Electrification in Convection (Charges as possible Tracers to Study the Structure of Thermals)

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Presented at the XVI OSTIV Congress, Châteauroux, France (1978)

Abstract
The dynamic process of thermal convection is simulated by computer. The model provides for tagging the thermals with electrically charged dust and smoke particles.
In theory, the electric charge and field distribution indicates that under steady state conditions thermals may have structure, where the charged particles distribute in well-defined patterns.
Preliminary experiments over industrial smoke plumes which are artificially tagged by electrostatic precipitators, indicate that thermal structure can be correlated to the simulation model.
It is proposed to use a feedback system between simulation and experiment to elucidate the correct structure of thermal convection.

Synopsis
Convection, thermal lift or, in short, thermals are triggered when the vertical temperature gradient is steeper than the adiabatic temperature lapse rate. It is generally assumed that thermals in their initial stage rise from the ground as low-density air bubbles due to differential heating of the ground. Subsequently, air is drawn from the surrounding as indicated by sudden gusts of wind, and eventually a vertical circulation pattern is established, where the air rises in a quasi- cylindrical column and subsides on the outside.
In the ideal case, the air rises up to the next temperature inversion, where it is deflected towards the periphery and sinks on the outside to complete the vertical cycle of airflow.
The real thermal is probably more complex. For one, thermals are not isolated events. They appear to be organized in patterns: From soaring experience we deduce that very often daughter thermals are triggered in the vicinity of the major lift: it appears as if the thermals are whipped up in waves. Secondly, thermals very often occur as vortices, where the air is rotational around a vertical axis. This is reflected in the fact that sailplanes may climb more rapidly turning in one direction rather than in the other. Based on this experience, it appears that most thermals – at least in the Northern Hemisphere – follow the Corriolis forces and turn to the left. Hence, flying turns to the right seem to facilitate the climb. Of course, the rotation of dust devils in the desert can actually be observed and generally about 75% are found to rotate to the left. Additional complications arise, if turbulent flow at boundaries interferes with the laminar flow patterns.
In order to elucidate the structure of thermals, we propose to use the fact that convection apparently sets up perturbations in the atmospheric electric field, because electrical charges are redistributed under the influence of convection dynamics.
Under normal conditions, electric charges are generated and distributed throughout the atmosphere contributing to an ever present electric field. Under conditions of clear, unperturbed air the magnitude of this field close to the ground is about 100 to 120 V/m and decreases exponentially towards higher altitudes. However, perturbations in the electric field arise, if unusual amounts of dust, ice or water particles are present. Most pronounced are these perturbations under local conditions of thunderstorms, man-induced air pollution, dust stroms, volcanic, and similar activities.
Computer simulation of the atmospheric electric field as it is perturbed by the convective process indicates well-defined patterns of the charge and field distribution. Also, since thermals over artificial air pollution sources are generally charged by electrostatic precipitators, we believe that instruments measuring electric charges and/or the electric field may be used to elucidate the three-dimensional structure of thermals, if proper correlation is found to the simulation model. This is elaborated in the following discussion.

The Model of Convective Electrification
(A) General Discussion
The atmosphere may be considered a spherical capacitor in which the electrodes are represented by the surface of the earth and the ionosphere. For all practical purposes, the surface is at a homogeneous electrical potential as is the ionosphere. There is a potential difference between the condenser plates of several hundred thousands of Volts. This results in an electric field whose vertical and horizontal components depend on a variety of parameters.
For one, natural radioactivity and radiation in the environment continuously create electric charges which modify the field. Water droplets, dust and smoke particles scavenge in part the ions, thus reducing the overall ionic mobility. Ions may recombine upon collision.
Secondly, various micromechanisms of charge creation (droplet and dust particle collision, friction, etc.) and subsequent selective separation in strong convection such as in cumulonimbus clouds will set up large areas of positive and negative charges: Local perturbations generate large areas of potential electrostatic energy. As a chonsequence, there is thunderstorm activity around the globe and around the clock. Discharge of the local fields towards the ground and towards the ionosphere contributes to a permanent global atmospheric electric field.
Whenever the magnitude of the local electric fields exceeds 10 000 V/m, point discharges and lightning will occur which will partially lead to field relaxation.
In line with our initial arguments a simplified model of thermal convection is as follows:
In the center air rises with a maximum vertical velocity component, while the horizontal wind velocity is negligible. At some altitude, say at an inversion layer of an arbitrary 5 000 m or so the air flow is deflected from the center towards the periphery of an assumed cylindrical thermal. At some radial distance, r. from the center the air flow turns downward with maximum sink velocity. At the surface another deflection of the airflow returns the air towards the center again. A steady state situation is created which eventually

leads to an ideal vertical circulation pattern.

