Atmospheric Electric Field Measurements with a Sailplane in Thermal Convection

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Abstract
Measurement of atmospheric electric fields in convective plumes and small cumulus clouds suggests that convection influences the atmospheric electric field. In updraft regions outside the clouds, the electric field decreases with respect to the fair weather value and even changes polarity at lower levels in the atmosphere. In downdraft regions, the fair weather electric field increases. This effect diminishes with increasing altitude but is still noticeable near convective clouds at 7000 ft. It is speculated that thermals generally carry negative space charges from the ground into the atmosphere, which agrees with other scientists' observations of dust devils. The electric field in cumulus clouds at higher altitudes where ground effects are apparently negligible (between 7000 and 11,500 ft) follows qualitatively Ruhnke's electric cloud prediction model.

1. Introduction

Electric fields in and around convective and advective processes have been measured by several investigators. In particular, ground based and airborne instrumentation has been used to study the electric field around cumulonimbus clouds for a better understanding of thunderstorms. An understanding of the dynamic and electric mechanisms in thunderstorms is, of course, important for possible modification of lightning and charge production.

Unfortunately, the destructive forces in a thunderstorm often prohibit direct penetration by airborne carriers of scientific instrumentation. Balloon soundings, on the other hand, might provide only an incomplete picture of the cloud dynamics and the overall electric behavior, since the measurements are essentially one-dimensional.

Although speculation exists on possible electrification mechanisms by convective processes (Vonnegut, 1955), and experimental data are available on the low-level atmospheric electric field in and around advective and convective processes, little direct correlation has been sought between the dynamic mechanism of thermal motions and the electrification process.

Clear air convective electrification had been previously measured by ground stations (Freier, 1960; Crozier, 1964) when, by accident, dust devils passed close by (20 m and 450 m) and were recorded as a strongly negative field. (In this paper, positive is used for the polarity of fair weather fields.)

Bradley and Semonin (1963) made a thorough attempt to assess the electric field in a few dust whirls by flying over them in a single-engine aircraft. They were able to make only a single pass each time during several flights over the already dissipating dust whirl; however, they found strong changes in the electric field with negative space charges in the lower portions of the whirl.

Harris (1969) measured the electric field during the Harmattan dust haze in northern Nigeria and found essentially negative fields during the daytime with peak values between 0900 and 1000 LT. He attributed the electric field's reversal from essentially positive values during the night to strongly negative values during the day to convective turbulence after sunrise, but he failed to show a direct correlation between rising air currents and the distribution of the electric field.

Bradley (1968) obtained aircraft soundings of potential gradients, space charge, and conduction current in relation to precipitation. During these flights, no cloud penetration was apparently attempted. He found that the potential gradient increases essentially up to the cloud base or up to the potential condensation level, and then it decreases toward higher altitudes. Again, no direct correlation between the dynamic and electric behavior of the convective process was sought.

Because a better understanding of the electrification mechanism as a function of the convective motion in clear air, and/or a function of small cumulus cloud convection, might eventually lead to a better assessment of the electrification processes in cumulonimbus clouds, we equipped a high-performance sailplane (Rolladen-Schneider LS 1b) with an electrometer and the necessary flight instrumentation for vertical velocity measurements.

We felt that in this case a sailplane had several advantages over other airborne vehicles as carriers for scientific instrumentation. Compared with balloons and dropsondes, a sailplane can be directed in three dimensions and make discrete or continuous measurements at various points in the atmosphere.

Sailplanes, of course, are built to take advantage of the vertical air motion in thermal and cloud convection. By using a sensitive variometer and knowing the sailplane's characteristic polar curve*, we can then calculate the actual vertical up and downward air motions in and around regions of convection.

On the other hand, a powered airplane, though more manageable, has the disadvantage of being too insensitive to vertical velocities of the air and might also create its own electric field due to exhaust gases from the engine.

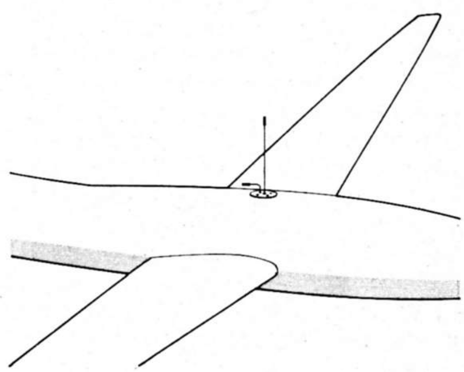
In this paper we attempt to bring about a better understanding of electrification as a function of convective processes. In particular, we describe the results of several sailplane flights in and around clear air and in and around cumulus convection. The data can be correlated to a mathematical model of the electrification process in convective conditions, whose gravitational settling of particles can be neglected.

