$ | % | August 14 days pC m$^{-3}$ | % | September 6 days pC m$^{-3}$ | % | June-Sept 41 days pC m$^{-3}$ | % |
|---|---|---|---|---|---|---|---|---|---|---|
| 00h00 | -166.7 | 120 | -191.1 | 116 | -194.0 | 251 | -11.1 | 22 | -162.2 | 142 |
| 01h00 | -158.3 | 114 | -169.5 | 103 | -320.3 | 414 | -79.3 | 157 | -206.2 | 181 |
| 02h00 | -114.3 | 82 | -149.9 | 91 | -275.2 | 356 | -93.2 | 185 | -179.2 | 157 |
| 03h00 | -159.3 | 114 | -171.8 | 105 | -144.9 | 187 | -189.2 | 375 | -163.3 | 143 |
| 04h00 | -199.0 | 143 | -180.6 | 110 | -190.9 | 247 | -237.2 | 470 | -195.1 | 171 |
| 05h00 | -103.2 | 74 | -185.4 | 113 | -200.0 | 259 | -130.7 | 259 | -170.3 | 149 |
| 06h00 | -134.0 | 96 | -178.7 | 109 | -70.6 | 91 | +104.2 | -207 | -93.9 | 82 |
| 07h00 | -36.8 | 26 | -121.7 | 74 | +26.4 | -34 | +192.5 | -382 | -12.7 | 11 |
| 08h00 | -35.8 | 26 | -103.8 | 63 | +83.8 | -108 | +205.7 | -408 | +15.5 | -14 |
| 09h00 | -75.5 | 54 | -124.8 | 76 | +33.4 | -43 | +149.0 | -295 | -23.5 | 21 |
| 10h00 | -27.2 | 19 | -153.5 | 94 | +68.9 | -89 | +121.7 | -241 | -18.8 | 16 |
| 11h00 | -88.8 | 64 | -178.7 | 109 | +43.9 | -57 | +130.8 | -259 | -44.3 | 39 |
| 12h00 | +31.3 | -22 | -194.5 | 119 | +81.9 | -106 | +119.0 | -236 | -21.2 | 19 |
| 13h00 | -33.3 | 24 | -115.7 | 71 | +64.6 | -84 | +130.2 | -258 | -6.1 | 5 |
| 14h00 | -125.0 | 90 | -187.3 | 114 | +14.6 | -19 | -6.2 | 12 | -82.7 | 72 |
| 15h00 | -214.3 | 154 | -147.6 | 90 | -62.0 | 80 | -52.5 | 104 | -114.2 | 100 |
| 16h00 | -290.2 | 208 | -122.6 | 75 | -57.9 | 75 | -292.2 | 579 | -149.9 | 131 |
| 17h00 | -128.5 | 92 | -181.1 | 110 | -88.9 | 115 | -437.5 | 868 | -179.4 | 157 |
| 18h00 | -175.8 | 126 | -254.0 | 155 | -66.4 | 86 | -220.7 | 438 | -173.6 | 152 |
| 19h00 | -186.7 | 134 | -236.7 | 144 | -113.1 | 146 | -136.5 | 271 | -172.5 | 151 |
| 20h00 | -221.2 | 159 | -134.0 | 82 | -71.2 | 92 | -134.7 | 267 | -125.4 | 110 |
| 21h00 | -170.7 | 122 | -181.5 | 111 | -30.0 | 39 | -115.5 | 229 | -118.5 | 104 |
| 22h00 | -265.7 | 191 | -86.9 | 53 | -146.8 | 190 | -170.2 | 337 | -145.7 | 128 |
| 23h00 | -239.7 | 172 | -154.9 | 94 | -123.6 | 160 | -96.2 | 191 | -148.1 | 130 |
| 24h00 | -166.7 | 120 | -191.1 | 116 | -194.0 | 251 | -11.1 | 22 | -162.2 | 142 |
| Month mean | -139.4 | | -164.1 | | -77.3 | | -50.4 | | -114.1 | |

Table 7.10 Average hourly values of calculated space charge densities obtained at Kloof in 1974 expressed in pC m$^{-3}$ and as percentages of the monthly mean values. The signs refer to the polarity of the space charge.

| Time Hours Z | June 6 days | | July 15 days | | August 14 days | | Sept. 6 days | | June-Sept. 41 days | |
|---|---|---|---|---|---|---|---|---|---|---|
| | μA | % | μA | % | μA | % | μA | % | μA | % |
| 00h00 | 24.75 | 85 | 27.50 | 95 | 25.65 | 102 | 26.83 | 88 | 26.37 | 95 |
| 01h00 | 26.17 | 90 | 25.47 | 88 | 28.07 | 112 | 25.00 | 82 | 26.39 | 95 |
| 02h00 | 25.67 | 89 | 26.00 | 90 | 26.93 | 107 | 24.83 | 81 | 26.10 | 94 |
| 03h00 | 25.00 | 86 | 26.27 | 91 | 23.50 | 93 | 28.83 | 94 | 25.51 | 92 |
| 04h00 | 27.00 | 93 | 26.27 | 91 | 23.50 | 93 | 32.33 | 106 | 26.32 | 94 |
| 05h00 | 24.17 | 83 | 26.80 | 93 | 26.07 | 104 | 32.17 | 105 | 26.95 | 97 |
| 06h00 | 28.33 | 98 | 29.93 | 104 | 28.43 | 113 | 30.83 | 101 | 29.32 | 105 |
| 07h00 | 29.83 | 103 | 33.00 | 114 | 25.14 | 100 | 26.17 | 85 | 28.85 | 104 |
| 08h00 | 35.50 | 123 | 31.53 | 109 | 25.86 | 103 | 24.50 | 80 | 29.15 | 105 |
| 09h00 | 33.67 | 116 | 33.20 | 115 | 26.64 | 106 | 25.83 | 84 | 29.95 | 107 |
| 10h00 | 29.83 | 103 | 33.33 | 116 | 25.57 | 102 | 28.83 | 94 | 29.51 | 106 |
| 11h00 | 33.00 | 114 | 33.27 | 115 | 25.21 | 100 | 26.83 | 88 | 29.54 | 106 |
| 12h00 | 28.33 | 98 | 33.20 | 115 | 26.79 | 107 | 29.00 | 95 | 29.68 | 107 |
| 13h00 | 32.00 | 110 | 30.33 | 105 | 24.29 | 97 | 31.50 | 103 | 28.68 | 103 |
| 14h00 | 32.33 | 112 | 34.07 | 118 | 24.21 | 96 | 32.33 | 106 | 30.20 | 108 |
| 15h00 | 31.00 | 107 | 25.67 | 89 | 24.07 | 96 | 33.00 | 108 | 26.98 | 97 |
| 16h00 | 36.00 | 124 | 24.33 | 84 | 22.64 | 90 | 34.67 | 113 | 26.98 | 97 |
| 17h00 | 31.17 | 108 | 25.00 | 87 | 21.93 | 87 | 40.33 | 132 | 27.10 | 97 |
| 18h00 | 30.67 | 106 | 26.67 | 92 | 23.50 | 93 | 35.67 | 116 | 27.49 | 99 |
| 19h00 | 29.50 | 102 | 29.07 | 101 | 25.36 | 101 | 33.17 | 108 | 28.46 | 102 |
| 20h00 | 27.33 | 94 | 28.53 | 99 | 24.50 | 97 | 34.33 | 112 | 27.83 | 100 |
| 21h00 | 25.17 | 87 | 30.73 | 107 | 24.71 | 98 | 32.67 | 107 | 28.15 | 101 |
| 22h00 | 26.00 | 90 | 26.87 | 93 | 26.64 | 106 | 38.33 | 125 | 28.34 | 102 |
| 23h00 | 27.17 | 94 | 26.73 | 93 | 23.93 | 95 | 31.17 | 102 | 26.49 | 95 |
| 24h00 | 24.75 | 85 | 27.50 | 95 | 25.65 | 102 | 26.83 | 88 | 26.37 | 95 |
| Mean(μA) | 28.97 | | 28.85 | | 25.15 | | 30.64 | | 27.87 | |
| Mean(V $m^{-1}$) | 109 | | 107 | | 96 | | 119 | | 101 | |

Table 7.11 Average hourly values of potential gradient (entered as field mill reading in μA) obtained at Kloof during 1974 for those days when space charge densities were calculated. The potential gradients are also expressed as percentages of the monthly mean values.

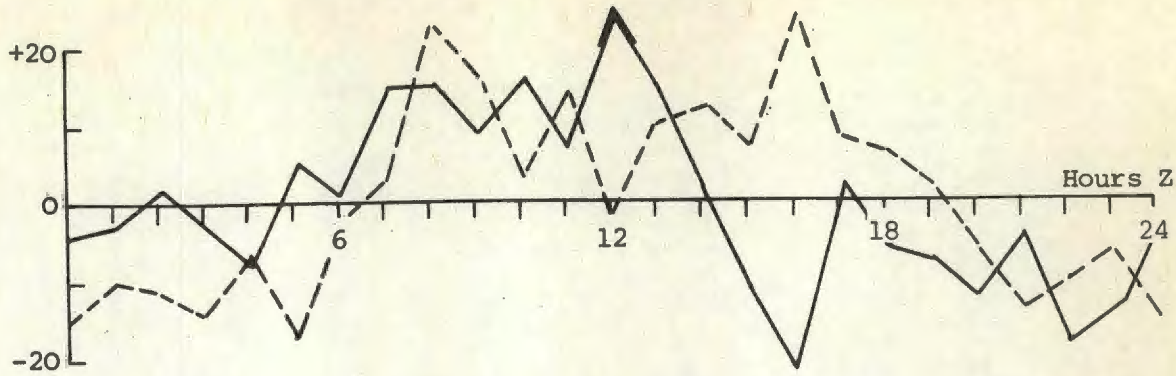
the monthly average space charge was negative. This meant that when the space charge density was more positive than the mean, the deviation was a negative number. Hence the sign was arbitrarily reversed so that a more positive space charge density was plotted as a positive value in the graphical representation of these results shown in Figure 7.11. In order to perform the sign reversal and to normalise the deviations listed in Table 7.12 a normalising factor f was calculated by finding the maximum positive value of p and dividing this by the maximum negative value of s. Thus for the entries for June 1974 in Table 7.12 it is seen that f = +24/-122 = -0.20. Each value of s for the month of June was then multiplied by this value of f and the resulting product sf listed in Table 7.12. The deviations p and sf for each set of data are represented graphically in Figure 7.11.

From Figure 7.11(e) it is apparent that there is a good correlation between the diurnal variations of potential gradient and space charge density. This correlation is not quite so obvious in Figure 7.11(a), (b) and (c) while in Figure 7.11(d) there is a very good anti-correlation between these two parameters. This set of results shows that the increases in potential gradient are almost exactly out of phase with the occurrence of increased positive space charge. These results refer to only six days in September when the overall average space charge density was -50 pC $m^{-3}$. It thus appears that while the two parameters may appear to vary independently of one another during short periods, taken over a longer term there is a very good correlation between these variations.

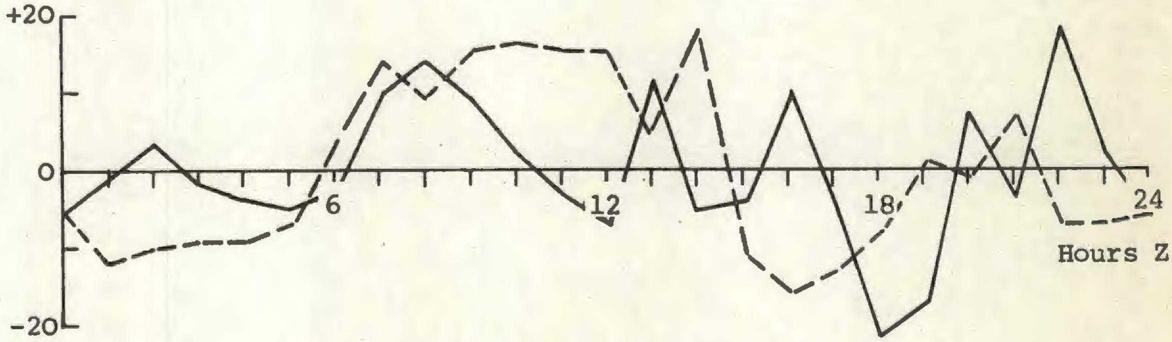
One result of this finding is that the existence of space charge density variations at the Kloof site might well be a sufficient cause to render the global diurnal potential gradient variation undetectable. This variation in space charge, and hence in potential gradient, if it is accepted that the space charge variation is the fundamental variation - in other words if it is the cause of the potential gradient variation - appears to have a cyclic nature. From midnight to about 05h00 Z it is negative, between 06h00 Z and 15h00 Z it is positive and after 15h00 Z it

| Time hours Z | June 6 days | | | July 15 days | | | August 14 days | | | September 6 days | | | June-Sept. 41 days | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | p | s | sf | p | s | sf | p | s | sf | p | s | sf | p | s | sf |
| 00h00 | -15 | +20 | -4 | -5 | +16 | -6 | +2 | +151 | -9 | -12 | -78 | +5 | -5 | +42 | -3 |
| 01h00 | -10 | +14 | -3 | -12 | +3 | -1 | +12 | +314 | -20 | -18 | +57 | -4 | -5 | +81 | -6 |
| 02h00 | -11 | -8 | +2 | -10 | -9 | +3 | +7 | +256 | -16 | -19 | +85 | -5 | -6 | +57 | -4 |
| 03h00 | -14 | +14 | -3 | -9 | +5 | -2 | -7 | + 87 | -5 | -6 | +275 | -17 | -8 | +43 | -3 |
| 04h00 | -7 | +43 | -8 | -9 | +10 | -4 | -7 | +147 | -9 | +6 | +370 | -23 | -6 | +71 | -5 |
| 05h00 | -17 | -26 | +5 | -7 | +13 | -5 | +4 | +159 | -10 | +5 | +159 | -10 | -3 | +49 | -3 |
| 06h00 | -2 | -4 | +1 | +4 | +9 | -3 | +13 | -9 | +1 | +1 | -307 | +19 | +5 | -18 | +1 |
| 07h00 | +3 | -74 | +15 | +14 | -26 | +10 | 0 | -134 | +8 | -15 | -482 | +30 | +4 | -89 | +6 |
| 08h00 | +23 | -74 | +15 | +9 | -37 | +14 | +3 | -208 | +13 | -20 | -508 | +32 | +5 | -114 | +8 |
| 09h00 | +16 | -46 | +9 | +15 | -24 | +9 | +6 | -143 | +9 | -16 | -395 | +25 | +7 | -79 | +6 |
| 10h00 | +3 | -81 | +16 | +16 | -6 | +2 | +2 | -189 | +12 | -6 | -341 | +21 | +6 | -84 | +6 |
| 11h00 | +14 | -36 | +7 | +15 | +9 | -3 | 0 | -157 | +10 | -12 | -359 | +23 | +6 | -61 | +4 |
| 12h00 | -2 | -122 | +24 | +15 | +19 | -7 | +7 | -206 | +13 | -5 | -336 | +21 | +7 | -81 | +6 |
| 13h00 | +10 | -76 | +15 | +5 | -29 | +11 | -3 | -184 | +12 | +3 | -358 | +23 | +3 | -95 | +7 |
| 14h00 | +12 | -10 | +2 | +18 | +14 | -5 | -4 | -119 | +7 | +6 | -88 | +6 | +8 | -28 | +2 |
| 15h00 | +7 | +54 | -11 | -11 | -10 | -4 | +4 | -20 | +1 | +8 | +4 | 0 | -3 | 0 | 0 |
| 16h00 | +24 | +108 | -21 | -16 | -25 | +10 | -10 | -25 | +2 | +13 | +479 | -30 | -3 | +31 | -2 |
| 17h00 | +8 | -8 | +2 | -13 | +10 | -4 | -13 | +15 | -1 | +32 | +768 | -48 | -3 | +57 | -4 |
| 18h00 | +6 | +26 | -5 | -8 | +55 | -21 | -7 | -14 | +1 | +16 | +338 | -21 | -1 | +52 | -4 |
| 19h00 | +2 | +34 | -7 | +1 | +44 | -17 | +1 | +46 | -3 | +8 | +171 | -11 | +2 | +51 | -4 |
| 20h00 | -6 | +59 | -12 | -1 | -18 | +7 | -3 | -8 | 0 | +12 | +167 | -11 | 0 | +10 | -1 |
| 21h00 | -13 | +22 | -4 | +7 | +11 | -4 | -2 | -61 | +4 | +7 | +129 | -8 | +1 | +4 | 0 |
| 22h00 | -10 | +91 | -18 | -7 | -47 | +18 | +6 | +90 | -6 | +25 | +237 | -15 | +2 | +28 | -2 |
| 23h00 | -6 | +72 | -14 | -7 | -6 | +2 | -5 | +60 | -4 | +2 | +91 | -6 | -5 | +30 | -2 |
| 24h00 | -15 | +20 | -4 | -5 | +16 | -6 | +2 | +151 | -9 | -12 | -78 | +5 | -5 | +42 | -3 |
| f | -0.20 | | | -0.38 | | | -0.06 | | | -0.06 | | | -0.07 | | |

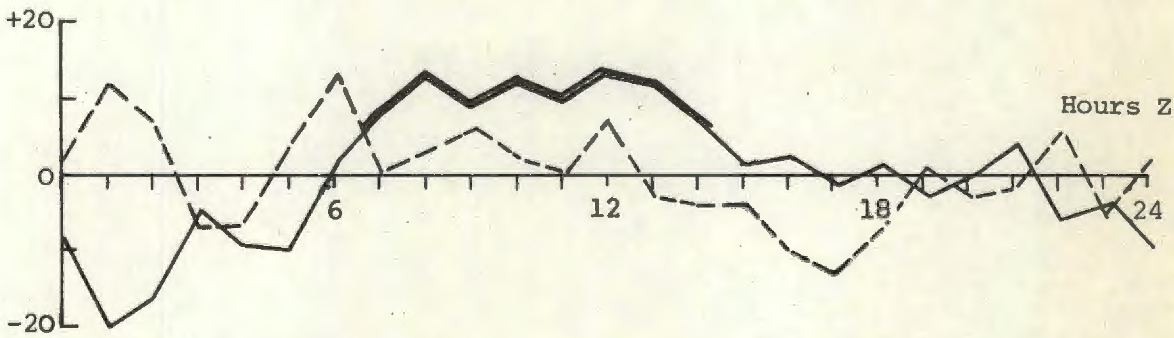
Table 7.12 Values of the percentage deviations from the mean of the potential gradient (p) and adjusted values of the deviations from the mean of the space charge density (sf).




