Aircraft Soundings of Potential Gradient, Space Charge and Conduction Current, and Their Relation to Precipitation

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ABSTRACT

Forty-five aircraft electrical soundings were flown to an altitude of 3 km MSL over West Plains, Mo., during the summer of 1963. Measurements were taken of the vertical electrical potential gradient and polar conductivities. Calculations were made of the electrical potential at 2.9 km plus the vertical variation of space charge and conduction current density. The potential gradient usually increased with altitude in the first 300–600 m above the surface, and then gradually decreased to the top of the sounding.

The soundings were compared with the occurrence or nonoccurrence of precipitation in the 5 hr following each sounding. The magnitude of the gradient between 2 and 3 km was found to correlate well with the presence or absence of high pressure systems in the area, but it was concluded that precipitation is not necessarily preceded by a unique large-scale set of atmospheric electrical conditions in the lower atmosphere.

1. Introduction

Evidence indicating that cloud electrification enhances the precipitation process has been accumulating from recent field studies and laboratory experiments (Moore and Vonnegut, 1960; Semonin and Plumlee, 1966). Determining the origin of cloud electrification is thus an important step in understanding the mechanics of precipitation. Of the many theories which have been proposed to explain thunderstorm electrification, all but a few have been discarded as unfeasible according to present knowledge of thunderstorm dynamics, electrification and microphysics. Of the thunderstorm charging theories now being considered, none has been conclusively shown to be the only electrification mechanism operative in all thunderstorms.

The cloud electrification theory proposed by Grenet (1947) and independently by Vonnegut (1954) relies on the convection of charge, such as fair-weather space charge, charged hydrometeors, etc., into a cloud to initiate the charging process. Other charging mechanisms may also be indirectly influenced by the magnitude of the fair-weather space charge, or more specifically, the initial electric field within a developing cloud. The mechanism proposed by Elster and Geitel (1885, 1913) and modified by Sartor (1954), as well as those suggested by Wilson (1929) and Müller-Hildebrand (1954) depend upon the polarization of the water drops or ice crystals by the initial electric field within the cloud. If one or more of these mechanisms play a role in the initiation of thunderstorm electrification, it is possible that the electrical nature of the atmosphere, i.e., the electrical conductivity and potential gradient, the amount of space charge in the air, its location, magnitude, polarity, etc., might be influential in determining whether or not a cloud becomes electrified, and/or the rate at which electrification initially proceeds. Likewise, since cloud electrification is intimately associated with the formation of rain, the electrical nature of the atmosphere may be associated with the occurrence or nonoccurrence of rainfall. It was the purpose of this research to determine if such an association exists, but it must be understood that neither the Vonnegut hypothesis nor the other charging theories necessarily suggest or require a difference in the electrical nature of the atmosphere between days with and days without precipitation.

An investigation of a possible relationship between fair-weather atmospheric electrification and precipitation began during the summer of 1963. Forty-five aircraft soundings to determine the electrical characteristics of the lower layers of the troposphere were made over south central Missouri. Measurements were made of the vertical component of the potential gradient, positive and negative ionic conductivity, altitude, temperature and humidity. The results from the soundings were compared with the occurrence or nonoccurrence of precipitation in the area during a specific period of time following the sounding. This was done to determine if the electrical nature of the atmosphere prior to rainfall is different from that prior to rainless periods.

2. Instrumentation

The aircraft used for the soundings was a C-45, twin-engine Beechcraft. Signals from the various sensors were recorded on an oscillograph. The instrumentation used for measuring the vertical potential gradient is similar to that described by Vonnegut *et al.* (1961), and uses two radioactive probes mounted symmetrically above and beneath the wing.