2. Instrumentation

The electric field was determined by a lightweight electrometer which used two Ra^{226} radioactive probs of 20μ Curies. The first probe is about 25 cm above the upper surface of the glider fuselage, and the second one is close to the fuselage (Fig. 1). The second electrode is grounded to the instrument package, while the upper probe is insulated from the ground and the fiberglass fuselage. The output signal from the electrometer is a frequency of pulses in the audible range and is used for voice recording of flight data and visual observations during the flight.

Flight instruments used during these measurements were a sensitive altimeter, an airspeed indicator, and a variometer compensated for total energy, i.e., the variometer was compensated

Fig. 1. The radioactive probes of the electrometer on top the fuselage.



with a venturi to adjust for possible changes in the kinetic and/or potential energy of the glider due to «stick thermals». Therefore, only changes in total energy due to rising or descending air were indicated.
Additional instruments not actually used for the measurements, but necessary for flying in clouds, were an electric turn and bank indicator, a clock, a magnetic compass, a 4096-code transponder driven by a 12 V lightweight battery, and a 90-channel transceiver.

3. Operation

Since instrument flights had to be conducted in the controlled airspace of heavy air traffic, cooperation with the Air Traffic Control Center (ATC) was obtained. After some initial logistical problems, one instrument flight in high cumulus clouds was successful. Three others were aborted because of communication difficulties. The residual flights were conducted under visual flight rule (VFR) conditions and measured the electric field around clouds and in and around smoke and dust devils.
Under instrument flight rules (IFR), the Control Center was notified about an impending flight approximately 1 hr. before takeoff. The zero point of the electrometer was determined before or after the flight by shorting the leads of the electrometer input. Also some general data (temperature and altimeter settings) were recorded on the ground. In general, the recorder was kept running from takeoff through landing. The glider was towed around the clouds for release on top and, in case of an IFR flight, clearance was requested on the frequency assigned by ATC.

4. Results

The electrometer signals recorded during flight were transposed onto chart paper by a frequency-to-analog converter, and the flight instrument data, as recorded on the second tape track, was handwritten in the appropriate places on the electrometer curve. Results and general weather data of the individual flights are summarized below. Typical electrometer curves of flights in thermal convection in clear air or below cumulus clouds are shown in Figs. 2 and 3. Altitude readings are listed in feet above mean sea level (MSL), airspeed in kilometers per hour, and vertical velocity in meters per second. Airspeed and variometer readings are raw, uncorrected data. This is sufficient for this paper, where primarily relative trends are discussed. More precise information can be obtained if the vertical air velocity is computed from altitude and time data which are corrected for the pertinent sink rate of the sailplane as evaluated from its polar curve.

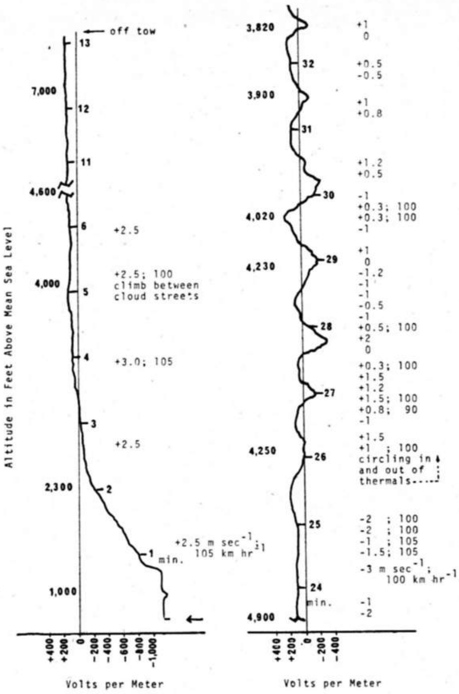


Fig. 2. Typical electrometer curve (Flight No. 1).