(a) June 1974 : 6 days. (f=-0.20)

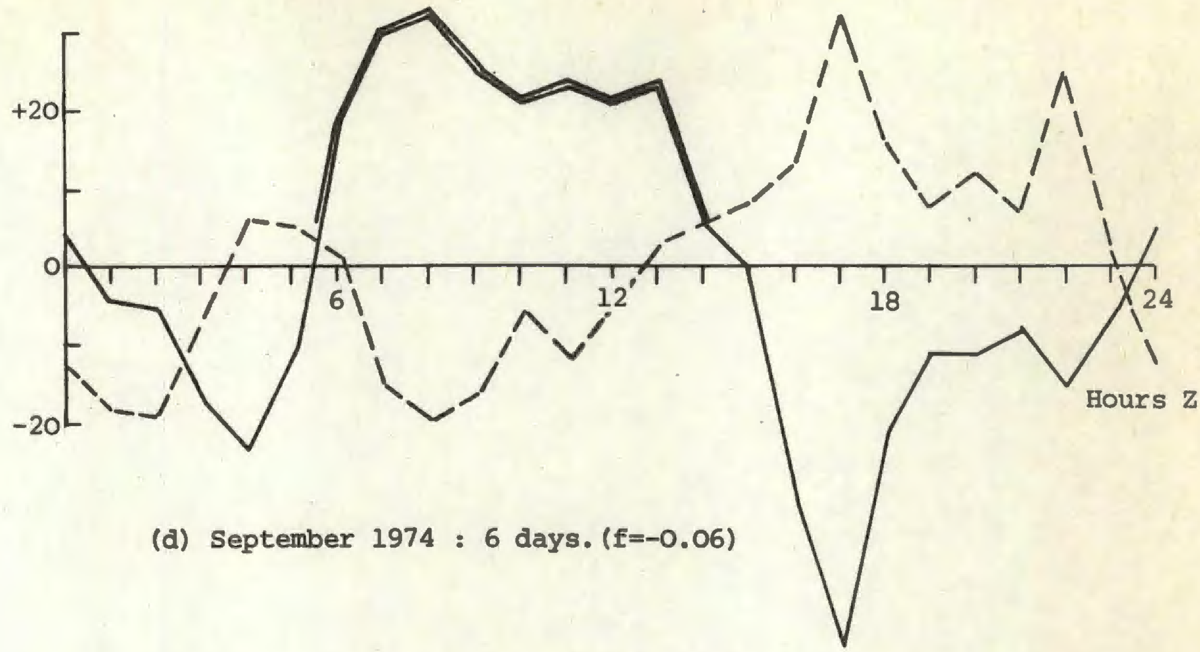



(b) July 1974 : 15 days. (f=-0.38)

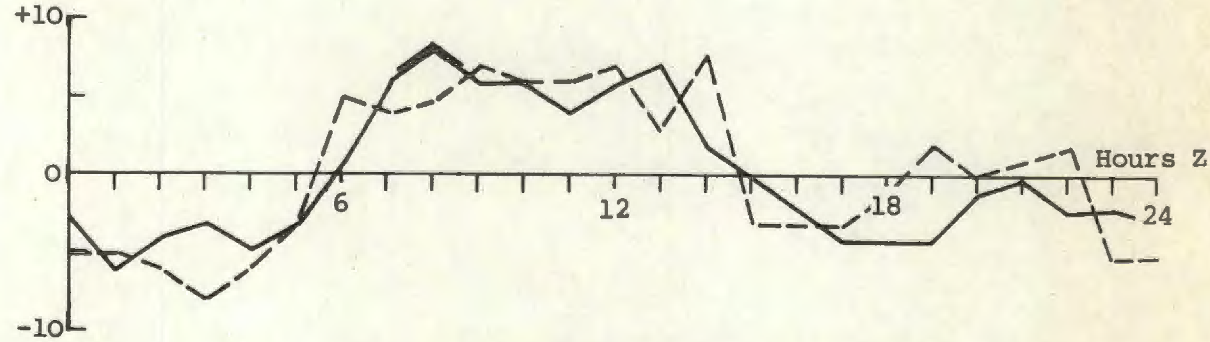



(c) August 1974 : 14 days. (f=-0.06)

Figure 7.11 Comparisons of diurnal variations of potential gradient (dashed line - plotted as % deviation from mean) with space charge density (solid line - plotted as a factor f times % deviation from mean). Regions of positive space charge density are shown as double lines. In each diagram the relevant factor f is indicated (continued).




(d) September 1974 : 6 days. (f=-0.06)




(e) June to Sept. 1974 : 41 days. (f=-0.06)

Figure 7.11 (Contd.) Further diurnal variations in potential gradient and space charge density. Note the change in vertical scale in (e).

remains predominantly negative. The individual months don't show this cyclic pattern quite as clearly as does the set of combined data. The 14 fair weather days recorded in August most closely resemble the combined data, while the 6 days of September show a decided cyclic variation of space charge density which is almost exactly out of phase with the cyclic potential gradient variation.

Reference to Figure 6.3 will show that the potential gradient results recorded during September most nearly matched the modified Whipple-Scrase thunderstorm activity curve, while the consolidated results showed the least resemblance to the Whipple-Scrase curve. It thus seems possible that the correlation between the potential gradient variation and the Whipple-Scrase thunderstorm activity variation might be apparent only when there is an anti-correlation between the potential gradient and space charge density variations. This may be regarded as evidence for the fundamental nature of the space charge density.

It remains to investigate how space charge density variations could explain such different sets of results as, for instance, those illustrated in Figures 7.11(d) and 7.11(e). In an attempt to make this explanation, two proposed models of the electrical structure of the atmosphere in the region of the mills are illustrated in Figure 7.12. In the first of these, a cloud of negative space charge extending from the ground to above the upper mill goes less negative due to a net influx of positive charge. This mechanism would explain the results illustrated in Figure 7.11(e). The increasing positive charge could well be meteorological in origin, for example associated with the hazy atmosphere often encountered in winter. This haze is often present on fine winter days and in Kloof it generally seems to become apparent from about 11h00 S.A.S.T. (09h00 Z). Usually by the later afternoon, typically about 17h00 S.A.S.T. (15h00 Z) the air is tending to become clearer again. A feasible mechanism for this process would be atmospheric convection. The positive charge associated with the haze is most probably generated in the Pinetown urban and industrial complex lying about 8 km to the east of Kloof and about 230 m lower in altitude. Once the ground and lower levels of the atmosphere

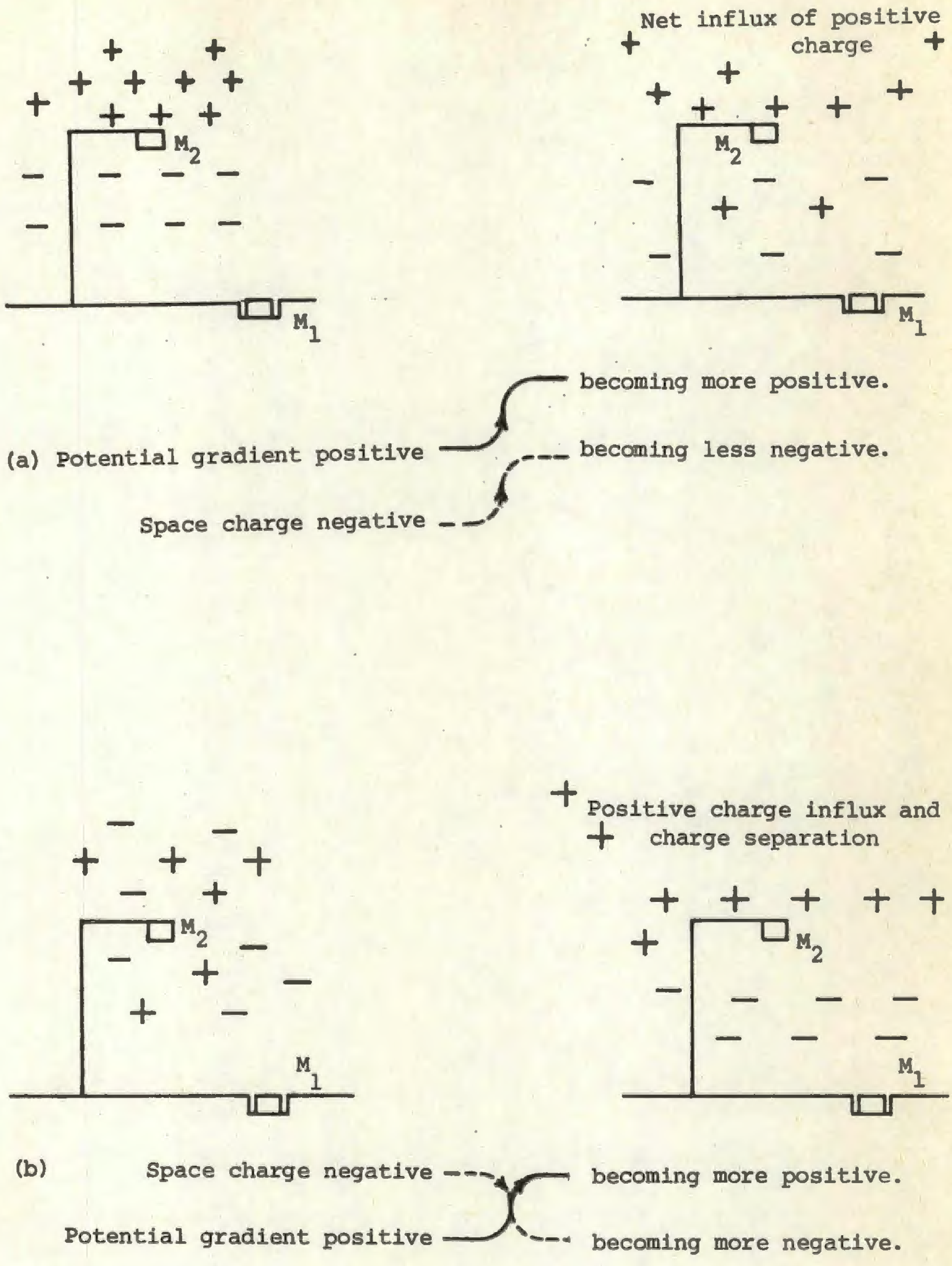



Figure 7.12 Two proposed models of space charge movements.

in this region become warmed, convection commences and the positively charged hazy air rises and moves inland over Kloof with the prevailing wind. It is of interest to note that the concept of positively charged haze used in this model is similar to the finding made in Durham, and discussed earlier in this chapter, where a dense haze observed in winter was positively charged.

The model proposed to explain the results of Figure 7.11(d) is considerably more complex. Although the positive correlation between diurnal potential gradient variation and global thunderstorm incidence might only be apparent when results similar to those of Figure 7.11(d) apply, these must, from the evidence produced here, be regarded as anomalous results. These results may be explained in terms of a model in which either there is an influx of both positive and negative charge, with the negative charge confined to the region between the mills, or where there is an influx of positive charge at higher levels and a separation of charge as suggested in Figure 7.12(b). This separation of charge cannot be due to conduction, since the prevailing potential gradient was positive, and some other process (some other generator?) must be sought to explain the bipolar nature of the space charge layer.

To explain this observation, either the existence of an artifical source of negative space charge must be postulated, or it must be assumed that the effect is due to a change in the conductivity of the air close to the ground. This latter explanation, which is similar in detail to the mechanism proposed in Section 7.5.5, would seam to be the more likely of the two since no obvious artifical sources of negative charge existed nearby.

### 7.6.3 Conclusion

It has been suggested in this chapter that evidence exists to show that the space charge in the atmosphere exerts a controlling influence on the potential gradient, As a result of this it appears that the Whipple-Scrase diurnal variation of potential gradient is in fact an anomalous result, rather than a normal one. This suggestion would conform to the discovery by DOLEZALEK (1972) that the well known Whipple-Scrase curve appeared to be an accidental result rather than a representative one.

Since the Whipple-Scrase curve has been confirmed by other workers, notably SHARPLESS, ASPINALL and HUTCHINSON (1971) and KASEMIR (1972), it would appear that the locality of the site, and probably the climate at the site, are of greatest importance in determining whether or not the generally accepted diurnal potential gradient curve will result. It is possible that the term 'globally representative' is misleading, and that in fact the generally accepted meaning of this term will only apply under certain conditions of space charge in the atmosphere, which may in fact be anomalous conditions.

It is clear that at Kloof (although the potential gradient may appear typical of a globally representative site in the generally accepted meaning of the term), on account of the controlling influence of the space charge, the site is not globally representative. It is also apparent that potential gradient may not be the best parameter to use in deciding on the 'global' nature of a recording site.

## Chapter Eight

# THE SUNRISE EFFECT: ONE ASPECT OF THE INFLUENCE OF SOLAR ACTIVITY ON ATMOSPHERIC ELECTRICITY

*An hour before the worshipp'd sun*
*Peer'd forth the golden window of the east.*

W. Shakespeare (1564-1616)
Romeo and Juliet

## 8.1 INTRODUCTION

Variations in the electrical parameters of the atmosphere which are apparently linked with sunrise are known generally as the 'sunrise effect'. Specifically, one of the best known manifestations of the effect is the increase in the potential gradient in the atmosphere near the ground at about sunrise. The first report of the sunrise effect was made by NICHOLS (1916) who found that the electrical parameters (potential gradient $E$, conductivity $\lambda$, conduction current density $j$ and space charge density $\rho$) of the atmosphere showed a tendency to decrease during the night until about sunrise and thereafter to increase. Nichols' records were not continuous and only showed values at intervals of about 1 hour.

There have been many attempts at explaining the sunrise effect. Several workers, among them ISRAEL (1953), CHALMERS (1957) and OGAWA (1960) have considered the introduction of nuclei of anthropogenic origin into the atmosphere at about dawn as a possible source of the effect. Such an explanation, however, does not account for the existence of the effect in rural areas remote from man-made pollution.

KASEMIR (1956) discussed the sunrise effect with particular reference to the exchange generator as being the cause of the effect. He showed that it was possible to explain many of the observed effects by means of the exchange generator. CHALMERS (1957) found that Kasemir's model was not altogether satisfactory in explaining the increases in potential gradient and current density after sunrise since these increases would seem to require an increase in the positive space charge density. Kasemir's explanation of the effects observed in the pre-sunrise period would be more convincing if there were an associated rise in the temperature of the air during this period. Another explanation which is in some ways similar to Kasemir's, and which would in part meet Chalmers' objection to the Kasemir theory, was advanced by MÜHLEISEN (1958). Mühleisen introduced the concept of an 'evaporation generator' to explain the effect. His observations of the positive space charge produced in a closed room by evaporation of water and by heating of the air, led him to the conclusion that the presence of water vapour in the atmosphere was the main source of the effect. However, the sunrise effect observed in the absence of a rise in air temperature, or in the clean dry air on mountain top stations is not readily explained in terms of the evaporation generator. It is apparent from both Kasemir's and Mühleisen's work that the sunrise effect actually commences before ground sunrise. This finding was also reported by OGAWA (1960) who further suggested that the conductivity sunrise effect was due not to the evaporation generator, or any other meteorological cause, but to the production of man-made nuclei.

LAW (1963) also found that the sunrise effect started before sunrise. He showed that the theory that the increase in man-made nuclei brought about a decrease in the conductivity and hence a rise in the potential gradient could not be accepted. He favoured a mechanism whereby a convection current component in the total air-Earth current reverses due to a change in space charge sign from negative to positive. This reversal in convection current requires an increased conduction current, and hence the potential gradient would rise. The change in sign of the space charge was considered to be of natural origin, but the precise mechanism was not defined. The fact that the conduction current varied, and the possible importance of convection currents to sunrise effect theories was first appreciated by KASEMIR (1956), although he stated quite definitely that the reversal in sign of the convection current could not be the cause of the sunrise effect.

CHALMERS (1967 p 168) summarized the findings prior to 1967 in his book and stated that the peculiarity of the phenomenon was the simultaneous increase in potential gradient and in air-Earth current with little change in the conductivity. He found too, that the effect was more pronounced in summer than in winter and that, while less noticeable at mountain tops than at lower levels, it was nevertheless present at high altitudes. He made the suggestion that the phenomenon may be due to a photoelectric effect. ISRAEL (1973) in his book discussed the sunrise effect in some detail. On page 406 of this book he stated that the potential gradient increase frequently begins before sunrise and that this fact has not yet been explained; while on page 407 he concluded that although the significance of the sunrise effect has been widely discussed, no completely satisfactory explanation has been forthcoming.

Recently KAMRA (1969b) published records covering a period of one year. He argued that a rise in air temperature shortly before sunrise and the subsequent convection may have caused some of the observed effects. He pointed out that it had been observed that the presence of a continuous sheet of cloud, without precipitation, suppressed the occurrence of the sunrise effect. If human activity were the sole cause of the effect, then the presence of the cloud cover should not suppress it. By means of a diagram, Kamra related the time of onset of increase in potential gradient with the time of sunrise. This diagram is reproduced here as Figure 8.1. An estimate of the time intervals between the two events, made from this diagram, shows that the beginning of the potential gradient increase occurs on the average about 33 minutes before ground sunrise.

The fact that the onset of the sunrise effect often occurs some half-an-hour before the time of ground sunrise led the author (MUIR, 1975) to propose an alternative mechanism in an attempt to explain the effect. This mechanism involves processes in the upper atmosphere, in the region

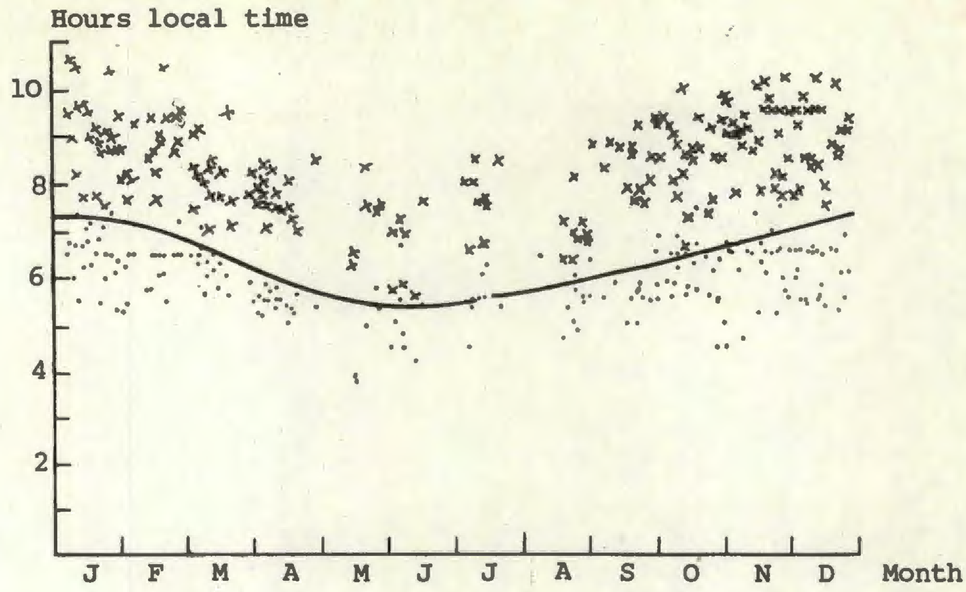



Figure 8.1 Diagram relating the beginning of the increase in potential gradient (dot) with the time of ground sunrise (solid line). The potential gradient rises to a sunrise peak which is reached at the point marked by a cross. (After KAMRA, 1969b).