The positive and negative polar conductivities were measured with a Gerdien tube and vibrating-reed electrometer. The Gerdien tube and preamplifier are mounted in the nose of the aircraft, where air is ducted into the condenser through a 2.54-cm diameter tube protruding 43 cm ahead of the aircraft. Inside the aircraft, the intake tube expands to the 10-cm diameter of the Gerdien tube, and then exhausts out the side of the plane through a reverse scoop. The device alternately measures positive and negative conductivity.

Temperature and humidity measurements were made with an AMQ-7 temperature and humidity sensor using a carbon humidity element and thermistor. Unfortunately, the response time of the thermistor was too slow and the ascent and descent temperatures appeared considerably different. The rainfall data were obtained from 16 U. S. Weather Bureau recording raingages plus 21 recording gages installed by the University of Chicago for its Project Whitetop, a cloud seeding study. Fig. 1 shows the distribution of gages within the network. The center of the network is located at approximately 36°40′N, 91°40′W.

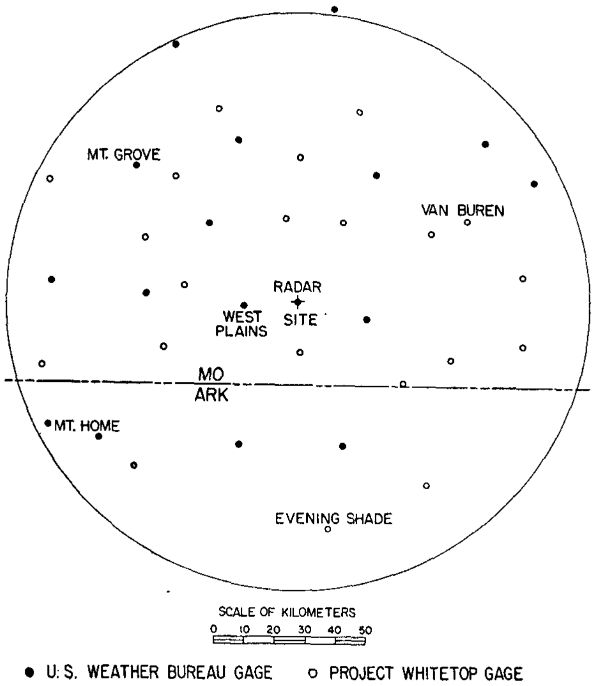

FIG. 1. University of Chicago and U. S. Weather Bureau raingages, summer 1963.

3. Operations

Forty-five flights were made during the two periods of 13–26 July and 1–14 August 1963 from the municipal airport in West Plains, Mo. The terrain in the area varies from 300–350 m MSL with rolling hills. The aircraft soundings to 3.0 km MSL were taken twice a day, when possible, at approximately 0830 and 1415 CST. The flights paths were over the raingages and usually extended southward in a straight line unless a course change was necessary to avoid clouds. Measurements were taken as the plane both ascended and descended at a rate of 150 m min^{-1}.

Few electrical measurements taken in the first 100 m or so above ground could be used in the analyses, for two reasons. First, the large clouds of dust created during takeoff on the sod runway produced a considerable temporary charge on the aircraft, and the data indicated that the potential gradient device did not completely cancel this unusually large transitory aircraft charge. Second, on the approach for landing the sounding instruments usually were turned off about 100 m above the ground as a safety precaution because the inverter heavily taxed the available aircraft power at low throttle. Measurements of potential gradient taken during ascent were compared with a few measurements taken all the way to the ground during descent. These comparisons indicated that on the ascent, above 100 or 150 m, the aircraft charge had decayed enough that it did not affect the potential gradient measurements. It was unfortunate that measurements could not be made closer to the surface for air in this layer must contribute significantly to the air convected into a cloud.

4. Data processing

The data were prepared for analysis in the following manner. The oscillograph records were converted to punch-card form with an analog-digital data reduction instrument. The cards were then processed by a computer which performed calculations, applied calibrations, and plotted the soundings on a cathode ray tube. Photographs of the plot were used for the analysis.