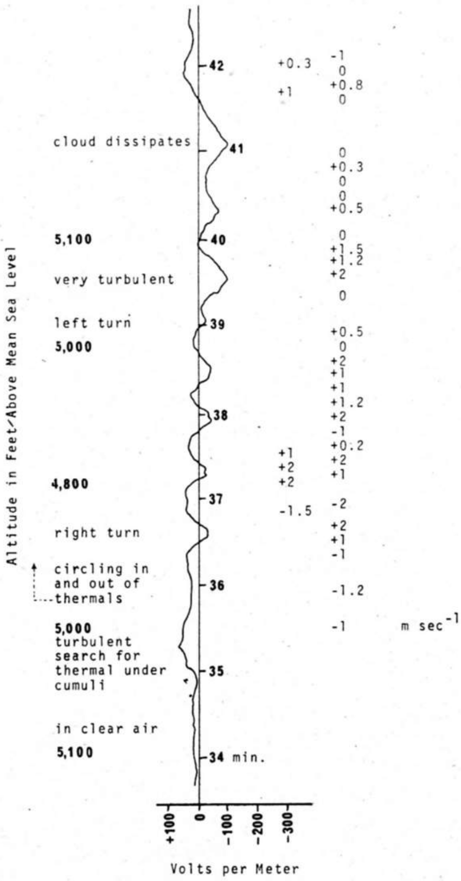


Fig. 3. Typical electrometer curve (Flight No. 4).

Since the frequency data from the electrometer hat to be transposed into voltage and electric field data, the plotted analog curves were calibrated with a frequency generator. A calibration chart of electrometer frequency versus input voltage was used to assess the actual values of the electric field from the voltage and the distance between the two electrometer probes. No corrections due to temperature fluctuations were attempted. A calibration flight (Flight No. 2) was done to assess possible charging of the glider. The resulting errors in absolute values of the electric field are estimated to be less than a factor of 2.
(a) Flight No. 1, 13 September 1971
Takeoff time: 1452 CDT. The flight was planned mainly to test the electrometer during flight. The Chicago Midway Airport sounding indicated at 1124 CDT a possible convective condensation level at around 5000 ft with a strong inversion layer at about 7000 ft. The weather on this afternoon varied between 2/10 and 6/10 of cloud cover of well developed cumulus clouds with a distant inversion layer observed at 7000 ft MSL. During the lift-off the electrometer reading dropped to strong negative values and increased gradually to the clear air value. No significant field change was observed in calm air under the claer portions of the sky. Tops of the cumulus clouds were about 7000 ft above MSL, while the bases appeared to be at around 5000 to 5500 ft MSL. The electrometer reading changed significantly when the plane flew below the clouds in thermal lift and sink areas. In particular, the electric field seemed to increase above fair weather values on the average in the sink areas before the glider entered the thermal, and to decrease when an updraft was encountered. Variations of the field during this flight were as much as ± 300 V m^{-1}.
(b) Flight No. 2, 14 September 1971
Takeoff time: 1455 CDT. The Midway soundings at 1142 CDT indicated an inversion layer between 3000 and 4000 ft. The dew point soundings led to the prognosis of a clear day. Extrapolation of the temperature curve to the ground temperature suggested that reasonable lift was to be expected only to about 3000 ft, with a measured ground temperature of 35C. Surface winds were south-southwest at an estimated 20 knots, and the sky was clear.
The main objective of this flight was to check the behavior of the electrometer in calm air above the temperature inversion during turns and speed changes. Calibration on the ground after the flight indicated an electric field of approximately 240 V m^{-1}. During the tow, the positive electric field decreased with increasing altitude in accordance with literature data on the fair weather field (Mason, 1957). The top of the inversion layer was about 5000 ft above MSL. Changes in the airspeed did not alter the reading of the electrometer in stable air; however, turns with a 45° bank did decrease the reading by about 25–30% from the fair weather value which agrees with a $\cos\alpha$ relationship (α= angle of bank). Since little thermal activity was present, it was decided to fly over some pollution sources about 3 miles from

the airfield. This decision produced the most exciting findings of this flight. A flight through thin smoke resulted in strongly positive and negative deviations from the average electrometer reading. We encountered some turbulence while in the smoke. The effect on the electrometer persisted on the way back, several miles downwind from the origin of the smoke with negative deviations predominant in the visible smoke. Back on the ground, the zero point was taken.

(c) Flieght No. 3, 21 September 1971
Takeoff time: 1555 CDT. With the ground temperature at 24C, the temperature soundings indicated that lift was to be expected up to about 6000 ft. The dew point curve suggested a clear day. The pressure on the surface at 1148 CDT was relatively high (1,004 mb). Surface wind was calm.