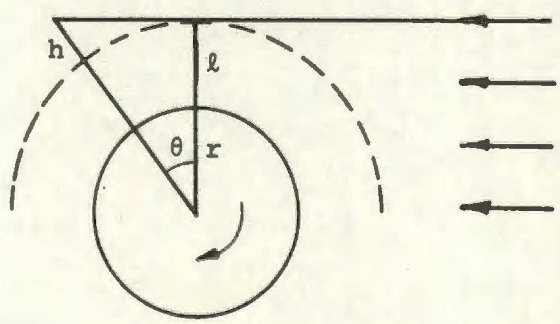



Figure 8.2 The Earth, viewed from a point directly above the pole, showing solar radiation impinging on a point a height h above an absorbing layer of thickness $\ell$.

called the electrosphere, in spite of the fact that ISRAEl (1973 p 406) has stated that the effect cannot be a process connected with the overall atmospheric electric system. In fact, the work which will be described here is not in conflict with Israel's statement since his statement referred to the increase at sunrise and in the post-sunrise period. This work is concerned specifically with events in the pre-sunrise period and in this connection Israel stated that the fact that the increase frequently begins before sunrise is as yet unexplained.

## 8.2 ASPECTS OF THE THEORY INVOLVING THE ELECTROSPHERE AS THE SOURCE OF THE SUNRISE EFFECT

### 8.2.1 The potential of the electrosphere

In terms of the well known spherical capacitor theory of atmospheric electricity described earlier in this thesis, the Earth forms one electrode of the capacitor and the electrosphere the other. The electrosphere, of potential V relative to the Earth, is generally held to extend upwards from about 50 km (see Section 2.3). It is assumed to be an equipotential region and its variation of potential in time is reflected in potential gradient variations at globally representative stations, for example over the oceans and in polar regions in fine weather.

It was shown in Section 2.3 that the columnar resistance R of a column of atmosphere 1 $m^2$ in cross-sectional area stretching between the Earth and the electrosphere, the potential gradient E at the ground, the conduction current density j and the conductivity of the atmosphere at the ground, $\lambda$, are related by

$$j = V.R^{-1} \tag{8.1}$$

and

$$E = V(R\lambda)^{-1}$$

It is immediately apparent from these equations that if R and $\lambda$ remain constant, an increase in V will cause an increase in both j and E.

The suggestion which is made here is that an increase in the potential of the electrosphere will cause the observed increase in the potential gradient, and that the increase in electrosphere potential is in some way associated with sunrise in the upper atmosphere. This aspect of the theory will now be discussed.

8.2.2 Solar radiation and the upper atmosphere

If the increase in potential gradient detected on Earth has its origin in an increase in the potential of the electrosphere, this increase in electrosphere potential will commence about half-an-hour before ground sunrise. Consequently an estimate of the height of this region may be made.

Figure 8.2 represents a plane through the Earth, at a latitude $\phi$. The radius r of this circular plane is given by $r = R \cos \phi$ where R is the radius of the Earth, which is assumed spherical (R = 6371 km). The radiation responsible for causing the increased potential in the electrosphere is assumed to be absorbed in the lower part of the atmosphere of thickness $\ell$. This radiation, which has just grazed the absorbing layer of thickness $\ell$, will impinge on a point a height h above this layer and this is defined as sunrise at the point for the radiation in question. Clearly this point will experience sunrise some time, say $\Delta t$, before the surface of the Earth immediately below it experiences ground sunrise for visible light. The angle $\theta$ shown in Figure 8.2 represents this time $\Delta t$. If $(h + \ell) \ll r$, then $\cos \theta \doteqdot 1 - h(r + \ell)^{-1}$. Also, for small angles $\cos \theta \doteqdot 1 - \frac{1}{2}\theta^2$.
Therefore

$$\theta = \left(2h/(r + \ell)\right)^{\frac{1}{2}}.$$

Now $\Delta t$ and $\theta$ may be related by

$$\Delta t = \frac{24\theta}{2\pi} \; 60 \text{ minutes}$$

thus, putting $r = R \cos \phi$ and rearranging terms one gets

$$h = 9.52 \times 10^{-6} (R \cos \phi + \ell)(\Delta t)^2 \qquad (8.2)$$

where h, $\ell$ and R are in kilometres, $\Delta t$ is in minutes.

To find the height of the illuminated point $(h + \ell)$, a value for $\ell$ must be assumed. (Clearly the value of $\ell$ will depend on the particular radiation being considered). Table 8.1 gives values of $(h + \ell)$ corresponding to various values of both $\ell$ and $\Delta t$ for the South African field stations, for all of which $\phi$ is approximately $30^{o}$. If, for example, visible light is assumed to be responsible for the increased potential at the illuminated point, $\ell = 0$ and for Kamra's results of $\Delta t = 33$ min it will be seen from Table 8.1 that $(h + \ell) = 57$ km. On the other hand, from considerations of the D-region of the ionosphere, MITRA (1952 p 316) suggested that a value of $\ell = 35$ km should be used, when $(h + \ell) = 93$ km; while SCHOUTE-VANNECK and WRIGHT (1968) used $\ell = 60$ km which leads to $(h + \ell) = 118$ km.

To try to decide on the correct value of $\ell$ to apply in this case, it is necessary to consider the known processes involving the interaction of solar radiation with the upper atmosphere. Essentially the process involved must consist of two separate parts. Firstly some component in the solar radiation must be responsible for increasing the ionization in the region in question. Secondly, there must exist a mechanism whereby the area of the electrosphere should acquire increased positive charge and hence an increased potential relative to the Earth. This second mechanism may involve a polarization in the D-region, the increased conductivity of the D-region or, more probably, the mechanism may involve both of these processes.

### 8.2.2.1 Ionization

The D-region of the ionosphere is strongly controlled by the sun. Because of the difficulties associated with the probing of this region by radio methods it remains relatively unexplored and is certainly one of the least understood parts of the ionosphere (HUNT, 1973; THOMAS L, 1971).

| Time interval ($\Delta t$) (min) | Thickness ($\ell$) of absorbing layer (km) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| 25 | 33 | 38 | 43 | 48 | 53 | 58 | 63 | 68 | 73 | 78 | 83 | 88 | 93 |
| 26 | 36 | 41 | 46 | 51 | 56 | 61 | 66 | 71 | 76 | 81 | 86 | 91 | 96 |
| 27 | 38 | 43 | 48 | 53 | 58 | 63 | 68 | 74 | 79 | 84 | 89 | 94 | 99 |
| 28 | 41 | 46 | 51 | 56 | 61 | 66 | 71 | 76 | 81 | 87 | 92 | 97 | 102 |
| 29 | 44 | 49 | 54 | 59 | 64 | 69 | 74 | 79 | 84 | 90 | 95 | 100 | 105 |
| 30 | 47 | 52 | 57 | 62 | 67 | 72 | 78 | 83 | 88 | 93 | 98 | 103 | 108 |
| 31 | 50 | 56 | 61 | 66 | 71 | 76 | 81 | 86 | 91 | 96 | 101 | 106 | 111 |
| 32 | 54 | 59 | 64 | 69 | 74 | 79 | 84 | 89 | 94 | 99 | 104 | 109 | 114 |
| 33 | 57 | 62 | 67 | 72 | 77 | 82 | 88 | 93 | 98 | 103 | 108 | 113 | 118 |
| 34 | 61 | 66 | 71 | 76 | 81 | 86 | 91 | 96 | 101 | 106 | 111 | 116 | 121 |
| 35 | 64 | 69 | 74 | 80 | 85 | 90 | 95 | 100 | 105 | 110 | 115 | 120 | 125 |
| 36 | 68 | 73 | 78 | 83 | 88 | 93 | 98 | 104 | 109 | 114 | 119 | 124 | 129 |
| 37 | 72 | 77 | 82 | 87 | 92 | 97 | 102 | 107 | 112 | 117 | 123 | 128 | 133 |
| 38 | 76 | 81 | 86 | 91 | 96 | 101 | 106 | 111 | 116 | 121 | 127 | 132 | 137 |
| 39 | 80 | 85 | 90 | 95 | 100 | 105 | 110 | 115 | 120 | 126 | 131 | 136 | 141 |
| 40 | 84 | 89 | 94 | 99 | 104 | 109 | 114 | 120 | 125 | 130 | 135 | 140 | 145 |

Table 8.1 Values of $(h + \ell)$, the height above the ground of the illuminated point (km) for varying values of $\ell$(km) and $\Delta t$ (minutes).

In one of the classical early papers on the formation and morphology of the D-region NICOLET and AIKIN (1960) stated that radiations of solar origin penetrating to below 85 km are X-rays of wavelengths shorter than 1 nm which can ionize molecular nitrogen and oxygen; Lyman-$\alpha$ radiation, which can ionize nitric oxide; and radiations of wavelengths longer than 180 nm which can ionize various atoms such as calcium and sodium. Recent work has shown the very complex nature of the ion chemistry of the D-region. The name D-layer refers specifically to the electron density concentration, but of course there are also negative and positive ions and neutral particles in this region and in this thesis the name D-region is regarded as referring to all the particles in the upper atmosphere between about 50 and about 90 km.

According to BANKS and KOCKARTS (1973 p 278) the formation of negative ions starts with the attachment of electrons to molecules (or more rarely, atoms) with one of the most important reactions being a three-body collision

$$e + O_2 + O_2 \rightarrow O_2^- + O_2 + 0.45 \text{ eV}.$$

From this type of reaction it can be seen that there are electron loss processes, which apparently become more important at night when the D-layer disappears. Other important negative ions are $NO_3^-$ and $CO_3^-$ which were stated by THOMAS et al (1973) to be the major species of ion below 72 km. ARNOLD and KRANKOWSKY (1971) gave $O_2^-$ and $O^-$ as the dominant negative ion species above 79 km and $CO_3^-$ and $NO_3^-$ as the most abundant below this altitude, while at still lower heights the concentration of $NO_3^-$ became larger than that of $CO_3^-$. TURCO and SECHRIST (1972c) proposed a model in which $NO_3^-$ was the dominant negative ion at sunrise in the region between 60 and 80 km Both $NO_3^-$ and $CO_3^-$ are important sources of $O_2^-$ in addition to the three-body collision process mentioned earlier. These reactions involve atomic oxygen and they are

$$NO_3^- + O \rightarrow NO_2 + O_2^-$$

and

$$CO_3^- + O \rightarrow CO_2 + O_2^-.$$

The source of atomic oxygen in the D-region was shown by Turco and Sechrist to be a transport process which conveys atomic oxygen downwards into the D-region at night.

The $O_2^-$ ion would seem to be the most important source of electrons early in the sunrise. RISHBETH and GARRIOTT (1969 p 111) stated that both $O_2^-$ and $O^-$ could be destroyed by visible light. BANKS and KOCKARTS (1973 p 278) gave the reaction

$$O_2^- + h\nu \ (\lambda < 2800 \text{ nm}) \rightarrow O_2 + e,$$

so that it is obvious that visible light (400 to 650 nm) will very easily lead to photodetachment of these ions. Two other processes which may detach electrons from the $O_2^-$ ion were given by THOMAS and BOWMAN (1969) as

$$O_2^- + O \rightarrow O_3 + e$$

and

$$O_2^- + O_2(^1\Delta_g) \rightarrow 2O_2 + e.$$

It has been pointed out by RISHBETH and GARRIOTT (1969 p 111) that if ultra-violet light is regarded as the detaching agent no effect should occur when the grazing height is below about 30 km ($\ell$ = 30 in equation (8.1)) because of the absorption in the ozone layer. Visible light however, is screened only by clouds and the densest atmosphere within a few kilometres of the ground so that detachment occurs at larger values of the solar zenith angle. (It would thus seem reasonable to give $\ell$ a value of about 5 km in equation (8.1)).

In addition to the above processes, TURCO and SECHRIST (1972b) suggested that terminal negative ions may be photodetached by radiations of wavelength less than 300 nm by the reaction

$$X^- + h\nu \rightarrow X + e.$$

Because of the shorter wavelengths involved, these processes would become important later in the sunrise period.

Another important ionizing agent at sunrise has been stated by NESTOROV (1972) to be solar corpuscular radiation. He claimed that corpuscular radiation was at least as important an ionizing agent in the sunrise period as was electromagnetic radiation. (If this is the case, it may be expected that the D-region sunrise ionization would show a latitude effect).

Thus far this discussion has been concerned only with negative ions. Quite a lot of recent effort in the study of the D-region has been devoted to positive ion investigations. NARCISI and BAILEY (1965) have shown that positive ions exist in this layer between 80 and 110 km altitude, many of these ions being metallic. NARCISI (1966) has shown that below 82 km ions heavier than 45 a.m.u. are most abundant, followed by $37^+$, $19^+$ and $30^+$. These ions have been identified as $NO^+$ ($30^+$) and water-cluster ions $H_5O_2^+$ ($37^+$) and $H_3O^+$ ($19^+$) and according to FERGUSON (1971) the $NO^+$ will convert to a water-cluster ion following the reaction

$$(NO^+)(H_2O)_3 + H_2O \rightarrow (H_3O^+)(H_2O)_2 + NO + OH.$$

Ferguson also showed that photo-dissociation of positive - cluster ions in the D-region was not an important reaction in D-region ionization. ROSE and WIDDEL (1972) found two groups of positive ions in the height range 58 to 72 km. They concluded that negative ions and 'light' positive ions were molecule ions, whereas the heavy positively charged particles were aerosol particles. The $H_5O_2^+$ ion was found to be one of the predominant ions below 84 km by ARNOLD and KRANKOWSKY (1971), as was the $H_7O_3^+$ ion ($55^+$).

Brief reference has been made to metallic ions. In general these result from the ionization of the metal atoms, thereby contributing to the electron production in the D-region. GOUGH (1975) has shown that sodium in particular is likely to be an important source of electrons at large solar zenith angles.

Reverting to the water-cluster ions in the lower ionosphere, it is of considerable interest to note that SHLANTA and KUHN (1973) found that water vapour and ozone concentrations above and downwind of thunderstorms were some 40% higher than the upwind concentration. They concluded that thunderstorms inject substantial amounts of water vapour into the stratosphere and that growing, electrically active storms also generate ozone at their tops. Thus it may be that thunderstorms play an important role in supplying water vapour, which in turn becomes an important reagent in the D-region ion chemistry.

Finally, to conclude this discussion of ions and ionization processes in the lower ionosphere, it should be noted that TURCO (1974) concluded that highly stable, hydrated, negative ions could be converted by chemical reaction at sunrise into less stable hydrates, which could easily be photodetached.

### 8.2.2.2 Polarization

In the foregoing section the well known solar control of the D-region of the ionosphere has been briefly discussed. It has been shown that negative ions, as well as metal atoms, are likely sources of electrons. The agencies responsible for the production of electrons are ionization by solar radiation (electromagnetic or corpuscular) and photodetachment by solar electromagnetic radiation. These processes will begin at layer sunrise and become increasingly active as the sunrise progresses. From the evidence presented, it is apparent that there exists considerable support for the view that visible solar radiation may play an important part in the production of electrons early in the sunrise. There is evidence, both from rocket experiments such as that described by MECHTLY and SMITH (1968), and from different types of radio reflection experiments, such as those dealt with by HARGREAVES (1962), by FERRARO et al (1974) and by SCHOUTE-VANNECK (1974), that the electrons form a layer or ledge at 75 to 80 km during the day. It is this electron concentration which is known as the D-layer. A very good discussion of this region of the ionosphere has been given by AL'PERT (1973).

The pre-sunrise D-region of the ionosphere thus consists of positive and negative ions of various species, neutral particles and a few free electrons (probably about 1 $cm^{-3}$). Once the solar radiations commence to reach this mixture of particles additional electrons are produced by the processes described. For visible light ($\ell$ < 5 km) the photodetachment process is the most important. If the region in which these processes occur is regarded as being the electrosphere of the classical theory, then it is necessary to find a mechanism whereby the positive charge increases in order that this may be seen as an increase in electrosphere potential.

It has been shown in the preceding section that many of the positive ions are heavy ions (particularly many of the cluster ions). There is also evidence for processes, such as those given below, where both electrons and water-cluster ions result:

$$O_2(^1\Delta_g) + h\nu \rightarrow O_2^+ + e.$$

HUNTEN and MCELROY (1968) stated that the wavelength of the radiation necessary for this process lies between 102.7 and 111.8 nm. This is however regarded as an important source of electrons because of the high concentration of electronically excited $O_2(^1\Delta_g)$ molecules. According to FERGUSON (1971), the above reaction could be followed by

$$(O_2^+)(H_2O) + H_2O \rightarrow H_3O^+(H_2O) + O_2 + OH.$$

The water-cluster ion formed ($37^+$) has already been seen to have been found as one of the most abundant ions below 82 km by NARCISI (1966). Furthermore, the presence of $O_2(^1\Delta_g)$ in the ionospheric D-region has been investigated by TURCO and SECHRIST (1972a) who found that there was a peak in $O_2(^1\Delta_g)$ concentration near 55 km, and that this peak moved down to around 50 km as sunrise progressed.

The plasma which exists during sunrise consists of positive and negative ions and an increasing number of electrons. This plasma is mixed up with neutral particles and it will diffuse under the action of gravity, as well as under its own partial pressure. Although this diffusion will be considerably complicated by collisions with neutral particles, it seems reasonable to expect some polarization due to the differential force on the heavy ions and on the electrons. This polarization, which is probably small, would be influenced by electric fields already existing in the D-region. Under the circumstances described, a situation might arise where the electrons and lighter ions would be at a level above that of the heavier ions, leaving the lower part of the region with a net positive charge. (Plasma diffusion is discussed by RISHBETH and GARRIOTT, 1969 p 149).

Another process which may contribute to the polarization involves the interaction of the plasma with the magnetic field of the Earth. Assuming this to be a dipole magnetic field, it can be shown that the radial and tangential components ($\vec{B}_r, \vec{B}_t$) of the magnetic field intensity at any point on a particular field line are related by

$$\vec{B}_r = 2\vec{B}_t \tan \phi \qquad (8.3)$$

where $\phi$ is the latitude angle defined by the particular point. If charged particles (charge q) are transported with a velocity $\vec{v}$ in a magnetic field $\vec{B}$, then the particles are subject to a force

$$\vec{F} = q\vec{v} \times \vec{B}. \qquad (8.4)$$

FLEAGLE and BUSINGER (1963 p 237) state that air flows radially out from a point in the upper atmosphere slightly east of the sub-solar point. This results in a predominantly horizontal wind directed from east to west in the sunrise region. Results obtained in a recent experiment by STUBBS (1973) support this general finding; in a record covering some six consecutive days, the diurnal variation in wind in the region from 85 to 90 km is such that, between midnight and about 06h00 local time, it is directed from east to west.