The total conductivity of the air was computer-calculated by adding each positive conductivity measurement to the preceding negative measurement, and vice versa. The conduction current density i [A m^{-2}] was determined at all levels from $i = F\lambda$, where F is the potential gradient [V m^{-1}] and λ the total conductivity [mho m^{-1}].

The space charge distribution was found with Poisson's relationship by differentiating the potential gradient, $\rho = -\epsilon \partial F/\partial Z$, where ρ is the space charge concentration [coulombs m^{-3}], ϵ the permittivity of the atmosphere, and Z, the height in meters. The formula is valid if the atmosphere is in a state of quasi-static equilibrium, a condition which is met throughout most of the soundings during the forenoon, but may be deviated from to a small degree within the exchange layer in the afternoon.

5. Discussion of sounding data

a. Potential gradient and conductivity

Fig. 2 shows a typical set of soundings taken on 2 August. The morning (a.m.) sounding was taken from

0820–0910 CST in clear skies with several haze levels, while that taken during the afternoon (p.m.) from 1415–1500, had less than $\frac{1}{10}$ cumulus.

In most of the a.m. soundings the potential gradient increases with altitude up to 750–1000 m MSL, while the conductivity decreases slightly or remains constant. Above this level, the potential gradient gradually decreases and the conductivity gradually increases to the top of one or more haze levels where sharper changes occur. The altitude and magnitude of the maximum potential gradient is usually greater in the afternoon than in the morning, although this was not completely the situation shown in Fig. 2. The potential gradient increases with increasing altitude up to, or within 100 m of, the cumulus cloud base, if clouds exist. It then decreases rather abruptly with increasing altitude up to the vicinity of the cloud tops, above which the decrease becomes more gradual. Most of the sounding characteristics just described are also apparent in the average a.m. and p.m. potential gradient, conductivity, and current soundings (Fig. 3). The horizontal lines in the figure indicate the range of variation of the parameters.

The West Plains potential gradient soundings are similar to soundings taken over Massachusetts, described by Vonnegut *et al.* (1957), and those taken in Illinois, described by Moore *et al.* (1962). These soundings did not show a potential gradient that decreased from the surface as did those of Schweidler (1929). Forty per cent of the soundings discussed by Imyanitov and Shifrin (1962) also had potential gradients that increased in the first kilometer or so above ground. Many of their soundings, however, had the remarkable characteristic of changing polarities above 3000 m, indicating that the conduction current appeared to change direction at that elevation.

The vertical variation of conductivity and of potential gradient can be explained, for the most part, with the