The flight had two objectives: (1) to check our transponder under VFR conditions, and (2) to measure, in more detail, the electric field in and around artificial sources of pollution as a function of thermal convection.

The reading of the electrometer dropped considerably during the takeoff roll and recovered during climb on tow. After release from tow at about 4700 ft MSL, we headed toward the smoke. Close to the smoke, the electrometer reading decreased considerably. While circling in areas of lift and sink within the smoke, we observed strong deviations from the average fair weather value. Analysis of the data suggests that the reading decreases generally to an extremely negative field in strong lift of the smoke and in the lower portion of the thermal, but it increases equally strongly in areas of downdraft outside the lift. Also the average reading increased very much toward the top of the thermal. Smaller variations were still observed when we circled within some daughter thermal away from the main lift in the smoke. When we turned away from the smoke, the fair weather reading was re-established quickly. (Portions of this flight are evaluated in Figures 5 and 6.)

(d) Flight No. 4, 24 September 1971
Takeoff time: 1402 CDT. The 1145 CDT soundings at Midway suggested that with a ground temperature of 21C, lift might be expected to above 6000 ft with possible cloud formation above 4000 ft. The main objective was to attempt the first IFR flight for measurement in cumulus clouds. The flight was beset by logistical problems. In particular, we had to fly where the clouds appeared. It was unfortunate that the flight had to be conducted too close to the control area of O'Hare Approach Control because the humidity of the air mass decreased and the clouds soon began to disappear from the west. As a result only a short time was available to enter

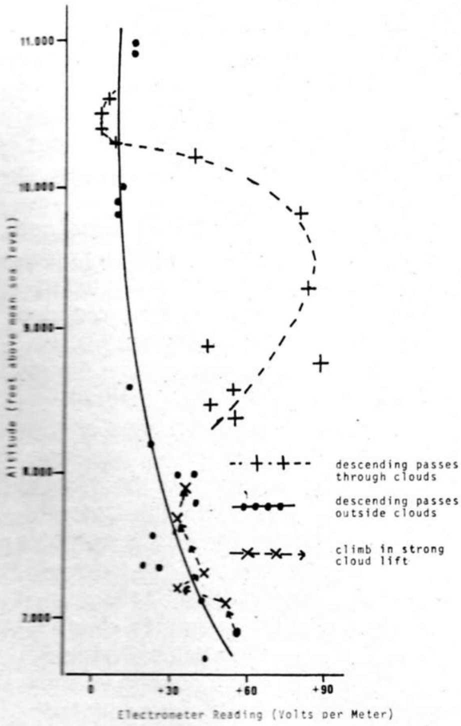


Fig. 4. The electric field in and around warm cumuli (Flight No. 5).

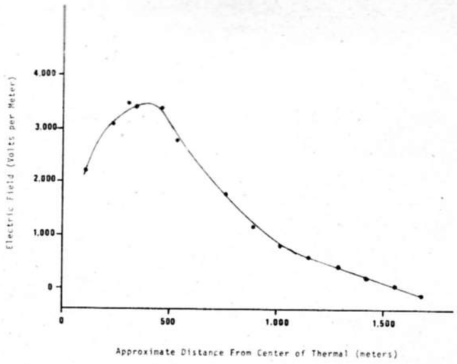


Fig. 5. Apparent radial profile of vertical electric field as a function of lateral distance from the center of the thermal between 5,500 and 5,700 ft MSL (Flight No. 3).

a dissipating cloud under IFR clearance. The rest of the flight was underneath the clouds in VFR conditions. The apparent field on the ground was about $+650\ \mathrm{V\ m^{-1}}$. Again the reading decreased to negative values during the takeoff roll and recovered to the fair weather value during tow. The cloud cover was 1/10th to 2/10th of cumuli with clouds dissipating during the flight. The tow was to about 7000 ft MSL towards a small cumulus cloud formed over some smoke.

When we approached the top of the dissipating cloud, after release, the electric field increased significantly, while it decreased when we made a pass through the cloud. Subsequently, we again observed that the electric field usually decreases in lift and increases in downdraft below the clouds.

(e) Flight No. 5, 1 october 1971
Takeoff time: 1415 CDT. The electric field on the ground was about $+120\ \mathrm{V\ m^{-1}}$ measured after the flight.