Figure 8.3 represents the Northern hemisphere of the Earth and shows the components $\vec{B}_r$, $\vec{B}_t$ of the magnetic field $\vec{B}$ at a point in the ionosphere which defines a latitude angle $\phi$ at the given height. The wind velocity vector $\vec{v}$ at the point at sunrise is directed into the plane of the paper. Positive ions carried by this wind will be subject to a force, given by equation (8.4), directed downwards towards the Earth due to the tangential component of the magnetic field. The radial component of the field will tend to cause a drift of positive ions from north to south. These ions thus enter regions of greater $B_t$ and consequently experience a greater downward force. In the same way, negative ions carried by the wind will tend to move up away from the Earth. Clearly these motions of ions will be considerably complicated by various collision and capture processes involving both neutral particles and other charged particles. Another major complicating factor is the existence of electric fields in the ionosphere, both those created by polarization within the D-region and those due to processes occurring in the higher levels of the ionosphere above the D-region. Another effect is the variation of wind with altitude, which will mean that, in general, positive ions move downward towards regions of lower wind speed while the negative ions and electrons move upward into regions which may well have higher wind speed (CRAIG, 1965 p 99). One consequence of this is that the more negative upper part of the region will be subject to a higher wind speed, thus tending to carry negative charge away from the sunrise region into the Earth's shadow. WHITTEN and POPPOFF (1965 p 130) published results of rocket soundings, made on two consecutive days in summer, which showed a region of enhanced positive ion density between 60 and 70 km altitude, in addition to the main enhancement above 100 km. Within this lower region the positive ion density increased by a factor of about 4, from approximately $6.5 \times 10^3$ to approximately $2.5 \times 10^4$ $cm^{-3}$ between 00h10 and 14h10 local time. Thus the charge density of a positive ion layer at about 70 km increases with decreasing solar zenith angle, as expected.

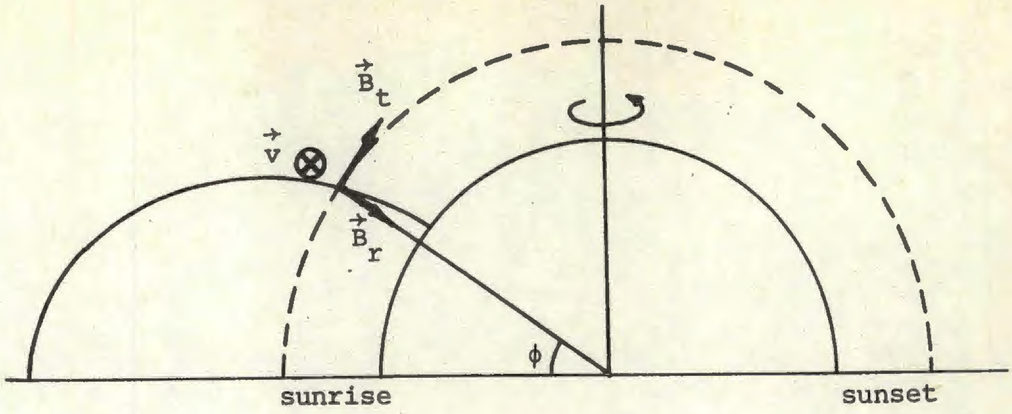



Figure 8.3 The Northern hemisphere as seen from space between the Earth and the Sun. $\vec{B}_r$ and $\vec{B}_t$ are the components of the magnetic field intensity and $\vec{v}$ the wind velocity at an ionospheric point which defines a latitude angle $\phi$.

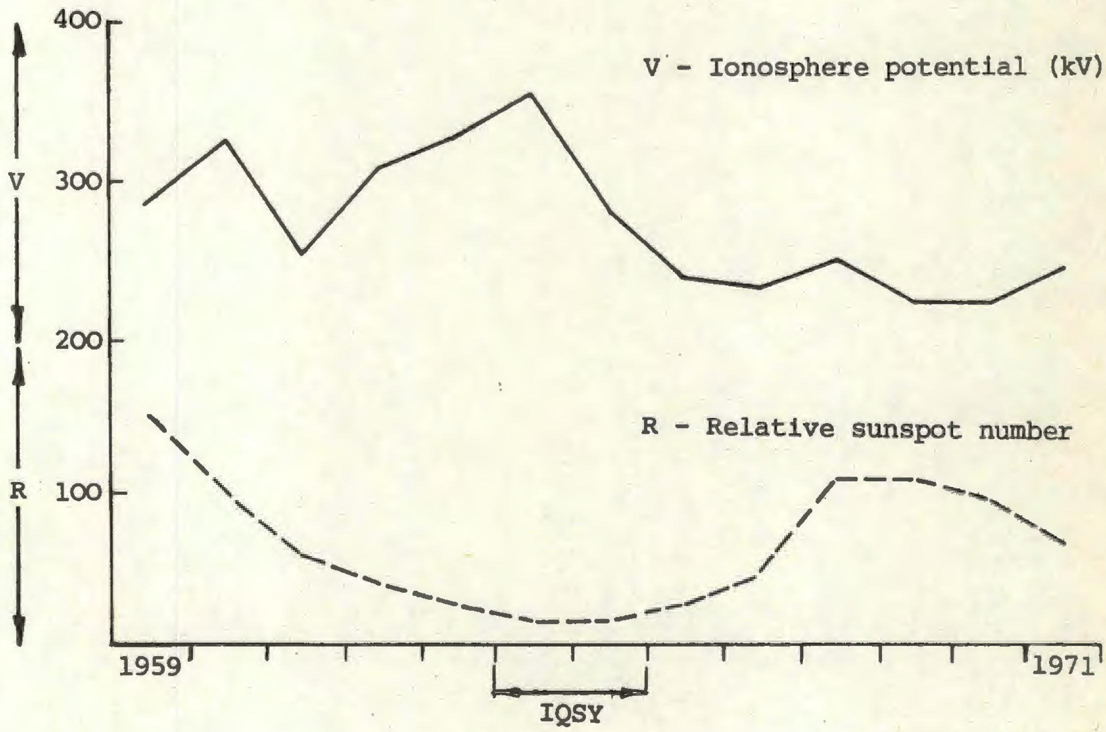



Figure 8.4 The relationship between the potential of the electrosphere and solar activity (adapted from MÜHLEISEN, 1971).

The model proposed for the sunrise conditions in the lower D-region of the ionosphere may be summarized as follows: Early in the sunrise solar visible light, for which $\ell < 5$ km impinges on the ionosphere at a height given in Table 8.1 as 62 km (for $\Delta t = 33$ minutes). The gases at this height consist of neutral atmospheric gases and aerosol particles, some metallic atoms, positive and negative ions of various types and a few free electrons. The mixture as a whole is probably electrically neutral, or nearly so. With the commencement of sunrise, the visible radiations which are capable of penetrating to this area cause photodetachment and there will be an increase in the number of free electrons. (As sunrise progresses, other solar radiations, notably Lyman-$\alpha$ and X-rays will become increasingly important). The processes of diffusion and of transport of the gases in the Earth's magnetic field in the sunrise region may both contribute to a polarization of the charged particles in this region, with the negative charge being situated at a higher average altitude than the positive charge. As this polarization progresses, the negative part may be removed by the wind, leaving an area of the lower D-region with a net positive charge. If negative charge is removed by the wind as suggested, it is carried into the Earth's shadow region, thereby increasing the total negative charge of this region. Consequently, as an area of the D-region emerges from shadow at sunrise it might undergo a fairly large increase in potential relative to the Earth.

It is interesting at this point to consider briefly some of the findings made by WEBB (1968) in his global theory of atmospheric electricity. According to Webb, phenomena such as the fair weather electric field, thunderstorms, lightning discharges and aurorae, among others, may be explained in terms of the dynamo currents in the ionosphere. It was postulated by Webb that these dynamo currents are driven by an impressed electromotive force produced by charged particle mobility differences in the lower ionosphere. The thermally driven tidal motions responsible for advecting the charged particles were found to be vertical at low latitudes in the sunlit hemisphere.

Webb found that, at low latitudes, this vertical motion due to the tidal circulation would result in electrical charge separation in the morning and early afternoon. This charge separation would be vertical, with the positive charges forced downwards by collision between the positive ions and molecules of the neutral flow. According to Webb, the charge separation process and its opposing electric field (which at 80 km would be about 0.07 V $m^{-1}$ upwards) will rigidly maintain a positive space charge in the stratopause region and a negative space charge in the ionosphere. (Typically the stratopause is at 50 km. See for example NAWROCKI and PAPA, 1963 p 1-1). Webb quotes a figure of $6 \times 10^5$ V potential difference at the base of the E-region between the early morning sector and the early afternoon sector for each 1 m $s^{-1}$ of the vertical down wind of the tidal circulation. The direction of this potential gradient is such that the potential rises during the day from a low value near sunrise to a maximum near 14h00. The figures quoted by Webb apply to latitudes up to about $15^{\circ}$, with the effects diminishing at higher latitudes. Webb also pointed out that the summer hemisphere will have stronger tidal circulations than will the winter hemisphere, and consequently the electron concentrations, dynamo currents and potential differences will be greater in the summer hemisphere.

As a result of the processes outlined thus far in this section, it appears that the D-region between about 50 km and about 70 km will undergo an increase in positive charge density. This will be a local effect, confined to a strip of the ionosphere which is just emerging from the Earth's shadow into sunlight. Clearly this local increase in positive charge will necessitate the existence of horizontal electric fields in the lower D-region, but since it is generally accepted that there may be horizontal fields in the electrosphere (see DOLEZALEK, 1972), this is not a new concept to atmospheric electricity. As sunrise progresses, the role of visible light as an agency producing free electrons becomes progressively less important. The shorter wavelength radiations become increasingly important, the rate of ionization increases and the situation in the D-region becomes increasingly complex. Another mechanism which will tend to enhance the positive charge in the lower D-region and the stratopause is the increasing d.c. conductivity of this region. Very simply, if charge separation occurs with positive charge below the negative charge, and if the medium between the separated charges becomes more conductive due to an increasing number of free electrons, then the effect of the negative charge will be largely screened from below by the conducting region, while the influence of the positive charge will still be apparent at lower altitudes.

KASEMIR (1974) has shown that a potential difference in the D-region would map down to 10 km altitude with an attenuation of only some 10%. This means that the effect of ionospheric events may be very apparent only 10 km above the ground, which brings these very much into proximity with the austausch, or exchange, region. It may be that a sunrise induced D-region potential difference which maps down with little attenuation to near the top of the exchange layer plays a part in the 'switching on' of the exchange generator proposed by KASEMIR (1956). After the time of ground sunrise the exchange generator becomes the dominant process, with the normal lower atmosphere effects becoming increasingly apparent. (It should be mentioned that it is also a consequence of the finding, made by KASEMIR (1974) concerning the mapping of potential differences, that effects detected in the lowest 10 km of the atmosphere may originate equally well in events occurring at 10 km or at 100 km altitude).

#### 8.2.2.3 Seasonal, solar cycle and latitude variations

Before discussing variations in the sunrise effect it is necessary to define precisely what aspect of the effect is varying. In most of the earlier work on the sunrise effect, the effect was taken to refer generally to the increase in potential gradient occurring at about the time of ground sunrise. For the present work two quite specific aspects of the effect will be defined. The first of these is the increase in potential gradient ($\Delta E$) measured by the difference between the value of E at ground sunrise and the minimum value of E during the 1 hour preceding ground sunrise. The second aspect is the time interval ($\Delta t$) between the time when the minimum value of E was recorded and the time of ground sunrise.

According to ISRAEL (1973 p 406), the annual variation reveals a clear increase in the sunrise effect from winter to summer. Although this statement refers to the increase in potential gradient at about sunrise, it may be taken to refer to $\Delta E$ as defined above. Israel also stated that $\Delta E$ increases with an increasing number of condensation nuclei and that the effect appears to be enhanced under conditions of poor visibility. Increasing altitude results in smaller values of $\Delta E$, but the effect still remains clearly apparent at 3600 m (measured in the Alps).

The D-region exhibits a characteristic seasonal behaviour, and AL'PERT (1973) stated that the ionization at fixed heights was more variable in winter than in summer. He explained this as being due to an enhancement in the circulation of the atmosphere during winter, which influences the D-region. (This is one example of the relationship between meteorological conditions in the lower atmosphere and the D-region. In this regard, THOMAS L. (1971) has shown that the transport of minor constituents associated with atmospheric disturbances could have important consequences for both electron and ion conçentrations in the D-region).

Reverting to the seasonal variation, RISHBETH and GARRIOTT (1969 p 161) stated that, at all heights, summer values of electron densities exceeded equinox values, which in turn exceeded winter values. They excluded from this statement days during winter when anomalous absorption was observed. The anomalous absorption referred to is caused by increased ionization below the D-region. The concentration of electrons in this lower altitude ionization has been named the C-region and is ascribed to ionization by galactic cosmic radiation. HARGREAVES (1962) stated that a temporary enhancement of ionization occurred at ionosphere sunrise, with the temporary layer being more apparent in winter than in summer and being variable from day to day. According to AL'PERT (1973), during periods of minimum solar activity, particularly in winter at mid-latitudes, a subsidiary maximum in electron density becomes distintly apparent at heights of 65 to 70 km. As mentioned earlier, this additional ionization has generally been ascribed to galactic cosmic rays, whose intensity is enhanced during the periods mentioned.

Finally, on the subject of the seasonal variation, there is the finding made by WEBB (1968) that the summer hemisphere will have a stronger tidal circulation, enhanced electron concentrations and thus stronger dynamo currents and greater potential differences than will the winter hemisphere.

It thus appears, from the evidence of the seasonal variation, that the sunrise effect should be related to D-region ionization rather than C-region ionization. This effect must be seen as being superimposed on larger scale variations, such as the variation in measured ionosphere potential with sunspot activity reported by MÜHLEISEN (1971).

This variation reported by Mühleisen is shown as Figure 8.4 and it can be seen that a fairly clear inverse correlation exists between the relative sunspot number and the electrosphere (or lower ionosphere) potential. Since galactic cosmic radiation incident on the Earth shows a similar inverse correlation with solar activity, it might be expected that the potential gradient at the ground should be a minimum during periods of maximum solar activity. This expectation results from the discussion in Chapter Three, where it was pointed out that MARKSON (1971) had made the suggestion that galactic cosmic radiation may have been a cause of enhanced thunderstorm activity during the quieter solar periods and, as a result of increased thunderstorm activity, the potential gradient would increase. The question would thus appear to reduce to one of establishing whether an increase in galactic cosmic ray activity causes increased electrosphere potential, and as a result an increase in thunderstorm activity; or whether the galactic cosmic radiation in some way increases the thunderstorm activity, and as a result the potential of the electrosphere is increased. Of course it is also possible that both the decrease in cosmic ray activity and the decrease in electrosphere potential which accompany an increase in solar activity are caused by a third agency (for example, some process involving the increased thermal energy entering the atmosphere and ionosphere).

From the work of WEBB (1968) it is apparent that, if the downward movement of positive charge into the stratopause region is a significant source of the increased electrosphere potential at sunrise, then the sunrise effect should be most clearly observed between latitudes 15$^{o}$N and 15$^{o}$S. At higher latitudes the effect will become less apparent. Any contribution to the increased electrosphere potential due to the physical transport of the D-region plasma across the magnetic field of the Earth will also have its minimum effect at high latitudes, with the maximum being at the equator.

8.2.3 Conclusion

Summarizing briefly the situation which has been detailed in the preceding sections, the suggestion which is made here is that visible solar radiation, largely through the agency of photodetachment, causes an increase in the ion and free electron concentrations at about sunrise in the lower D-region. Polarization of this region results through the interaction of the plasma and the Earth's magnetic field, through the tidal motions of the upper atmosphere and possibly to a small extent through plasma diffusion in the gravitational field. As a result of the charge separation, and because of the differential horizontal wind velocities and the increasing d.c. conductivity of the region, the potential of the electrosphere is effectively increased at sunrise. Under suitable conditions in the lower atmosphere, this increase in electrosphere potential will be detected as an increase in potential gradient $\Delta E$ at the ground. The value of $\Delta E$ will depend very much on a large number of different variables, but for a given year or so of the solar cycle, $\Delta E$ should be larger during summer than during winter, it should be less variable in summer than in winter and it should be most readily apparent at latitudes between $15^{o}N$ and $15^{o}S$.

The time of onset of the increase in electrosphere potential before ground sunrise, and hence the value of $\Delta t$ as defined in Section 8.2.2.3 above, will also be variable. In summer the solar radiations are more intense, and are thus capable of penetrating further into the atmosphere, while the average height of the D-region is less in summer than it is in winter (see for example BELROSE, 1965). Thus the processes leading to an increase in electrosphere potential should start at a lower altitude in summer, which means that $\Delta t$ should be less in summer than in winter.

In an attempt to investigate some of these aspects of the sunrise effect, specifically the events occurring before ground sunrise, the experimental work described in the next section was carried out. The data published by KAMRA (1969b) were also more closely examined and the results of this are discussed later in this chapter.

## 8.3 EXPERIMENTAL INVESTIGATIONS

### 8.3.1 Experimental arrangements and data handling

The essence of this investigation was the study of the potential gradient measured at the ground at about the time of ground sunrise. In all the measurements conventional field mills were used, in each case the output of the field mill being in the form of a direct current recorded on a miniature strip chart recorder. The techniques of obtaining absolute values of the potential gradients have been adequately described elsewhere in this thesis and they will not be discussed further here.

The first attempt to investigate the sunrise effect was made in the Ballito Bay experiment in May 1973. This was done simply as part of the synoptic observation of the potential gradient at Ballito Bay (for a description of the recording sites see Sections 6.3.1 and 7.5.2).

In order to study more closely the behaviour of the potential gradient at about the time of ground sunrise, the following procedure was adopted. Firstly, the time of ground sunrise was marked on the record for each day. Secondly, marks were made on each record at 2.5 minute intervals for 1 hour either side of ground sunrise. Thirdly, readings were taken of potential gradient at each 2.5 minute time mark over the two hour period in question. In fact, the 1 hour period following ground sunrise was subsequently shortened as it was the pre-sunrise period which was primarily of interest. Since the potential gradient could vary considerably from day to day, the results were normalized by subtracting the lowest value of potential gradient recorded in each daily set of data from every reading in that set. In this way each set of data had a lowest value of zero. The resulting values for each corresponding 2.5 minute time mark were then added together and averaged, so that a final normalized set of data was obtained. The variability of these data was then reduced by a smoothing process which involved taking 3 consecutive values of potential gradient and averaging these. In this way readings 1,2 and 3 were averaged, then 2,3 and 4; 3, 4 and 5 and so on through the set.

This technique of normalizing and smoothing the data was subsequently used on the results obtained during a further experiment conducted at Kloof in 1975. An attempt had been made at examining the synoptic potential gradient data recorded in 1974, in a manner similar to that done at Ballito Bay, but because the timing was not always sufficiently accurate this proved unsuccessful. For the 1975 Kloof experiment, a battery operated field mill was used in the interests of minimum noise. The site used was the same as that used for the 1974 synoptic observations, and this is described in Section 6.4.1. The field mill was switched on about 75 minutes before ground sunrise and the calibration was checked about 60 minutes before ground sunrise and again when the mill was switched off about 15 minutes after ground sunrise. The two calibration checks allowed corrections to be made to compensate for any variations in the performance of the field mill due to variations in the voltage of the dry-cells used for the amplifier power supply, or of the batteries powering the motor. The short time for which the field mill was in use allowed an accurate check of the timing to be maintained.