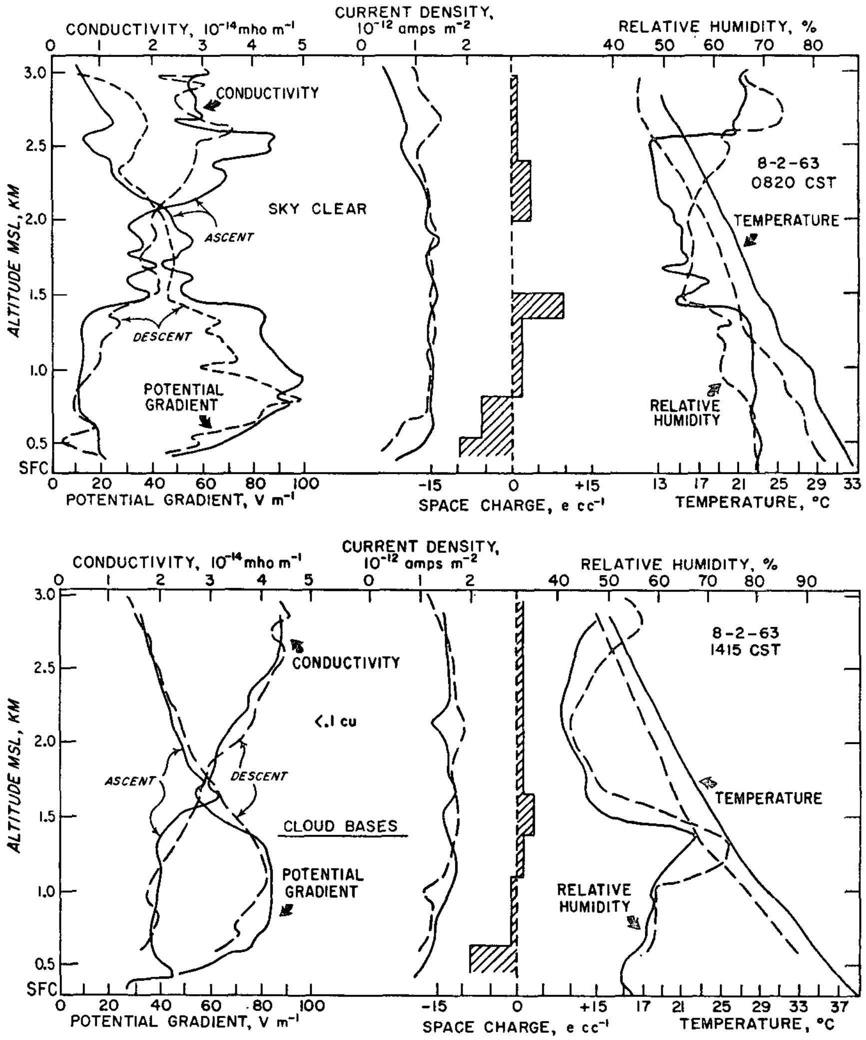

FIG. 2. Soundings of 2 August 1963, West Plains, Mo.

conventional physical model of the atmosphere. A current flowing from the ionosphere to the earth across the resistance of the atmosphere results in a potential drop, or potential gradient, throughout this region. The conductivity of the air is the result of ionization by radioactivity in the soil and air, and cosmic radiation. The conductivity is nearly constant throughout the exchange layer where thorough mixing tends to promote a homogeneous distribution of nuclei. Above the exchange layer, or cloud base altitude, the decrease in nuclei concentration is rapid. The presence of fewer nuclei for fast ions to become attached to and greater ionization from cosmic radiation at higher elevations result in an increase in conductivity and decrease in potential gradient with progressively higher altitudes.

b. *Conduction current density*

The current density soundings in Figs. 2 and 3 show the current was lowest near the top and bottom of the soundings, with random variations in between. These variations in the current density with altitude indicate that the atmosphere is not is a perfect state of quasi-static equilibrium, although the reasonably good agreement that exists between ascent and descent electrical parameters suggests that the atmosphere is not far from such a steady state.

The initial increase in the potential gradient with increasing altitude was not always accompanied by a corresponding decrease in conductivity. As a result, the conduction current density i, calculated from λ and F, sometimes increased with altitude in the first 300–600 m. The reason for this change in i near the surface on many of the soundings is not clear. It may have been the result of a convection current lifting negative space charge upward 300–600 m or more. The integration of the potential gradient curve indicates negative space charge within this layer (Fig. 2), but the physical means by which the charge might be lifted is not evident. Kraakevik (1961) discussed processes by which a convection current might be formed in the exchange layer. He suggested that the space charge may be attached to condensation nuclei which follow their own laws of diffusive separation. This increase in i with increasing altitude in the first 300–600 m in the presence of negative space charge is similar, but of opposite polarity, to the situation Kraakevik found over the ocean. His measurements showed decreases in current density with increasing altitude in the presence of a positive space charge. In his soundings over land, Kraakevik reported a higher current density and greater range of variation of i within the exchange layer up to an altitude of 2.6 km than at higher altitudes. Likewise, on many of the West Plains soundings, i decreased above 2.6 km, but this elevation is 600–900 m above the top of the p.m. exchange layer and is apparently not directly associated with it. Because the West Plains soundings were taken to only 3 km, it is not known whether the current would have stabilized at a lower value above that altitude.