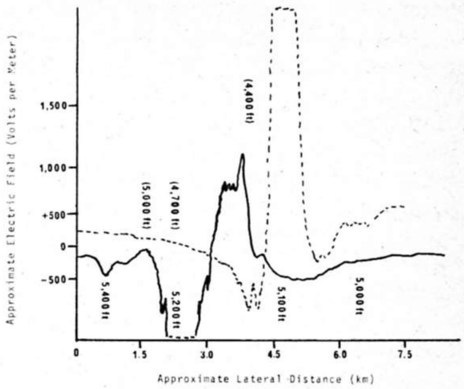


Fig. 6. Partial cross sections of the electric field through thermals associated with smoke and dust. (Obtained through straight penetrations of the thermal, Flight No. 3). Altitudes in parentheses pertain to dashed curve.

At a ground temperature of about 33C, the soundings indicated a possible lift to 10,000 ft with possible cloud development between 7000 and 10,000 ft. The cloud cover developed eventually to between 5/10th and 7/10th cumulus. The tow was to a release altitude of 11,500 ft MSL. We were able to establish excellent contact with ATC and received IFR clearance over nearby Morris airport.

The fair weather reading away from the clouds appeared to be of negligible magnitude at high altitude. Close to the clouds the electric field changed significantly. While penetrating the clouds on different headings and altitudes during slow ascent, we observed that the deviations of the vertical field from the fair weather values were less pronounced than during flights at lower altitudes below clouds an in smoke, as measured in earlier flights. Similar trends, although much weaker, were observed during this flight. When we climbed back into the clouds from the base at around 7000 ft MSL to 8000 ft MSL in strong lift, the electric field decreased only marginally and stayed relatively constant as long as the sailplane was properly centered in the lift. When we left the clouds again on a straight heading, the vertical electric field increased significantly at the cloud boundary. (This flight is evaluated in Fig. 4.)

(f) Flight No. 6, 7 october 1971
Takeoff time: 1405 CDT. The soundings at 1152 CDT indicated that strong thermals might develop if the temperature on the ground would rise above 20C. Only a slight chance existed for cloud development. It turned out, however, that cumulus clouds formed above 6000 ft.

The objective of this flight was again to measure the field in the clouds. We had problems with ATC communications, and the clouds gradually dissipated during the flight.

The electric field on the ground was about $+150\ \mathrm{V\ m^{-1}}$. The electric field changed again whenever we circled close to cloud formations. In particular, the electric field decreased significantly to negative values in lift below the clouds and increased above the clear air value in downdraft. At higher altitudes, the deviations became less pronounced. At the end of this flight, we flew over the smoke again and observed very strong deviations consistent with earlier observations.

5. Evaluation

Graphic evaluations of portions of flights No. 3 and 5 are shown in Figs. 4, 5, and 6. These two flights yielded the most interesting results, since they represent flights at opposite ends of the convective spectrum. Flight No. 3 was at relatively low altitudes on a clear day under strong thermal conditions with visible smoke and dust haze present. Flight No. 5 proceeded at much higher altitudes within and around warm cumulus clouds.

Table 1
Apparent Electric Field in the Core of a Strong Thermal as a Function of Altitude.

Altitude (ft MSL)	Electric Field* ($V\ m^{-1}$)
5,200	− 700
5,300	− 160
5,400	+ 520
5,500	+ 980
5,600	+1,200
5,700	+1,580
5,750	+1,800

* These data were evaluated during a climb in strong lift (Flight No. 3). Values of the electric field are averaged and are only approximate.

Table 1 lists the average potential gradient as a function of altitude, while the sailplane climbed in strong lift with dust and smoke particles all around (Flight No. 3). The sailplane climbed between 4,300 and 5,750 ft MSL with a maximum lift of about 2.2 m sec^{-1} (calculated as an averaged value which neglects sudden variometer fluctuations due to gust, from altimeter and time information between 4,300 and 5,100 ft MSL). At an average forward velocity of 100 km hr^{-1}, this corresponds to a vertical air velocity of about 3 m sec^{-1}. The average overall lift during this climb between 4,300 and 5,750 ft MSL was about 1.7 m sec^{-1}, or the vertical air velocity was about 2.5 m sec^{-1}. The climb in the lower portion of the thermal showed an electrometer indication of a strong negative field ($<$1000 V m^{-1}). During the climb to above 5,200 ft, the average electric field increased considerably with altitude to high positive values (see Table 1). Circling in what we thought was the center of the lift, the field changed rapidly from strongly positive deviations on one side of the circle to strongly negative values on the opposite side of the circle. This indicates that either the center of the negative charge does not quite coincide with the center of the thermal, or that we still were not within the strongest portion of the lift. Also, the rapid change in sign indicated a fast relaxation time of the electrometer-glider configuration. The fast relaxation time and the approximate $\cos\alpha$ relationship between clear air electric field and angle of bank are indications that the recorded field is not much influenced by the sailplane.