### 8.3.2 Results

#### 8.3.2.1 Ballito Bay - May 1973

Average values of the potential gradients, normalized as outlined above, are listed in Table 8.2 for times from 24 units of 2.5 minutes, or 60 minutes, before the time of ground sunrise (GSR) to $15 \times 2.5 = 37.5$ minutes after ground sunrise. These results were smoothed by averaging them in groups of 3 consecutive readings, as described above, and the smoothed averages are included in the table. The results are also displayed graphically in Figure 8.5. In fact, the normalized and smoothed potential gradient figures plotted (and shown in the table) are in units of μA, as read directly from the chart recorders. Reference to Figure 8.5 will show that the set of results obtained at the beach (broken curve) need to be multiplied by a factor of 180 V $m^{-1}$, while those obtained inland (solid curve) need to be multiplied by 150 V $m^{-1}$, to convert them into absolute potential gradients of average magnitude for these sites.

It is immediately apparent from Figure 8.5 that the sunrise effect at the beach was not nearly as well defined as was that obtained at the inland site. This is due to the much more variable potential gradient recorded at the beach, where large and rapid changes in potential gradient were quite frequent. These variations were due to wind borne space charge and they were either not present, or very much reduced at the inland site

| Time in units of 2.5 min | POTENTIAL GRADIENT | | | | | |
|---|---|---|---|---|---|---|
| | INLAND ($\times$ 150 V $m^{-1}$) | | | BEACH ($\times$ 180 V $m^{-1}$) | | |
| | Normalized Value | Sum of three | Average | Normalized Value | Sum of three | Average |
| -24 | 0.89 | | | 0.87 | | |
| -23 | 0.79 | 2.42 | 0.81 | 0.90 | 2.64 | 0.88 |
| -22 | 0.74 | 2.28 | 0.76 | 0.87 | 2.69 | 0.90 |
| -21 | 0.75 | 2.29 | 0.76 | 0.92 | 2.69 | 0.90 |
| -20 | 0.80 | 2.39 | 0.80 | 0.90 | 2.77 | 0.92 |
| -19 | 0.84 | 2.43 | 0.81 | 0.95 | 2.72 | 0.91 |
| -18 | 0.79 | 2.47 | 0.82 | 0.87 | 2.79 | 0.93 |
| -17 | 0.84 | 2.43 | 0.81 | 0.97 | 2.59 | 0.86 |
| -16 | 0.80 | 2.43 | 0.81 | 0.75 | 2.53 | 0.84 |
| -15 | 0.79 | 2.35 | 0.78 | 0.81 | 2.46 | 0.82 |
| -14 | 0.76 | 2.34 | 0.78 | 0.90 | 2.66 | 0.89 |
| -13 | 0.79 | 2.34 | 0.78 | 0.95 | 3.02 | 1.01 |
| -12 | 0.79 | 2.33 | 0.78 | 1.17 | 3.10 | 1.03 |
| -11 | 0.75 | 2.31 | 0.77 | 0.98 | 3.15 | 1.05 |
| -10 | 0.77 | 2.35 | 0.78 | 1.00 | 2.97 | 0.99 |
| - 9 | 0.83 | 2.33 | 0.78 | 0.99 | 2.97 | 0.99 |
| - 8 | 0.73 | 2.34 | 0.78 | 0.98 | 2.99 | 1.00 |
| - 7 | 0.78 | 2.24 | 0.75 | 1.02 | 2.94 | 0.98 |
| - 6 | 0.73 | 2.27 | 0.76 | 0.94 | 3.00 | 1.00 |
| - 5 | 0.76 | 2.25 | 0.75 | 1.04 | 2.75 | 0.92 |
| - 4 | 0.76 | 2.36 | 0.79 | 0.77 | 2.56 | 0.85 |
| - 3 | 0.84 | 2.43 | 0.81 | 0.75 | 2.46 | 0.82 |
| - 2 | 0.83 | 2.57 | 0.86 | 0.94 | 3.01 | 1.00 |
| - 1 | 0.90 | 2.55 | 0.85 | 1.32 | 3.58 | 1.19 |
| GSR | 0.82 | 2.50 | 0.83 | 1.32 | 3.69 | 1.23 |
| + 1 | 0.78 | 2.46 | 0.82 | 1.05 | 3.61 | 1.20 |
| + 2 | 0.86 | 2.53 | 0.84 | 1.24 | 3.43 | 1.14 |
| + 3 | 0.89 | 2.63 | 0.88 | 1.14 | 3.50 | 1.17 |
| + 4 | 0.88 | 2.78 | 0.93 | 1.12 | 3.28 | 1.09 |
| + 5 | 1.01 | 2.95 | 0.98 | 1.02 | 3.14 | 1.05 |
| + 6 | 1.06 | 3.16 | 1.05 | 1.00 | 2.94 | 0.98 |
| + 7 | 1.09 | 3.28 | 1.09 | 0.92 | 2.95 | 0.98 |
| + 8 | 1.13 | 3.31 | 1.10 | 1.03 | 2.98 | 0.99 |
| + 9 | 1.09 | 3.30 | 1.10 | 1.03 | 3.34 | 1.11 |
| +10 | 1.08 | 3.26 | 1.09 | 1.28 | 3.49 | 1.16 |

Table 8.2 The sunrise effect at Ballito Bay - May 1973

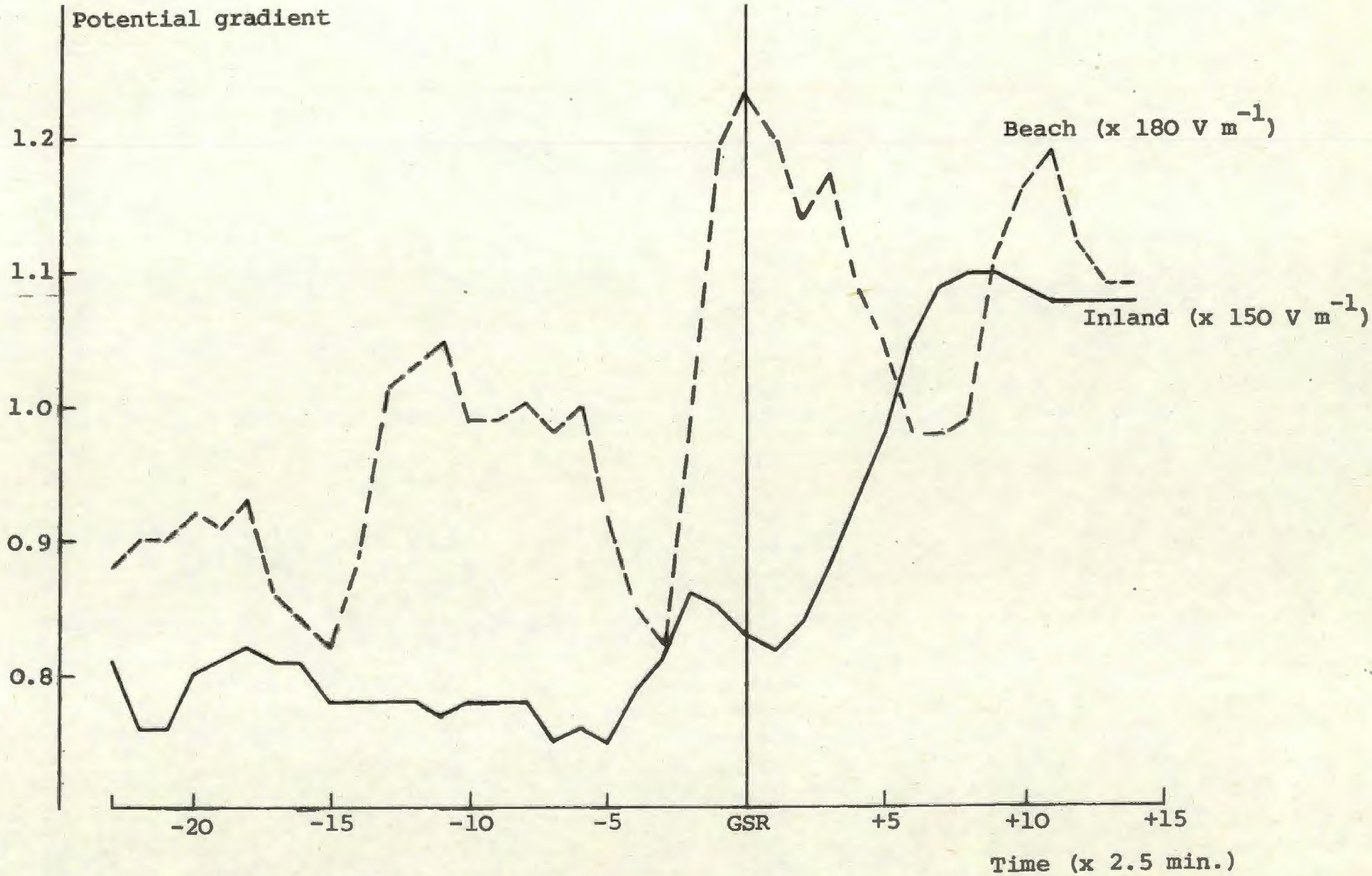



Figure 8.5 The sunrise effect at Ballito Bay - May 1973.

(in keeping with the findings of Section 7.5). Reference to Figure 8.5 shows that the values of $\Delta E$ and $\Delta t$, as defined in Section 8.2.2.3, were: Beach $\Delta E = 74 \text{ V m}^{-1}$ and $\Delta t = 7.5$ or 37.5 minutes; inland, $\Delta E = 12 \text{ V m}^{-1}$ and $\Delta t = 12.5$ or 17.5 minutes.

If an attempt is made to draw an idealized smooth curve through the inland data displayed, then values of about $9 \text{ V m}^{-1}$ and 30 minutes can be obtained for $\Delta E$ and $\Delta t$ respectively. It is worth noting that, at the inland site, the major increase in potential gradient occurs between the time of ground sunrise and about 20 minutes later. At the beach site the major increase occurs within the 7 minutes just prior to ground sunrise.

Theoretically, if sufficient data were available, the normalized averages used in this analysis would eliminate all random variations in potential gradient and leave only the 'real' effect (or effects) due to the sunrise. If this is used as justification for drawing an idealized curve through the data displayed, then one may conclude that at this time the height of the electrosphere was 52 km (from Table 8.1 with $\Delta t = 30$ minutes, $\ell = 5$ km). However, it must be realized that the procedure of sketching the idealized curve is by no means precise and that considerable variations are possible.

<u>8.3.2.2 Kloof - February to June 1975</u>

It was mentioned earlier that the Kloof sunrise effect experiment was a separate experiment and not simply one aspect of the earlier Kloof experiment. To this end the recording aspiration psychrometer was developed in order that records of air temperature and humidity should be available. Advantages of this experiment being restricted to an investigation of the sunrise effect were that more accurate calibration of the field mills was possible, more accurate timing was possible and a more suitable field mill sensitivity could be used.

Recordings of the potential gradient over the sunrise period were made on 68 mornings when the weather was suitable between 2/2/75 and 22/6/75. The combined results of these records are shown in Table 8.3. On 58 of the 68 days mentioned, aspiration psychrometer records were obtained. The potential gradient records for this set of 58 selected days are also shown in Table 8.3. The dry-bulb temperatures recorded by the aspiration psychrometer were normalized and smoothed in the same way as the potential gradient results were and these figures are also entered in the table. The normal procedure of expressing the moisture content of the atmosphere in terms of relative humidity, obtained from psychrometric tables, proved too insensitive to be of any use in the present experiment. The following method of obtaining a more sensitive indication of the water vapour content of the air was used. The dry-bulb temperature $T_d$ and the wet-bulb temperature $T_w$ were recorded by the psychrometer. The difference $\Delta T = T_d - T_w$ was calculated for each 2.5 minute time mark in the sunrise period and the 'dryness' of the atmosphere was then expressed by the ratio $\Delta T/T_d$. Once the dryness had been calculated for each time mark on each days records, the figures were normalized and smoothed in the same way as the potential gradient and air temperature results had been. The results, treated in this way are also shown in Table 8.3.

Figure 8.6(a) shows the sunrise effect exhibited over the full period of 68 days. In Figure 8.6(b) the sunrise effect over the 58 day period is compared directly with the variation in air temperature and dryness on the same 58 days. To aid the direct comparison, these results have all been plotted as percentages of their mean values. It will be seen from these results that $\Delta E = 8$ V m$^{-1}$ and $\Delta t = 35$ minutes for the 68 day period, while over the 58 days $\Delta E = 9$ V m$^{-1}$ and $\Delta t = 35$ minutes again.

Various aspects of the results of the sunrise effect experiment have been examined in detail, and these, together with a closer examination of the KAMRA (1969b) results, are discussed under the following sub-headings:

| Time in units of 2.5 min. | Potential gradient (x 2.4 V $m^{-1}$) 68 days | | Selected 58 days | | Dry bulb temp. ($^{o}C$) | | $(T_d - T_w)/T_d$ (x $10^{-2}$) | |
|---|---|---|---|---|---|---|---|---|
| | Value | Smooth Avge. | Value | Smooth Avge. | Value | Smooth Avge. | Value | Smooth Avge. |
| -24 | 7.74 | | 7.76 | | 0.53 | | 1.84 | |
| -23 | 7.42 | 7.33 | 7.54 | 7.42 | 0.51 | 0.50 | 1.67 | 1.85 |
| -22 | 6.83 | 6.73 | 6.95 | 6.78 | 0.47 | 0.49 | 2.05 | 1.85 |
| -21 | 5.95 | 6.51 | 5.84 | 6.56 | 0.49 | 0.49 | 1.82 | 1.88 |
| -20 | 6.76 | 6.41 | 6.89 | 6.49 | 0.50 | 0.50 | 1.76 | 1.81 |
| -19 | 6.53 | 6.39 | 6.74 | 6.53 | 0.54 | 0.50 | 1.86 | 1.74 |
| -18 | 5.87 | 6.08 | 5.95 | 6.18 | 0.47 | 0.49 | 1.61 | 1.69 |
| -17 | 5.84 | 5.84 | 5.86 | 5.90 | 0.46 | 0.47 | 1.61 | 1.64 |
| -16 | 5.81 | 5.62 | 5.88 | 5.68 | 0.47 | 0.46 | 1.69 | 1.65 |
| -15 | 5.21 | 5.36 | 5.31 | 5.47 | 0.44 | 0.45 | 1.64 | 1.62 |
| -14 | 5.07 | 5.13 | 5.21 | 5.23 | 0.43 | 0.43 | 1.54 | 1.63 |
| -13 | 5.10 | 5.26 | 5.16 | 5.36 | 0.41 | 0.42 | 1.72 | 1.59 |
| -12 | 5.60 | 5.54 | 5.72 | 5.69 | 0.43 | 0.42 | 1.50 | 1.69 |
| -11 | 5.93 | 5.58 | 6.19 | 5.77 | 0.41 | 0.44 | 1.86 | 1.86 |
| -10 | 5.21 | 5.77 | 5.40 | 5.98 | 0.49 | 0.45 | 2.21 | 1.98 |
| - 9 | 6.18 | 5.95 | 6.34 | 6.19 | 0.45 | 0.48 | 1.86 | 2.02 |
| - 8 | 6.46 | 6.61 | 6.82 | 6.95 | 0.49 | 0.48 | 1.98 | 1.99 |
| - 7 | 7.18 | 6.79 | 7.70 | 7.23 | 0.51 | 0.51 | 2.13 | 2.10 |
| - 6 | 6.72 | 7.22 | 7.18 | 7.69 | 0.52 | 0.51 | 2.18 | 2.13 |
| - 5 | 7.75 | 7.47 | 8.19 | 7.96 | 0.49 | 0.48 | 2.09 | 1.99 |
| - 4 | 7.93 | 7.84 | 8.51 | 8.36 | 0.42 | 0.44 | 1.71 | 1.83 |
| - 3 | 7.85 | 7.87 | 8.37 | 8.41 | 0.42 | 0.43 | 1.69 | 1.77 |
| - 2 | 7.84 | 7.96 | 8.35 | 8.50 | 0.44 | 0.45 | 1.91 | 1.93 |
| - 1 | 8.19 | 8.00 | 8.77 | 8.57 | 0.48 | 0.46 | 2.18 | 1.98 |
| GSR | 7.97 | 8.36 | 8.59 | 9.01 | 0.47 | 0.48 | 1.84 | 2.09 |
| + 1 | 8.91 | 8.85 | 9.67 | 9.62 | 0.49 | 0.48 | 2.26 | 2.14 |
| + 2 | 9.68 | 9.50 | 10.60 | 10.22 | 0.49 | 0.49 | 2.33 | 2.36 |
| + 3 | 9.92 | 9.95 | 10.40 | 10.62 | 0.49 | 0.50 | 2.50 | 2.41 |
| + 4 | 10.26 | 10.23 | 10.85 | 10.77 | 0.53 | 0.52 | 2.41 | 2.43 |
| + 5 | 10.51 | | 11.06 | | 0.54 | | 2.39 | |

<u>Table 8.3</u> Sunrise effect results at Kloof.

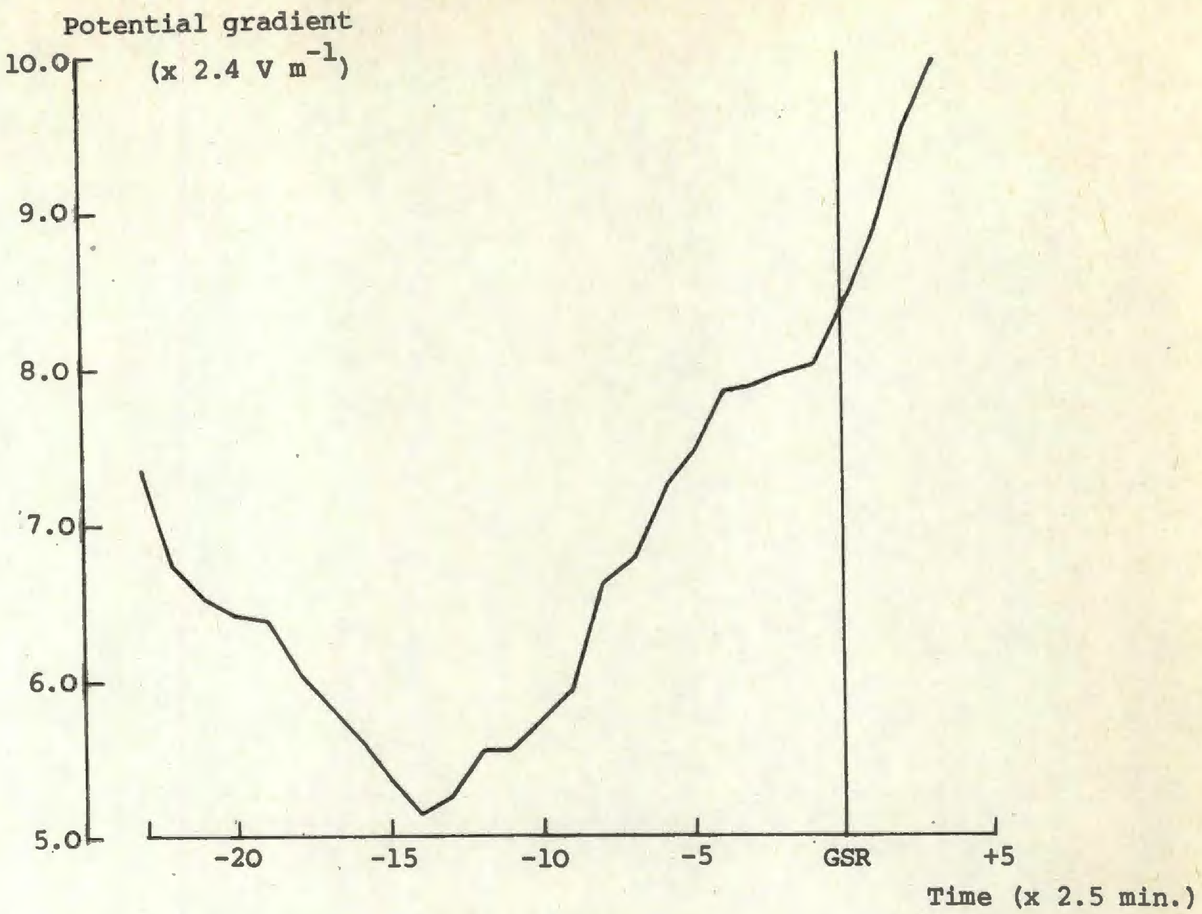



Figure 8.6 (a) The sunrise effect at Kloof - 1975.