Normal fair-weather space charge is usually considered to be positive. However, as mentioned above, negative space charge was usually encountered in the first kilometer or so over southern Missouri. If the Vonnegut charging mechanism were initiated by negative fair-weather space charge, the clouds would be charged with negative tops and positive bottoms. This

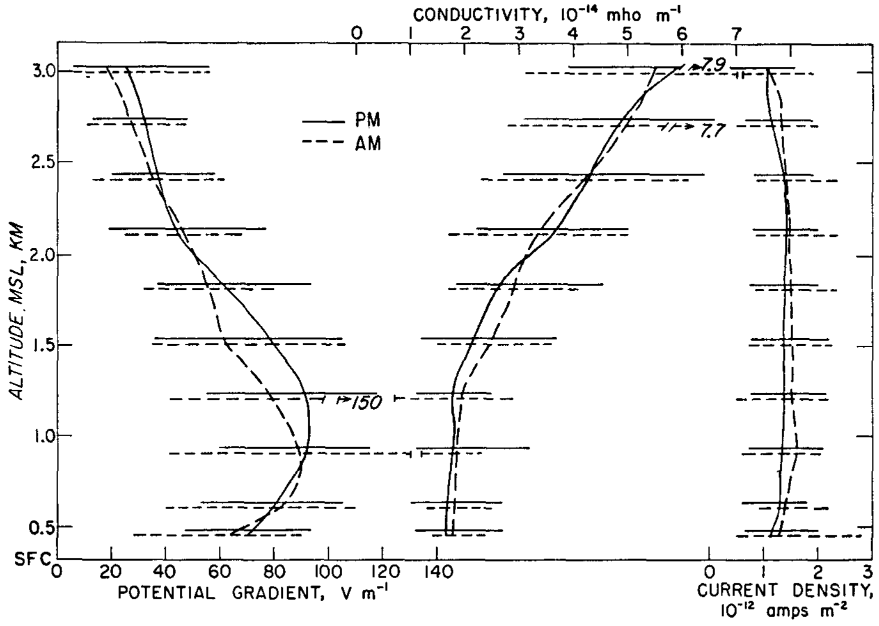

FIG. 3. Average electrical soundings for all flights with limits of variation.