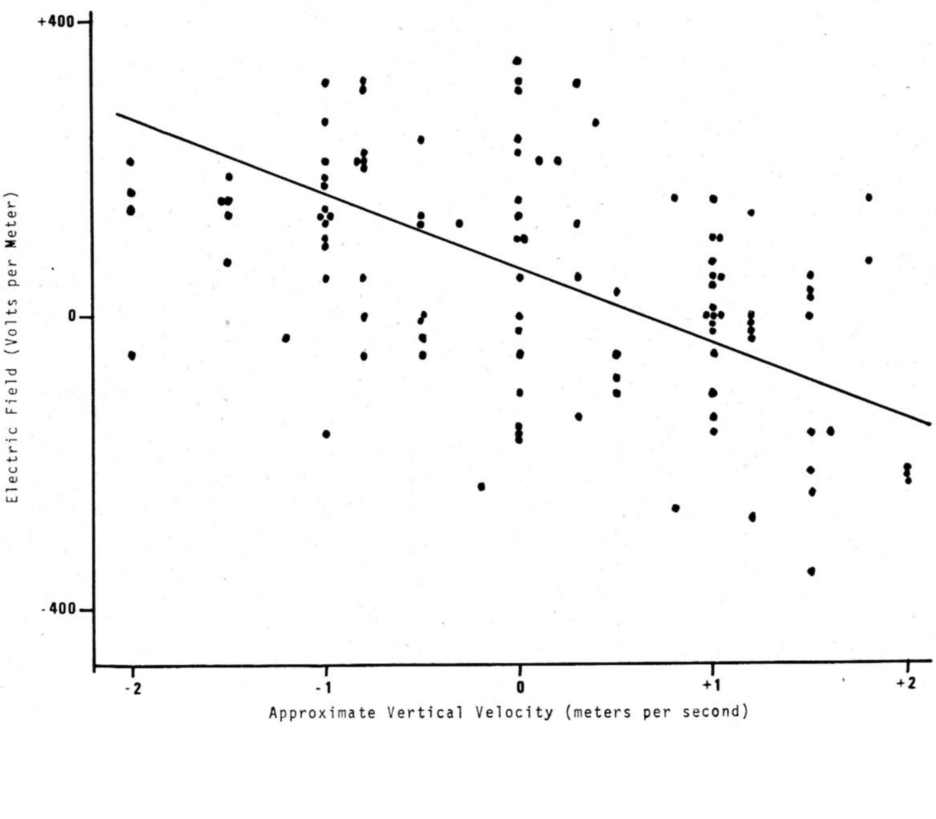
When leaving the thermal on a magnetic heading of 190°, we found an apparent radial field profile as evaluated in Fig. 5. For this figure, the core radius of the thermal is estimated as about 100 m; this was calculated from the average time it took to circle through 360° and the average airspeed of 100 km hr^{-1}. With the further assumption of a radial flight out of the thermal at 100 km hr^{-1}, we obtain the apparent radial field distribution. Fig. 5 indicates that at the outer limits of the thermal the field initially increases to higher positive values but eventually decreases to the fair weather value. Penetration of the smoke and dust on various headings resulted in cross sectional field distributions as shown in Fig. 6. The flight in the high cumulus clouds above 7000 ft indicated much smaller deviations in the electric field (Fig. 4). When entering the clouds on straight headings, we observed an altitude dependence of the field variations from the fair weather field outside the clouds. In relatively strong lift within the clouds, the overall electric field decreases only marginally, less than 50 V m^{-1}.

Finally, in Fig. 7 the first flight is evaluated in terms of the electric field as a function of the recorded indicated vertical velocity of the sailplane. Although less pronounced than during the flight through smoke and dust, the electric field on the average becomes negative where the air ascends, but it is more positive where air descends. The deviations are also less pronounced at higher altitudes.