(B) Simulation of Electrification

Ruhnke developed a cloud model (Ruhnke, 1970: 1972) which subsequently was modified by us to simulate ground-induced thermal convection (Rudloff, 1973; 1978). The following basic assumptions are an integral part of the model:

1. Steady state is assumed in the convective plume and the sum of convection and conduction current densities is divergence free. Essentially, we are assuming that we are dealing with an ideal closed-loop system.
2. In a separate subroutine we assume that dust is generated at the ground and carried into the plume. Consequently the electrical conductivity inside the lift will be reduced as compared to the outside.
3. Furthermore, we assume that charges are generated through frictional release of dust from the ground. The amount of produced charges is some function of the horizontal wind velocity close to the ground.

As a first approximation, we may assume that the vector field of air velocity behaves in some kind of undulating fashion radially from the center of the thermal column. We consider a cylindrical shape of the thermal column, where the air rises at maximum velocity in the center and descends at the periphery. We apply cylindrical coordinates and observe that a trigonometric function – such as a cosine type function – has a maximum in the center of the lift area, and a minimum at some radial distance from the center.

The main electrical parameters which enter into our considerations are, the charges and the charge distribution under "normal" clear air conditions which are interrelated with the electrical conductivites, and the electrical potential and potential gradient (i.e. the electric field). The vertical component of the electric field is inhomogeneous due to the inhomogeneous density of charges.

With change in atmospheric conditions, for example when air begins to flow in a circular vertical and/or horizontal pattern, charges will be redistributed and the local electric field will be perturbed under the established wind patterns.

In addition to the 'normal' clear air charges, conditions may arise which will add charges to the system: For example, strong winds may blow up dust from the ground which is charged through frictional release (as in dust devils or dust storms). Also, smoke over industrial stacks is artificially charged by electrostatic precipitators which release additional, charged particles. Thus, dust and smoke particles may be charged beyond the normal conditions. Certainly, charging in thunderstorms which appears to be intimately connected to icing and precipitation is another important mechanism.

The Mathematical Model

The mathematical equations pertinent to atmospheric electrification are as follows:

$$\text{div}\,(q^*v|\text{vector}| + \lambda^*E|\text{vector}|) = 0 \quad (1)$$

q is the space dependent charge concentration per unit volume, v|vector| the vector field of wind velocity: the wind velocity is essentially a trigonometric-type function where the maximum vertical velocity is to be found in the center of the thermal lift column. λ is the space dependent bipolar conductivity of air (including floating particulate matter), and E|vector| the electric field vector.

v and λ are considered independent variables, and we may apply Poisson's equation:

$$\text{div}\,(E|\text{vector}|) = q/\varepsilon \quad (2)$$

($\varepsilon = 8.859 \times 10^{**}-12$ [amp-sec/voltmeter])

The velocity distribution of v is assumed to be that of a rising column of air inside a cylinder with downdrafts on the outside necessary for a converging cycle of convectional air motion.

If we assume a noncompressible fluid, equation (1) can be modified to:

$$v|\text{vector}|^*\text{del}(q) + \lambda^*q/\varepsilon + E|\text{vector}|\,^*\text{del}(\lambda) = 0$$

Outside the cylindrical thermal lift and downdraft the electrical conductivity λ (0) is an exponential function of the altitude, h(m), as is applicable for clear air:

$$\lambda\,(0) = 10^{**}-14\ ^*\ \exp\,(2.3^*10^{**}-14^*h) \quad (4)$$

The conductivity at ground level in the center of the thermal is assumed to be less than on the outside due to dust formation with subsequent scavenging of charges:

$$\lambda = 10^{**}-16\ ^*\ f(h,r) \quad (5)$$

where f(h,r) is some reasonable function of altitude and radial distance from the center of the thermal. λ increases in some exponential fashion to the boundary value at the top and periphery of the cylinder. Essentially, equation (5) simulates the actual conditions in dust and/or smoke where charged particles of lower mobility than air molecules reduce the overall electrical conductivity of air (H. Israel, 1969).