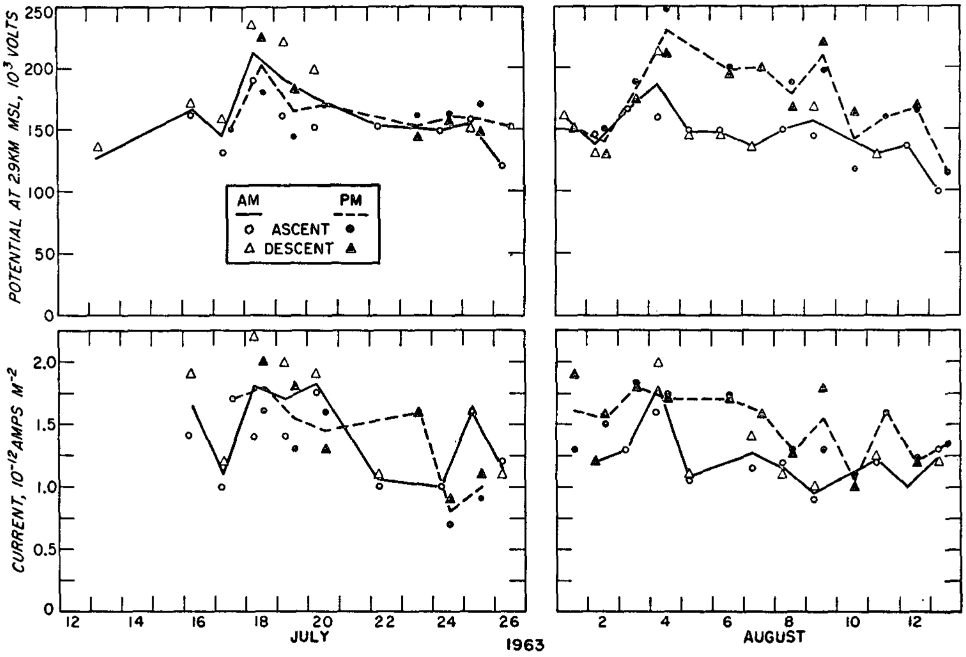

FIG. 4. Daily variation of potential at 2.9 km MSL and current density.

inverted charge distribution, while opposite to the conventional thunderstorm dipole configuration, would not hinder the Vonnegut charging mechanism, which, in theory, can operate on charge of either polarity. The scope of the project did not, however, include a census of cumulus charge configuration.

c. *Electrical potential*

The potential gradient curves were integrated to a height of 2.9 km to determine the total electrical potential at that altitude. The time variation of the potential and current density is shown in Fig. 4. There is farily good agreement between the ascent and descent values of the parameters except on 18, 19 and 20 July. On these dates a spare potential gradient transducer was being used while the original was being repaired. Apparently, the spare was not as well balanced so that differences in aircraft charge between ascent and descent may have given the descents a consistently higher potential gradient. The measurements were retained, however, because they were not in total disagreement with the other measurements.

For the July measurements the a.m. and p.m. potential values were nearly identical, but during August they differed considerably. The day-to-day variations in the potential are related to variations in the current, but it is apparent (Fig. 4) that they are not directly proportional to them, indicating the varying influence of the columnar resistance between 2.9 km and the surface. The variations in i between the a.m. and p.m. soundings that might be caused by the normal diurnal variations in the ionospheric potential are very small, amounting to less than 5%, according to Chalmers (1957).

The histogram in Fig. 5 gives the frequency distribution for potentials at 2.9 km. The potentials varied from 100×10^3–220×10^3 V with a maximum frequency from 150×10^3–160×10^3 V. Gish (1951) determined the potential of the ionosphere to be about 380×10^3 V. The West Plains soundings to 2.9 km were thus taken through about one-fourth to just less than one-half the total resistance of the atmosphere.

The p.m. potentials tend to average higher than the a.m., but most of the differences between the two potentials occurred during the August soundings, that is, the second half of the sounding period (Fig. 4). During August, the p.m. currents were often higher than the a.m. currents, thus tending to cause a higher average p.m. potential (Fig. 4). The tendency for higher p.m. currents is also apparent in Fig. 6, a histogram of the current density frequency distribution. The currents vary from 0.8×10^{-12}–2.0×10^{-12} A m^{-2} with an average near 1.4×10^{-12} A m^{-2}.

6. Comparison of rain and no-rain days

The data were examined to determine if the atmospheric electrical soundings preceding precipitation were significantly different from those soundings which were not followed by precipitation. Comparisons were made according to the general shape and magnitude of the potential gradient curves.

Data were used in this portion of the analysis only when rainfall had not occurred on the raingage network

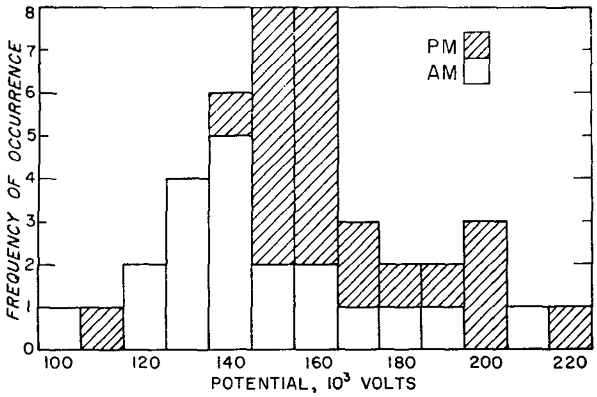

FIG. 5. Frequency histogram of potential at 2.9 km MSL.