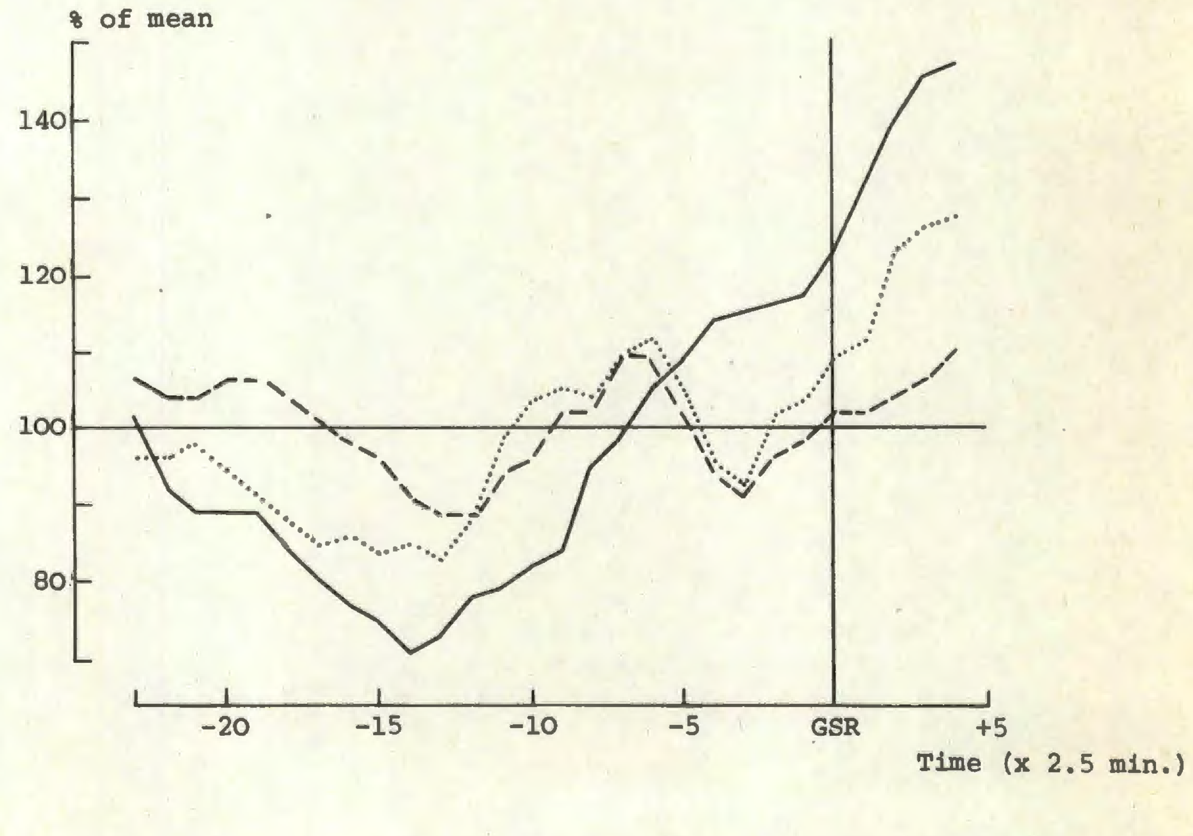



Figure 8.6 (b) Potential gradient (——), temperature (- -) and dryness (···) at Kloof during sunrise.

'seasonal variation', 'temperature and humidity effects' and 'effect of latitude'.

Seasonal variation. The data resulting from the Kloof experiment were examined with a view to detecting any variation in either $\Delta E$ or $\Delta t$ as the year advanced from the summer month of February to the mid-winter month of June. Values of these parameters obtained for the separate months were:

| | | | |
|---|---|---|---|
| February | $\Delta E = 10.3\ V\ m^{-1}$, | $\Delta t = 32.5$ min | (16 days) |
| March | $\Delta E = 10.4\ V\ m^{-1}$, | $\Delta t = 40.0$ min | (16 days) |
| April | $\Delta E = 0.6\ V\ m^{-1}$, | $\Delta t = 2.5$ min | (20 days) |
| May | $\Delta E = 13.0\ V\ m^{-1}$, | $\Delta t = 32.5$ min | (11 days) and |
| June | $\Delta E = 9.0\ V\ m^{-1}$, | $\Delta t = 36.3$ min | (15 days). |

Clearly there is no well defined trend in either of the two parameters.

To try and minimise local variations which may have affected the results over the short periods of 1 month (the daily results and results taken in groups of 10 days predictably showed even greater variability than did the monthly results), the results were examined in 2 groups of 3 months each and then in 4 groups of 2 months each. This was done by first taking the results of the months of February, March and April together as a group, and then the group consisting of the results of April, May and June. The results of this grouping are shown in Table 8.4, and they are displayed graphically in Figure 8.7(a). It will be seen from the diagram that $\Delta t$ was the same in the two cases, while $\Delta E$ was about 6 $V\ m^{-1}$ for the months February to April, and about 7 $V\ m^{-1}$ for April to June. It is quite evident that there is no significant difference between the two sets of results.

Finally, in case there was a trend in the variation of $\Delta E$ and $\Delta t$ which was hidden by the variability of the monthly and shorter period groups of results (and which would not be obvious from only 2 groups of

| Time in units of 2.5 min | Smoothed averages of potential gradients (x 2.4 V $m^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Feb. Mar. Apr. | Apr. May June | Feb. Mar. | Mar. Apr. | Apr. May | May June |
| -23 | 8.31 | 6.16 | 9.15 | 7.92 | 6.33 | 5.88 |
| -22 | 7.62 | 5.99 | 8.30 | 6.95 | 6.27 | 5.75 |
| -21 | 7.25 | 5.95 | 7.80 | 6.52 | 6.28 | 5.69 |
| -20 | 7.03 | 6.05 | 7.16 | 6.55 | 6.35 | 5.81 |
| -19 | 6.80 | 6.01 | 6.87 | 6.73 | 6.40 | 5.78 |
| -18 | 6.32 | 5.87 | 6.35 | 6.45 | 6.29 | 5.72 |
| -17 | 6.02 | 5.74 | 5.91 | 6.14 | 6.08 | 5.49 |
| -16 | 5.73 | 5.53 | 5.65 | 6.03 | 5.71 | 5.35 |
| -15 | 5.62 | 5.03 | 5.67 | 6.15 | 4.87 | 4.85 |
| -14 | 5.51 | 4.75 | 5.62 | 6.28 | 4.40 | 4.58 |
| -13 | 5.63 | 4.84 | 5.79 | 6.32 | 4.29 | 4.74 |
| -12 | 5.83 | 5.23 | 6.00 | 6.40 | 4.76 | 5.22 |
| -11 | 5.79 | 5.13 | 6.13 | 6.37 | 4.65 | 5.30 |
| -10 | 6.10 | 5.18 | 6.47 | 6.66 | 4.95 | 5.28 |
| - 9 | 6.40 | 5.09 | 6.92 | 6.88 | 4.93 | 5.22 |
| - 8 | 7.04 | 5.74 | 7.60 | 7.33 | 5.44 | 6.00 |
| - 7 | 7.14 | 5.86 | 7.86 | 7.00 | 5.24 | 6.32 |
| - 6 | 7.59 | 6.12 | 8.49 | 6.95 | 5.48 | 6.72 |
| - 5 | 7.94 | 6.04 | 9.12 | 7.07 | 5.60 | 6.72 |
| - 4 | 8.22 | 6.42 | 9.52 | 7.63 | 6.07 | 7.27 |
| - 3 | 7.84 | 6.83 | 9.10 | 7.59 | 6.24 | 7.95 |
| - 2 | 7.71 | 7.19 | 8.88 | 7.44 | 6.30 | 8.40 |
| - 1 | 7.56 | 7.27 | 8.85 | 7.21 | 6.27 | 8.72 |
| GSR | 8.06 | 7.50 | 9.44 | 7.63 | 6.51 | 8.99 |
| + 1 | 8.55 | 7.93 | 10.13 | 8.07 | 7.03 | 9.64 |
| + 2 | 9.34 | 8.61 | 10.85 | 8.80 | 7.82 | 10.20 |
| + 3 | 9.73 | 9.01 | 11.13 | 9.13 | 8.39 | 10.47 |
| + 4 | 9.91 | 9.48 | 10.95 | 9.50 | 9.08 | 10.60 |

Table 8.4 The influence of the season of the year on the sunrise effect.

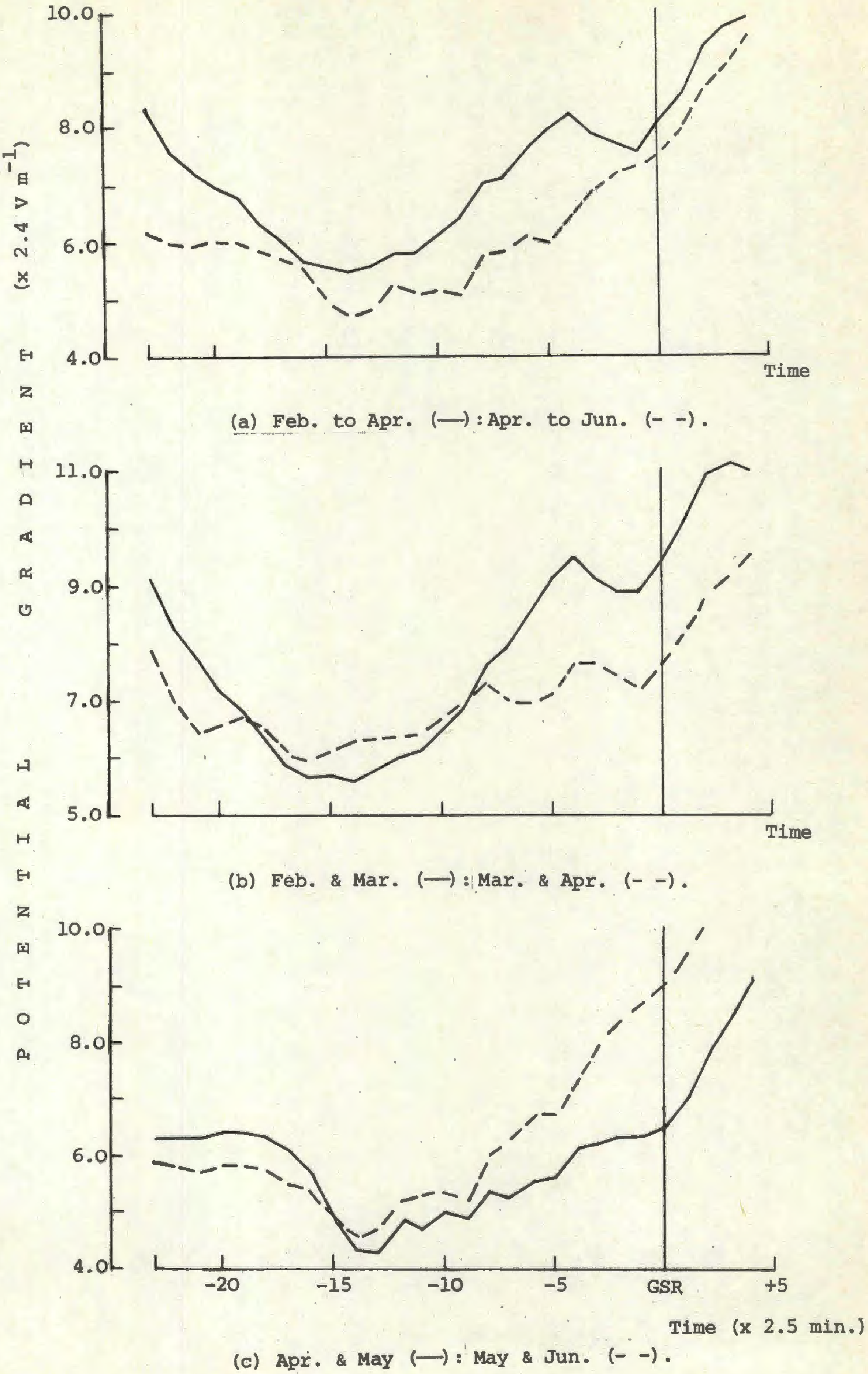



**Figure 8.7** Seasonal variation of the sunrise effect.

results), the months were taken together in pairs. These results are included in Table 8.4 and they are displayed graphically in Figures 8.7(b) and (c). Once again it is apparent that no systematic seasonal variation exists in either of the two parameters.

A definite indication of a seasonal effect is given by the absolute values of the potential gradients recorded during the sunrise effect experiment. The average values recorded on each day are shown in Table 8.5. It will be seen that the average potential gradient increases by a factor of about 1.8 between February and June. This increase of potential gradient with decreasing solar activity (going from summer to winter) is in keeping with the expectation discussed in Section 8.2.2.3 and mentioned earlier in Chapter Three.

It will be seen from Table 8.5 that 3 values, 2 in March and 1 in June were not included in the monthly mean. This was because these values were very much higher than normal. On each occasion they resulted after a particularly calm, clear night, and it is considered that the unusually high values were an indication of the presence of a positive space charge layer near the ground due to the electrode effect. Figure 8.8 shows clearly that when there was a noticeable electrode effect, the resulting potential gradient variation was very atypical of he normal sunrise effect behaviour. As a result of these findings it would seem possible that an electrode effect layer would tend to mask, rather than enhance, the sunrise effect.

While there are no readily discernible seasonal variations in the sunrise effect parameters recorded here, the results published by KAMRA (1969b) do show a suggestion of a seasonal effect. It has already been seen that the data published by Kamra, covering a 1 year period, yielded a value of $\Delta t$ = 33 minutes. If the year is divided into summer and winter, with the divisions being made at the end of March and at the end of September, then during the summer $\Delta t$ = 25 minutes and in winter $\Delta t$ = 38 minutes. This variation is in accordance with the theory outlined earlier in this chapter, and the values of $\Delta t$ obtained would put the

| Average sunrise period potential gradients (μA × 2.4 = V m$^{-1}$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| February | | March | | April | | May | | June | |
| Date | μA | Date | μA | Date | μA | Date | μA | Date | μA |
| 2/2/75 | 18.00 | 1/3/75 | 33.37 | 2/4/75 | 50.00 | 1/5/75 | 32.00 | 1/6/75 | 32.43 |
| 3/2/75 | 21.65 | 2/3/75 | 33.80 | 5/4/75 | 48.73 | 5/5/75 | 37.70 | 4/6/75 | 45.47 |
| 4/2/75 | 8.00 | 3/3/75 | 25.60 | 6/4/75 | 53.43 | 6/5/75 | 69.66 | 5/6/75 | 91.00* |
| 5/2/75 | 8.83 | 5/3/75 | 27.50 | 7/4/75 | 40.53 | 10/5/75 | 29.27 | 6/6/75 | 57.30 |
| 7/2/75 | 13.33 | 7/3/75 | 41.90 | 8/4/75 | 31.00 | 13/5/75 | 43.97 | 7/6/75 | 49.47 |
| 8/2/75 | 36.37 | 9/3/75 | 31.00 | 9/4/75 | 54.30 | 14/5/75 | 60.60 | 10/6/75 | 40.63 |
| 9/2/75 | 16.23 | 10/3/75 | 30.27 | 18/4/75 | 34.63 | 20/5/75 | 36.43 | 11/6/75 | 38.73 |
| 11/2/75 | 28.07 | 11/3/75 | 27.57 | 20/4/75 | 31.87 | 21/5/75 | 33.50 | 12/6/75 | 50.83 |
| 16/2/75 | 37.20 | 16/3/75 | 34.17 | 21/4/75 | 24.83 | 22/5/75 | 48.12 | 13/6/75 | 51.07 |
| 17/2/75 | 25.73 | 17/3/75 | 39.07 | 25/4/75 | 40.17 | 23/5/75 | 46.17 | 15/6/75 | 39.83 |
| 19/2/75 | 21.70 | 19/3/75 | 74.48* | | | 28/5/75 | 33.57 | 16/6/75 | 40.86 |
| 20/2/75 | 27.40 | 21/3/75 | 43.43 | | | | | 17/6/75 | 52.00 |
| 21/2/75 | 37.19 | 26/3/75 | 47.27 | | | | | 18/6/75 | 36.50 |
| 24/2/75 | 47.43 | 28/3/75 | 41.70 | | | | | 21/6/75 | 50.10 |
| 25/2/75 | 24.10 | 29/3/75 | 65.70* | | | | | 22/6/75 | 38.20 |
| 26/2/75 | 23.10 | 30/3/75 | 35.00 | | | | | | |
| Mean | 24.65 | | 35.12 | | 40.95 | | 42.82 | | 44.53 |

Table 8.5 Average potential gradients recorded during the sunrise period. Values marked * not included in the mean on account of the electrode effect - see text.