6. Discussion

We now compare recent electric atmospheric cloud models (Ruhnke, 1970 and 1972) with our experimental results and assess the validity of such models. The models are based on the assumption that in a steady-state condition in convective clouds, the sum of convection and conduction current densities are divergence free, that air conductivity inside clouds is less than outside, and that no charge separation by microphysical processes takes place. The model predicts a lower core of negative space charge in the center of the cloud's lift area, and a positive space charge cap on top. The electric field is substantially increased within the cloud if no convection current is present. Under strong lift conditions, however, the field in the center varies less with altitude throughout the cloud. This apparently agrees with the results of flight No. 5, where we climbed in the core of a relatively strong cloud lift. The electric field remains relatively constant throughout the climb. Also the deviations from the fair weather values are of similar orders of magnitude as those deviations the model predicts (generally less than 100 V m^{-1}, see Fig. 4).

Fig. 7. Statistical distribution of the electric field as function of vertical velocity (Flight No. 1).



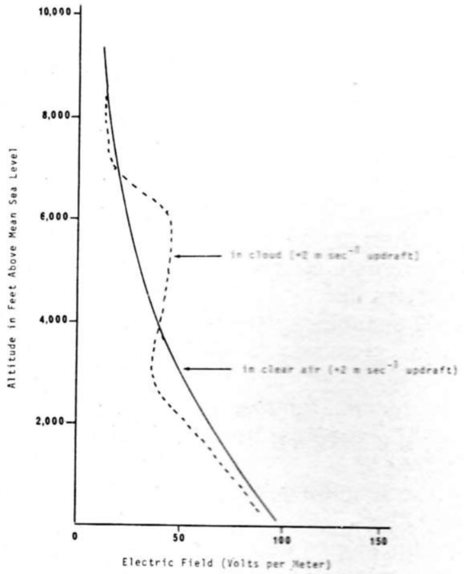


Fig. 8. Model of the electric field in clear air and cloud lift (Ruhnke, 1972).

Measurements during cross sectional passes through the clouds indicate that deviations of the electric field from the fair weather value can be positive and/or negative, apparently depending on the altitude at which we enter the clouds. For example, at high altitude, about 10,500 ft above MSL, we found slightly negative deviations ($\sim$–10 V m^{-1}) when we entered the clouds. At lower elevations, i.e., below 9,500 ft above MSL, the deviations were essentially positive. Away from the clouds, the field returned to the fair weather value. These results are quite consistent with the model. Fig. 8 shows the computed electric field for fair weather and for cloudy conditions with an assumed lift of 2 m sec^{-1}.

Although the assumed altitudes of the model are different from the altitudes actually encountered, the comparison is, nevertheless, qualitatively valid. At altitudes close to the cloud top, the deviations of the field in the clouds are slightly negative, while at lower altitudes the deviations are positive with respect to the fair weather field.

The model seems to be appropriate in clouds at higher altitudes, where the variations of the field are essentially a function of the fair weather field and the conductivity gradients. It is inadequate, however, to explain the strong deviations at lower altitudes in clear air thermals with smoke and dust devils around.

In this case, the model must be modified to allow for dust and smoke particles as charge carriers which considerably reduce the overall conductivity. The electric field values in and around convective dust plumes below 3000 ft suggest that considerable negative space charges are carried by dust and smoke to cumulus cloud altitudes. The productive mechanism for these charges remains unexplained, but frictional charging of dust during periods of ground contact seems a likely hypothesis, as Kunkel (1950) already pointed out.

The assumption that dust carries apparently negative charges aloft is verified by two separate observations: During liftoff the towplane whirls aloft a visible dust cloud which reduces the apparent electric field to strongly negative values. Of course, this build-up of charge could also be due to friction between the glider and the ground. However, a ground experiment on October 21, 1971, during a strong, gusty southerly flow showed on the average a strongly negative field, whenever the measurements were made inside dust carried aloft by the storm from a plowed field. On the other hand, the field was strongly positive when the wind was blowing over grassy areas in close lateral positions to the dust stream.

It thus seems obvious that the strong deviations in the electric field, even in fair weather conditions, are closely connected to negatively charged dust and smoke particles that are lifted from the ground by strong updrafts. Such polluted parcels of air will still have a continuously lower electrical conductivity than clear ambient air. Consequently, the negative charges in the lift area are inducing strongly positive influence charges at the top and in the surrounding sink areas.

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