during the 1.5–2.0 hr preceding the sounding. This was done to minimize the influence of previous storms on the soundings. Each sounding was arbitrarily chosen to be representative of the atmospheric electrical condition of the area for the 5 hr following it, i.e., from 0900–1400 for the a.m. sounding and from 1500–2000 for the p.m. sounding. Thus, only 10 hr of the daily precipitation were considered. A sounding was classified as a "pre-rain" sounding if there was rainfall on the network (Fig. 1) during the 5 hr following it, and a "no-rain" sounding if no precipitation occurred during that period.

The Vonnegut charging process could be active in convective clouds only, so it was desirable to determine if precipitation following the soundings was convective or stratified (Fig. 1). The time and areal distribution of the rainfall was therefore examined and the data strongly suggest that all of the precipitation was convective.

For the a.m. soundings, there were 16 soundings meeting the condition of no-rain in the preceding 1.5–2.0 hr. Of these 16, three were followed by rain in the next 5 hr, and 13 were not. The general characteristics of the three pre-rain soundings were similar in variability of shape and magnitude to the no-rain soundings below 2.0–2.5 km, but above these elevations, there were two categories of potential gradients. One group of 12 soundings had lower potential gradients of 12–28 V m^{-1} at 2.8 km, while the second group of 4 soundings had higher potential gradient values from 35–50 V m^{-1} at that altitude. The three pre-rain soundings fell into the first lower group of 12 soundings and were not distinguishable from the no-rain soundings in that group.

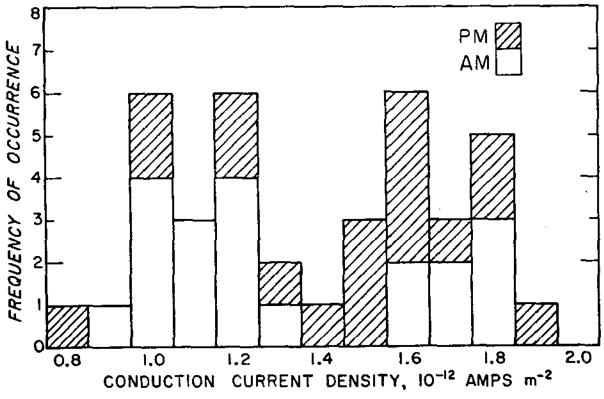

FIG. 6. Conduction current density histogram.

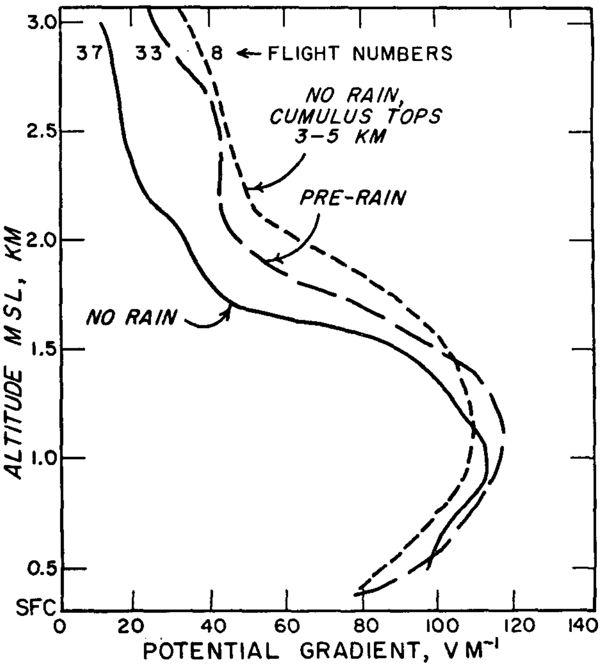

FIG. 7. Potential gradient soundings representative of no-rain, pre-rain, and no-rain with cumulus tops 3–5 km.