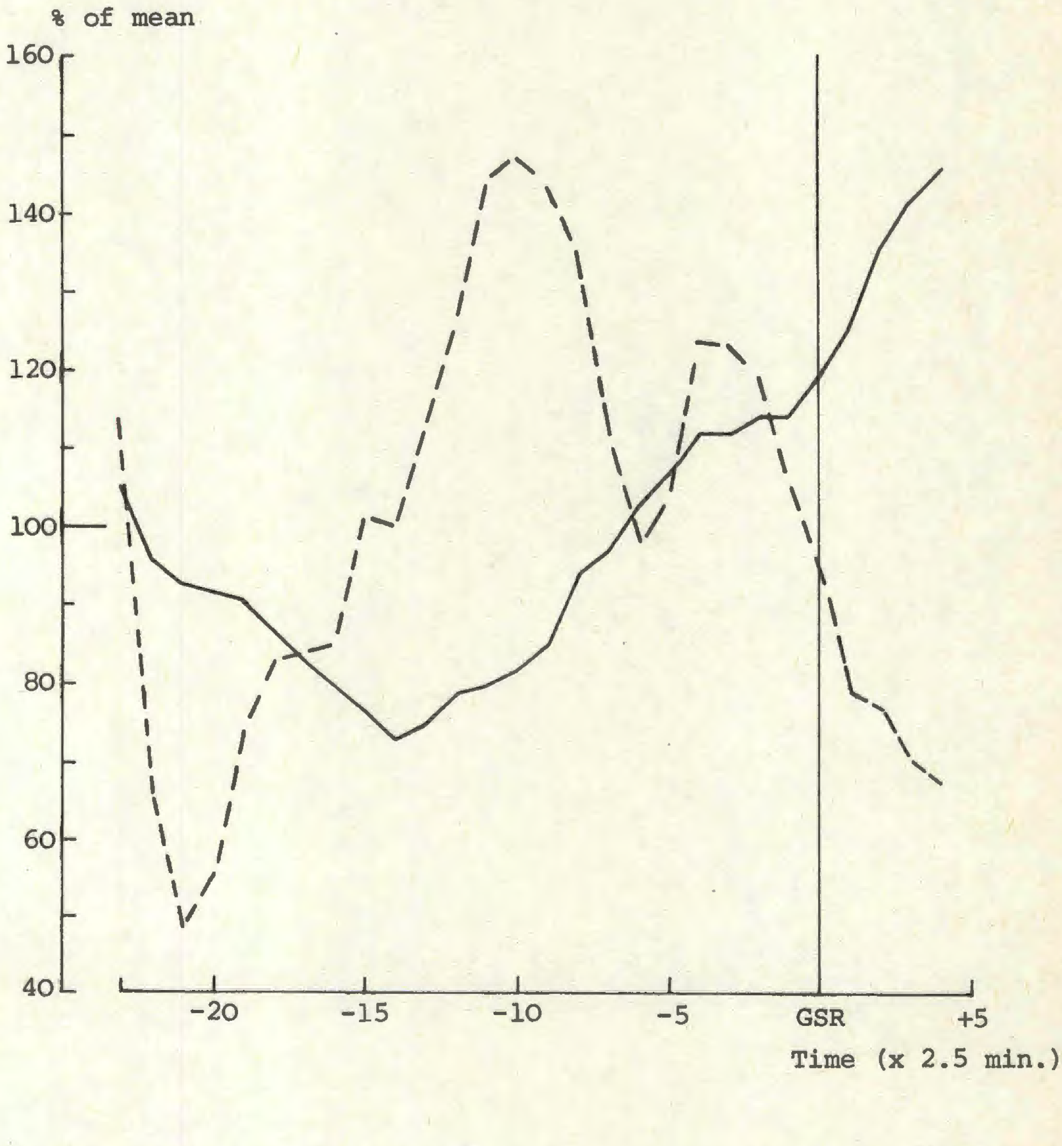



Figure 8.8 The potential gradient variation at sunrise under electrode effect conditions (- - -) compared with the normal sunrise effect (——).

electrosphere layer (using the term electrosphere in the sense of the ionospheric level at which increased ionization occurs) at 38 km in summer and 81 km in winter (from Table 8.1 with $\ell = 5$ km). Although the data published by Kamra do suggest this seasonal trend, it is very obvious from Figure 8.1 that there is a large scatter in the results and consequently the figures quoted here for $\Delta t$, which have simply been estimated from the diagram published by Kamra, should be treated with caution. Further reference to the seasonal effect will be made later under the discussion of the latitude effect.

Temperature and humidity effects. It was mentioned in the introduction to this chapter that MÜHLEISEN (1958) had proposed the evaporation generator as the explanation for the sunrise effect. Essentially this required that the air be warmed and its water vapour content be changed at about the time of sunrise. Values of air temperature and dryness (as defined earlier in this section) were obtained on 58 days. These values were normalized and smoothed and then displayed graphically as percentages of their mean values during the sunrise period. They are compared with the variation in potential gradient as shown in Figure 8.6(b). The temperature and dryness results show a similar variation to each other, as would be expected, but this variation bears only a superficial resemblance to the potential gradient variation.

In order to examine the possible temperature and humidity effects more closely, in particular to see if any seasonal effect became apparent here, they were treated in groups of 2 months again. The results obtained are listed in Table 8.6 and they are shown graphically, again plotted as percentages of the mean values, in Figure 8.9. It will be seen from Figures 8.9(a) and (b) that during February/March and during March/April the air temperature decreased significantly in the hour preceding ground sunrise. During this period the dryness remained relatively constant, with a few large excursions and a slight tendency to increase. During the same time the potential gradient exhibited a normal sunrise effect. The results in the April/May period and in the May/June period were

| Time in units of 2.5 min | Normalized and smoothed average values | | | | | |
|---|---|---|---|---|---|---|
| | February and March | | | March and April | | |
| | Potl. grad. (x 2.4 (V $m^{-1}$) | Air temp. $T_d$ ($^oC$) | Dryness $\frac{\Delta T}{T_d}$ (x $10^{-2}$) | Potl. grad. (x 2.4 V $m^{-1}$) | Air temp. $T_d$ ($^oC$) | Dryness $\frac{\Delta T}{T_d}$ (x $10^{-2}$) |
| -23 | 9.01 | 0.38 | 1.15 | 8.38 | 0.50 | 1.25 |
| -22 | 8.10 | 0.37 | 1.17 | 7.20 | 0.49 | 1.23 |
| -21 | 7.51 | 0.35 | 1.15 | 6.65 | 0.48 | 1.20 |
| -20 | 7.19 | 0.34 | 1.20 | 6.78 | 0.49 | 1.24 |
| -19 | 6.95 | 0.32 | 1.28 | 7.06 | 0.47 | 1.47 |
| -18 | 6.44 | 0.31 | 1.37 | 6.83 | 0.44 | 1.69 |
| -17 | 5.98 | 0.30 | 1.35 | 6.37 | 0.37 | 1.70 |
| -16 | 5.68 | 0.30 | 1.28 | 6.05 | 0.37 | 1.48 |
| -15 | 5.67 | 0.28 | 1.22 | 6.41 | 0.36 | 1.31 |
| -14 | 5.53 | 0.26 | 1.17 | 6.89 | 0.33 | 1.23 |
| -13 | 5.65 | 0.24 | 1.13 | 7.35 | 0.32 | 1.18 |
| -12 | 5.87 | 0.24 | 1.17 | 7.53 | 0.31 | 1.12 |
| -11 | 6.11 | 0.24 | 1.22 | 7.46 | 0.31 | 1.17 |
| -10 | 6.55 | 0.24 | 1.31 | 7.72 | 0.31 | 1.27 |
| - 9 | 7.08 | 0.24 | 1.29 | 7.98 | 0.33 | 1.35 |
| - 8 | 7.80 | 0.24 | 1.25 | 8.55 | 0.35 | 1.41 |
| - 7 | 8.07 | 0.24 | 1.22 | 8.29 | 0.36 | 1.53 |
| - 6 | 8.68 | 0.24 | 1.28 | 8.22 | 0.35 | 1.67 |
| - 5 | 9.32 | 0.23 | 1.24 | 8.46 | 0.31 | 1.59 |
| - 4 | 9.70 | 0.20 | 1.21 | 9.26 | 0.28 | 1.51 |
| - 3 | 9.26 | 0.19 | 1.17 | 9.24 | 0.25 | 1.50 |
| - 2 | 9.03 | 0.18 | 1.18 | 8.98 | 0.24 | 1.57 |
| - 1 | 8.96 | 0.17 | 1.17 | 8.72 | 0.22 | 1.58 |
| GSR | 9.51 | 0.14 | 1.20 | 9.49 | 0.18 | 1.57 |
| + 1 | 10.14 | 0.13 | 1.24 | 10.22 | 0.16 | 1.50 |
| + 2 | 10.86 | 0.11 | 1.35 | 11.32 | 0.14 | 1.60 |
| + 3 | 11.17 | 0.11 | 1.35 | 11.80 | 0.15 | 1.60 |
| + 4 | 11.00 | 0.12 | 1.37 | 12.30 | 0.16 | 1.65 |
| Mean | 7.96 | 0.24 | 1.24 | 8.27 | 0.32 | 1.43 |

Table 8.6 Potential gradient, temperature and dryness variations at sunrise. (Continued overleaf)

| Time in units of 2.5 min | Normalized and smoothed average values | | | | | |
|---|---|---|---|---|---|---|
| | April and May | | | May and June | | |
| | Potl. grad. (x 2.4 V m$^{-1}$) | Air temp. $T_d$ ($^oC$) | Dryness $\frac{\Delta T}{T_d}$ (x $10^{-2}$) | Potl. grad. (x 2.4 V m$^{-1}$) | Air temp. $T_d$ ($^oC$) | Dryness $\frac{\Delta T}{T_d}$ (x $10^{-2}$) |
| -23 | 5.95 | 0.60 | 2.16 | 5.69 | 0.62 | 2.90 |
| -22 | 6.18 | 0.60 | 2.18 | 5.58 | 0.61 | 2.87 |
| -21 | 6.31 | 0.68 | 2.24 | 5.56 | 0.64 | 2.98 |
| -20 | 6.54 | 0.74 | 2.35 | 5.76 | 0.70 | 2.82 |
| -19 | 6.64 | 0.75 | 2.27 | 5.80 | 0.70 | 2.51 |
| -18 | 6.72 | 0.73 | 2.49 | 5.68 | 0.69 | 2.24 |
| -17 | 6.36 | 0.69 | 2.50 | 5.45 | 0.67 | 2.07 |
| -16 | 5.93 | 0.67 | 2.50 | 5.37 | 0.67 | 2.12 |
| -15 | 4.80 | 0.61 | 2.08 | 4.96 | 0.67 | 2.17 |
| -14 | 4.44 | 0.56 | 1.85 | 4.65 | 0.66 | 2.27 |
| -13 | 4.46 | 0.55 | 1.81 | 4.75 | 0.67 | 2.31 |
| -12 | 5.35 | 0.61 | 2.30 | 5.17 | 0.65 | 2.54 |
| -11 | 5.10 | 0.71 | 2.75 | 5.24 | 0.71 | 2.88 |
| -10 | 5.36 | 0.77 | 2.88 | 5.20 | 0.73 | 3.06 |
| - 9 | 5.26 | 0.79 | 2.76 | 5.11 | 0.78 | 3.13 |
| - 8 | 5.97 | 0.81 | 2.75 | 5.93 | 0.80 | 3.08 |
| - 7 | 5.95 | 0.86 | 2.83 | 6.25 | 0.87 | 3.35 |
| - 6 | 6.33 | 0.88 | 2.79 | 6.60 | 0.90 | 3.37 |
| - 5 | 6.62 | 0.82 | 2.36 | 6.52 | 0.85 | 3.11 |
| - 4 | 7.36 | 0.74 | 2.10 | 7.03 | 0.78 | 2.78 |
| - 3 | 7.69 | 0.72 | 2.25 | 7.75 | 0.75 | 2.68 |
| - 2 | 7.74 | 0.74 | 3.00 | 8.21 | 0.77 | 3.04 |
| - 1 | 7.79 | 0.84 | 3.27 | 8.59 | 0.83 | 3.17 |
| GSR | 8.33 | 0.89 | 3.33 | 8.90 | 0.89 | 3.40 |
| + 1 | 9.26 | 0.86 | 3.06 | 9.64 | 0.91 | 3.49 |
| + 2 | 10.50 | 0.81 | 3.09 | 10.23 | 0.94 | 3.86 |
| + 3 | 11.48 | 0.78 | 3.01 | 10.57 | 0.97 | 4.00 |
| + 4 | 12.61 | 0.84 | 2.90 | 10.70 | 1.04 | 4.00 |
| Mean | 6.89 | 0.74 | 2.57 | 6.67 | 0.77 | 2.94 |

Table 8.6 (continued) Potential gradient, temperature and dryness variations at sunrise.

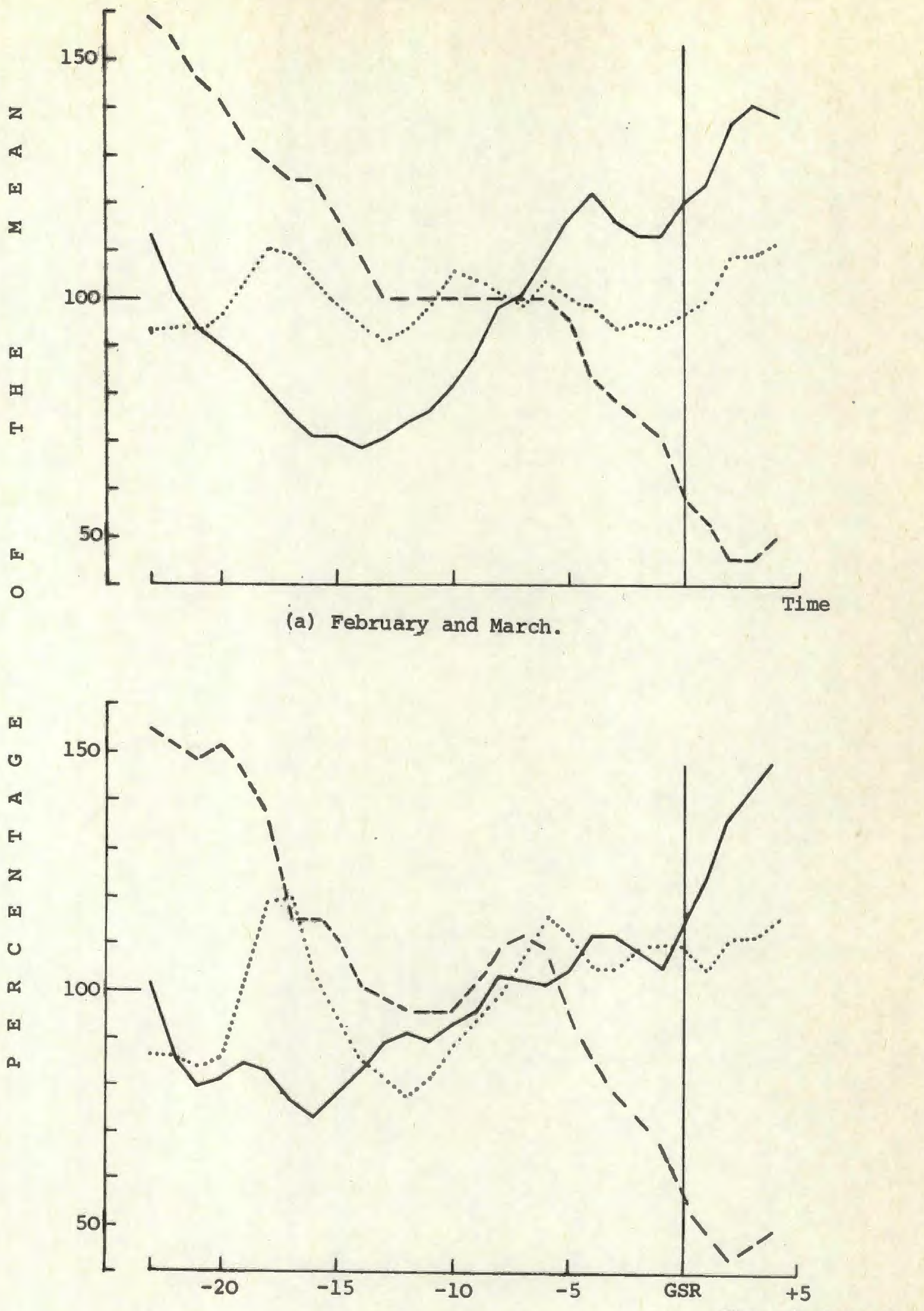
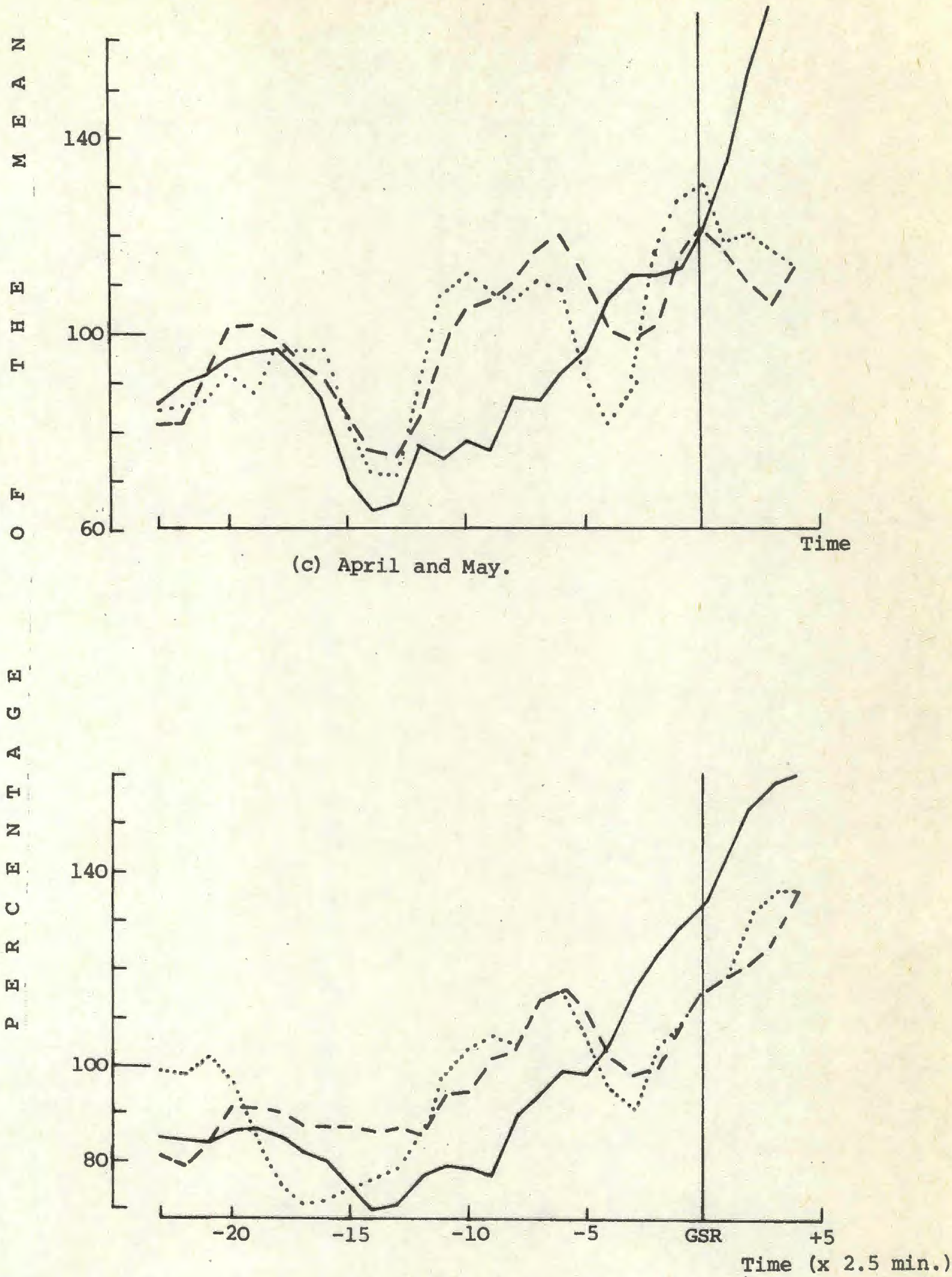



Figure 8.9 Seasonal variations at sunrise of potential gradient (——), temperature (- - -) and dryness (···) (continued overleaf).




(c) April and May.

(d) May and June.

Figure 8.9 (Contd.) Seasonal variations at sunrise of potential gradient (——), temperature (- - -) and dryness (···).

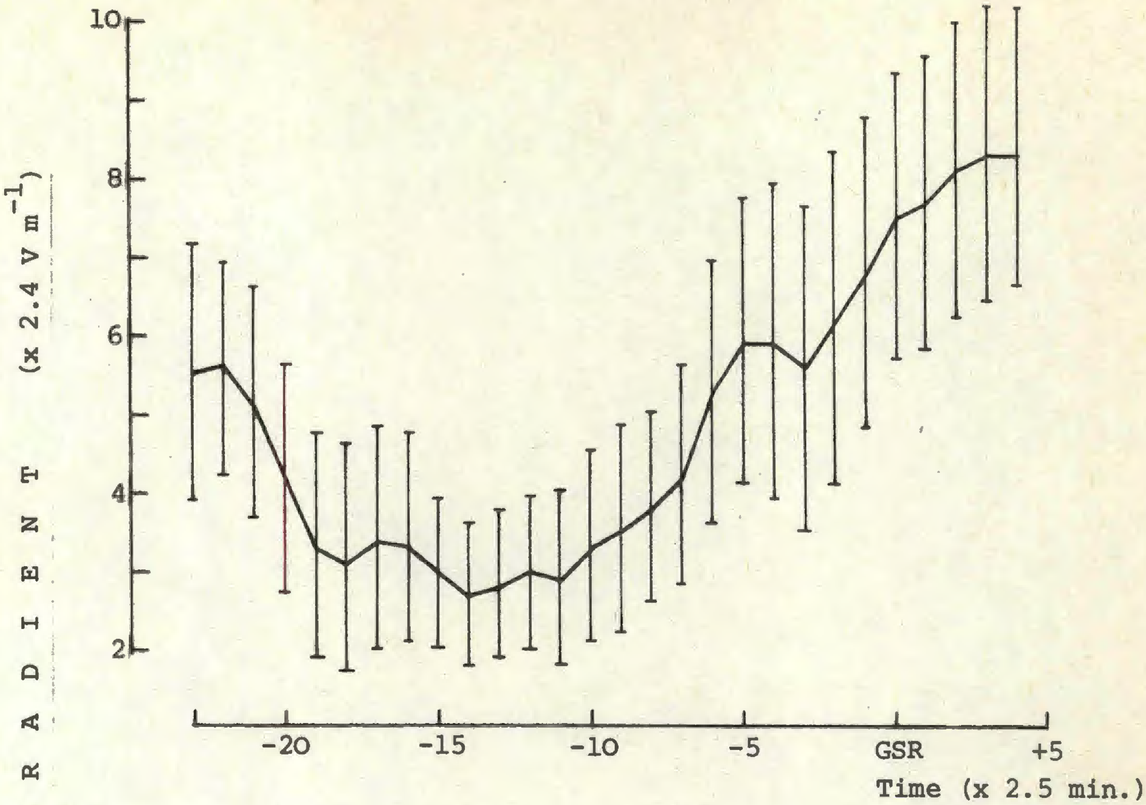
somewhat different. Here the average air temperatures during the sunrise period were about $13^{o}C$ and $11^{o}C$ respectively, compared with values of $20^{o}C$ and $18^{o}C$ for the February/March and the March/April periods. In both of the later sets of results, shown in Figures 8.9(c) and (d), the air temperature and dryness variations were similar to each other, but again showed fairly marked differences from the normal potential gradient sunrise effect. It is apparent that the normal potential gradient sunrise effect results in spite of very different behaviours of the air temperature and moisture content of the atmosphere. It is thus felt that the variations illustrated in Figure 8.9 show fairly conclusively that the sunrise effect is not the result of temperature or humidity variations in the lower atmosphere.

Effect of latitude. It has been seen that, following the work of WEBB (1968), it would be expected that the sunrise effect would be particularly noticeable within $15^{o}$ latitude of the equator. The same would be true of seasonal variations in the sunrise effect. Kloof has very nearly the same geographical coordinates as Durban, namely latitude - $29.82^{o}$, longitude $31.02^{o}$. Using the invariant coordinates due to THOMAS I.L. (1971), Kloof has a geomagnetic latitude of $-39^{o}$. This is quite a long way out of the $15^{o}$ belt given by Webb, and consequently it should be expected that the effects would be much less noticeable. The work reported by KAMRA (1969b), which did suggest a seasonal effect, was conducted at Roorkee in India (geographic coordinates, latitude $29.87^{o}$, longitude $77.98^{o}$) which has a geomagnetic latitude of about $19.5^{o}$. This is considerably nearer the $15^{o}$ belt than is the Kloof station and hence it is suggested that more noticeable effects would be expected at Roorkee.

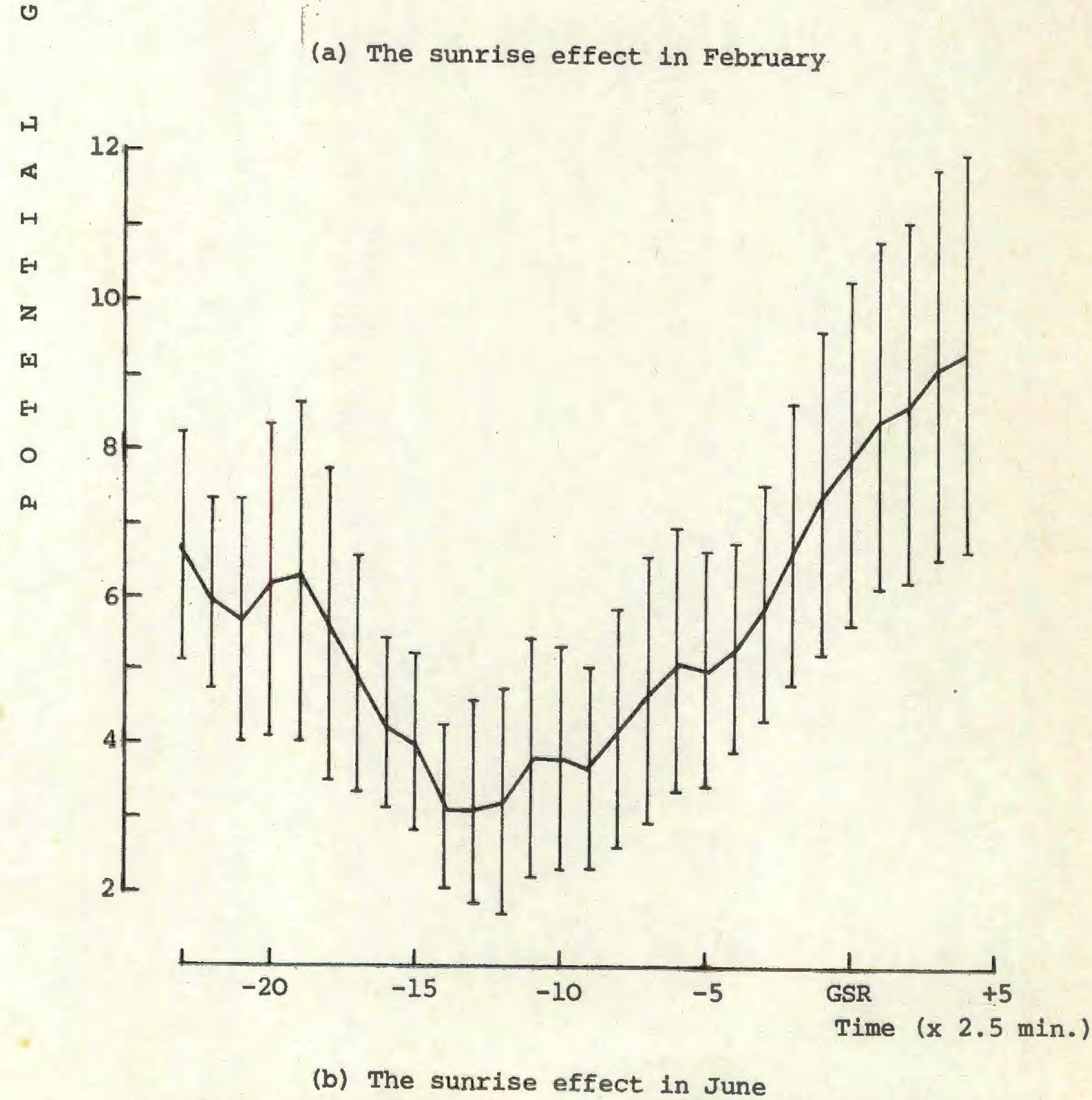
### 8.3.2.3 Summary

As a result of the experimental work described above it is clear that the sunrise effect cannot be simply explained by any lower atmosphere meteorological phenomena, such as warming of the air or increasing moisture content of the air. From the few results obtained it also does not appear likely that the electrode effect is in any way the primary source of the sunrise effect. It is suggested that the findings are consistent with the theory outlined earlier in this chapter whereby the source of the effect is in the electrosphere.

The geomagnetic latitude of the experimental site may be an important factor in determining the degree to which the effect will show variations with solar activity. It is also apparent that the value of $\Delta E$ may depend on the ambient potential gradient. In Section 8.3.2.1 the value of $\Delta E$ obtained at the inland site at Ballito Bay was 12 V $m^{-1}$. The average potential gradient at this site during the sunrise period was about 129 V $m^{-1}$, which makes $\Delta E$ 9.3% of the prevailing value of E. The inland site only has been used in this argument because of the much greater variability displayed by the beach site results, this variability clearly being caused by purely local effects. The value of $\Delta E$ over the 68 day period at Kloof was, on average, 8 V $m^{-1}$, while the average potential gradient over the sunrise period for these 68 days was about 90 V $m^{-1}$. This makes $\Delta E$ 8.9% of the prevailing field. This may be the explanation of the facts, mentioned at the beginning of this chapter (see also CHALMERS, 1967 p 168 and ISRAEL, 1973 pp 404-407) that the sunrise effect appears to decrease with increasing altitude and also that it appears to be enhanced when there is an increased number of condensation nuclei in the atmosphere. Generally as the altitude of the recording station increases, the air becomes cleaner and the prevailing potential gradient decreases. Thus the sunrise effect $\Delta E$, which will be about 10% of the prevailing E will also decrease. Similarly, when the number of condensation nuclei increases, E increases and so does $\Delta E$. If it is assumed that, during the period of sunrise, the conductivity and the total columnar resistance of the atmosphere remain fixed, then in order to produce a 10% increase in the potential gradient at the ground at sunrise, the potential of the electrosphere must increase by 10% (see equation (2.2) of Chapter Two). Obviously the increase in the




(a) The sunrise effect in February




(b) The sunrise effect in June

Figure 8.10 Mean values of the sunrise effect potential gradients showing the standard deviation.

potential of the electrosphere may be less than 10% if allowance is made for the fact that the effective lowering of the electrosphere at sunrise will change the total columnar resistance.

It is suggested that the increase of the order of 10% in the electrosphere potential, which is responsible for the effects observed before ground sunrise, also acts as the initiating mechanism for a process such as the exchange generator suggested by KASEMIR (1956). This process is then primarily responsible for producing the observed effects in the post ground-sunrise period. The initiating process, as outlined here, would then constitute a regional generator following the definition of DOLEZALEK (1972), which would differentiate it from both global scale and local generators.

Finally, it must be noted that the sunrise effect is generally a small effect. It is clearly very sensitive to local conditions in the lower atmosphere and may easily be amplified, obscured or even reversed by these local conditions, which obviously introduce a large degree of variability into the results. (The high degree of variability associated with atmospheric electric phenomena is of course well known). In spite of this variability the sunrise effect remains clearly discernible, as is illustrated in Figure 8.10. Here the smoothed average potential gradients are shown in the normal way, and for each point plotted one standard deviation is shown by a vertical line. It will be seen from Figure 8.10 that the winter results (June) exhibit the expected greater variability than do the summer months. (The values of potential gradient used to plot Figure 8.10 exclude some values which showed the possible existence of electrode effect conditions).

# Chapter Nine

## CONCLUSION

*This is the beginning of the end.*

De Tallyrand (1754-1838)
Napoleon's defeat at Borodino

The studies which have formed the subject of this thesis have resulted to some degree in an increase of our understanding of the Earth's atmosphere, particularly with regard to certain aspects of its electrical structure. Perhaps of greater importance, however, is the fact that some new ideas and theories have been put forward which require further investigations. It is in this way that the areas for future investigation are defined, and hopefully such investigations in turn may serve not only to elucidate problems, but also to redefine further problem areas.

The three chapters of this thesis which deal with the experimental investigations conducted during this work have each resulted in certain findings and in underlining certain problems. In this final chapter the findings will be summarized, chapter by chapter, and then in a similar fashion the suggestions for future investigations will be outlined.

Arising from the investigation of fair weather potential gradients, as described in Chapter Six, it was discovered that the average potential gradient at Durham, England, had apparently increased in recent years. This increase was suggested by the results obtained in the present work, which covered a rather restricted period of time, and also referred to the daytime only. However, the indications were that the increase was real (about 330 $V \cdot m^{-1}$ here compared with about half that value 5 years earlier) and it was suggested that the increase may have indicated a long term trend in the increase of atmospheric pollution.

The coastal environment investigation at Ballito Bay produced results which possibly also indicated increasing pollution. This was in an area where rapidly increasing urban development was taking place. The major finding resulting from the Kloof experiment was that, although Kloof produced an average potential gradient of much the sort of value expected of a globally representative site, the classical diurnal variation in potential gradient often associated with such a site was not reproduced here. This finding was discussed both in Chapter Six and in Chapter Seven.

Chapter Seven was concerned mainly with electric space charge in the atmosphere. It was confirmed, using a different technique from that employed by other workers, that negative charge was released into the atmosphere by melting snow and that positive charge resulted from splashing and bubbling in the surf zone of the ocean. An interesting finding here, too, was that concerning the persistence of the space charge, sometimes even under apparently good mixing conditions.

It was found that the surf was responsible for a positive charge density of several hundred pC $m^{-3}$, and that the layer of surf generated charge was from about 1 m to 4 or 5 m thick. The experiments indicated that the area of the surf was at least as important a factor as the roughness of the surf in determining the amount of charge generated. Another two (related) factors which may have had a bearing on the amount of charge entering the atmosphere were found to be the ambient potential gradient and the ambient space charge density. There were suggestions that when the space charge moved inland, the layer sometimes tended to collapse towards the ground, forming a region within a metre or so of the surface which behaved in much the same way as a conventional layer of haze of 1 to 2 km in thickness. On other occasions the surf generated charge was convected aloft, and this component should be included in any attempts made at drawing up global charge 'balance sheets'.

The most important finding in the Kloof experiment concerning space charge in the atmosphere was the apparent controlling influence of the space charge density near to the ground over the potential gradient. As a consequence it was found that although the prevailing potential gradient at Kloof was typically that of a globally representative site (in the region of 120 V $m^{-1}$), the apparently 'typical' potential gradient variation was in reality an anomalous result. Thus it was suggested that the prevailing climate might be as important a parameter as the ambient potential gradient in deciding on the global nature of a site. (The Durban region has a typical sub-tropical climate).

Chapter Eight dealt with the potential gradient sunrise effect. In this chapter it was found that the part of the effect which occurred in the pre-sunrise period could be reasonably explained in terms of a regional generator which was responsible for an increase of about 10% in the potential of the electrosphere relative to the Earth. This pre-sunrise effect was suggested as being responsible for initiating the exchange generator type of process which resulted in the continuing increase in potential gradient after sunrise. Other findings of importance here were that the effects occuring before ground sunrise were apparently unrelated to either temperature or humidity changes. Furthermore, these effects were easily obscured by large scale local effects such as wind borne space charge close to the surf, or an electrode effect layer formed at night during particularly calm conditions.

With regard to possible directions for future work in this field, it must be said at once that the possibilities are numerous. A few only will be mentioned here, namely some of those suggested by the present work. From Chapter Six emerges the ever current problem of the effects of pollution on potential gradient. While there are many techniques used which show the connection between atmospheric electricity and pollution, which have been discussed earlier in this thesis, monitoring of the potential gradient on a synoptic basis may be a most valuable aid towards determining long term trends in pollution.

Arising out of the work on atmospheric space charge is the need for more information on the relationship between diurnal potential gradient and space charge variations. It would be particularly valuable in this connection if comparisons could be made between the results obtained at recognized 'global' and 'non-global' sites. This would doubtless lead to a better understanding of whether the Whipple-Scrase diurnal potential gradient curve was a normal or an anomalous result. With regard to the surf generator, the outstanding problem is to find out more about the subsequent movement of the space charge in the atmosphere. Here it would be ideal to be able to measure potential gradients and space charge densities right in the surf zone and at several places at various distances from the shore. It would be instructive, too, if this type of experiment could be conducted in a typically polluted urban environment as well as in a clean rural atmosphere.

The sunrise effect experiment readily suggests several avenues for further exploration. Possibly most important among these would be a full-scale investigation of $\Delta E$ and $\Delta t$ over a period of at least a full year. The ideal site for such an investigation would be in a clean dry atmosphere (possibly desert conditions) close to the geomagnetic equator. Additional information which would need to be gathered would include routine meteorological data and space charge densities. The latter would have to use filtration techniques, as the double field mill technique developed in the course of this present work is insufficiently sensitive. Other important experiments would be investigations of the effects of latitude and of the solar cycle.

Finally, the point should be made that it would seem that there is increasing evidence to show that the electrical structure and behaviour of the lower atmosphere should be regarded in the context of solar activity (see the review papers by MARKSON, 1971; DOLEZALEK, 1972; KING, 1975 and WILCOX, 1975). It has often been the custom to confine the study of atmospheric electricity to phenomena occurring below the electrosphere, and to disregard events which occur outside this region. Indeed, CHALMERS (1967 p 34) defines the electrosphere as a shielding layer which separates those phenomena properly regarded as being atmospheric electricity from events occuring above about 50 km. While many useful discoveries have been made using this model, and the model still has its use for some investigations, the modern investigator should be fully aware of the limitations of the model. Particularly should he be aware of the fact that the Earth's atmosphere is not an entity divorced from the rest of space, but should rather be regarded as the most accessible region of the magnetosphere. It is certain that in future the investigation of atmospheric electricity on a global scale is going to show more and more the connection between the lower atmosphere and the more remote regions of space. Perhaps, in this connection, instead of the words of De Tallyrand quoted at the beginning of this chapter, the words used by Sir Winston Churchill (1874-1965) in a speech at the Mansion House in 1942 would have been more apposite:

> *This is not the end, it is not even the beginning of the end. But it is, perhaps, the end of the beginning.*

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