Sixteen p.m. soundings also met the conditions of no-rain in the last 1.5–2.0 hr, and five of these were followed by precipitation. Again, below 2.2 km, the pre-rain soundings resembled the no-rain soundings in general shape and magnitude of the potential gradient curve; but above 2.2 km all of the potential gradients of the pre-rain soundings were between 35 and 50 V m^{-1}, whereas 55% of the no-rain soundings had potential gradients between 15 and 30 V m^{-1}, or approximately half as large. The remaining 45% of the no-rain soundings had gradients of the same order of magnitude as the pre-rain soundings. According to the observer's flight notes for these five high gradient, no-rain soundings, on four of the five soundings there was evidence of vertical mixing above the usual 1.0–2.0 km of the normal cumulus clouds. Congestus clouds with tops to 3.0 km or more were within view. Fig. 7, showing three representative soundings, illustrates the similarity between the p.m. pre-rain sounding and the no-rain sounding, with mixing from 3.0–4.5 km, and shows how they both differ from the other no-rain sounding.

During the research period a series of five weather regimes occurred, but these consisted of only three different types of synoptic weather conditions. The first type was associated with east-west oriented stationary fronts lying north of the West Plains area. During the second type of weather system, the sounding region was influenced by high pressure systems. The third type of synoptic condition was associated with a post cold frontal high.

The three types of weather systems were compared with the presence of high or low potential gradients in the 2.2–3.0 km region. During the high pressure systems (the second and third types described above), the potential gradients were low during both the morning and afternoon soundings, with only one exception. These low gradients were apparently the result of subsiding or stable air associated with the high pressure system. The stable air is relatively clean, and therefore has a higher conductivity and lower potential gradient within the level considered. During periods when a stationary front was lying north of the sampling area and the 500-mb winds were light or westerly, there was a predominance of low morning gradients and high afternoon gradients, reflecting the diurnal convective injection of polluted air into the 2.2–3.0 km layer.

The afternoon pre-rain potential gradients were high because they were associated with the first type of weather system. The morning pre-rain gradients seemed to be low primarily because most of the morning soundings were low prior to convective mixing.

The data suggest that electrical conditions in the atmosphere (up to 3.0 km) during the several hours preceding precipitation do not differ substantially from those on days when precipitation does not occur. The higher gradients aloft would aid the in-cloud induction charging mechanisms, but the higher gradients are not necessary for the formation of rain. While the Vonnegut mechanism or any of the induction charging mechanisms may be operative in convective cloud charging and the promotion of precipitation, this data indicates that a specific atmospheric electrical condition is not required for the mechanism to be activated. That is, the initiation of precipitation apparently is not dependent upon a unique large-scale electrical state of the atmosphere such as a specific space charge concentration or distribution, or a particular polarity of charge within the region examined.

7. Summary

1) The potential gradient over Missouri usually increases from the surface up to about 750 m in the forenoon and about 1000 m in the afternoon. Then from these altitudes up through 3.0 km, it decreases. The conductivity is nearly constant up to about 1.2 km, or the level of the p.m. exchange layer, above which it increases. The current is somewhat variable with altitude but often increases in the first 300–600 m and decreases slightly between 2.5 and 3.0 km.

2) The fair-weather atmospheric space charge over Missouri is usually negative between 450 m (150 m above the surface) and 750–1000 m MSL, and then positive up to 3.0 km.

3) The magnitude of the potential gradient between 2 and 3 km is usually low both in the forenoon and afternoon in a high pressure system. With stationary fronts lying north of the sounding region the gradient between 2 and 3 km is usually lower in the morning and higher in the afternoon as a result of the diurnal mixing injecting pollution to the higher elevations.

4) The initiation of precipitation does not appear to be dependent upon a unique, large-scale electrical state of the atmosphere, such as a particular concentration, distribution or polarity of space charge.

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