Finally, the assumption of frictional charging is based on observations that dust storms set up a considerable electric field (W. E. Bradley and R. G. Semonin, 1963; W. P. Crozier. 1970, 1964; G. D. Freier, 1960; D. J. Harris, 1969; A. K. Kamra 1971, 1972).

In a first approximation we assume that the charge generation is proportional to the radial component of the wind velocity at ground level. In the model, for mathematical simplicity, the layer closest to the ground is considered to have a charge density proportional to the horizontal wind velocity near the ground.

In a second approximation, we consider that generation of charges is nonlinearly related to the wind velocity, i.e. charge-exponential f(v|horiz|).

Theoretical Results

From the point of view of atmospheric electricity, the change distribution is obviously influenced by various factors:

1. Under conditions of clear, unperturbed air the model computation leads to a simple exponential decrease in the vertical charge distribution. This is relatively uniform in the radial direction (Figure 1 and 2). Simulating a vertical wind pattern changes somewhat the magnitude

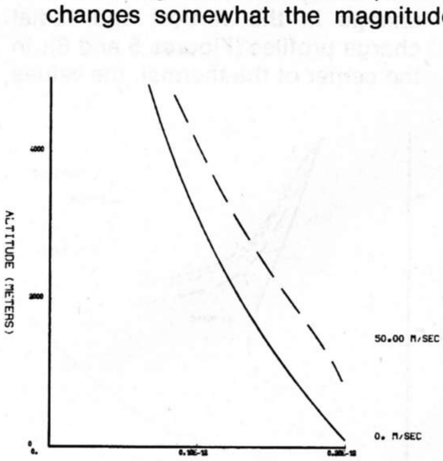

FIGURE 1
THE ELECTRIC CHARGE IN THE CENTER OF A THERMAL AS FUNCTION OF ALTITUDE
(M=51,N=21,DZ=100,DR=200,MN=1,40)
SEQUENCE OF SUBROUTINES CALLED:
AIR CHARGE WIND RELAX CHARGE
PLOTQC

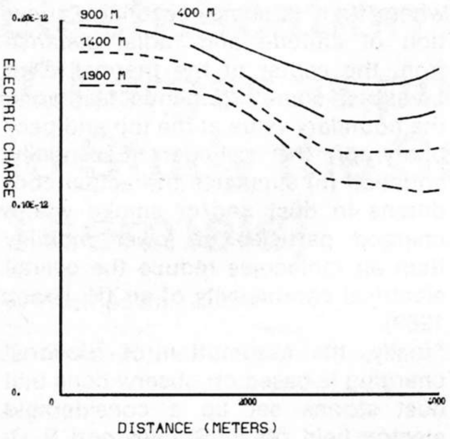

FIGURE 2
THE ELECTRIC CHARGE OF A THERMAL AS FUNCTION
OF RADIAL DISTANCE
(M=51,N=21,DZ=100,DR=200,MN=1,40)
SEQUENCE OF SUBROUTINES CALLED:
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of the charge density: It shows an overall increase. However, the curve shape stays approximately the same.

2. As we add dust to the system, the vertical charge pattern in the center and the radial distribution change. At zero wind (no lift), the vertical charge distribution increases through a maximum, and then decreases to the clear air values at the upper boundary of the thermal. Initiating a vertical wind circulation changes again the charge profile in the center. The maximum disappears and the curve shape is essentially that of a decreasing exponential function (Figures 3 and 4).
3. After we introduce frictional charging in the lowest layer of the thermal, we observe a most dramatic change in the vertical and radial charge profiles (Figures 5 and 6): In the center of the thermal, the values

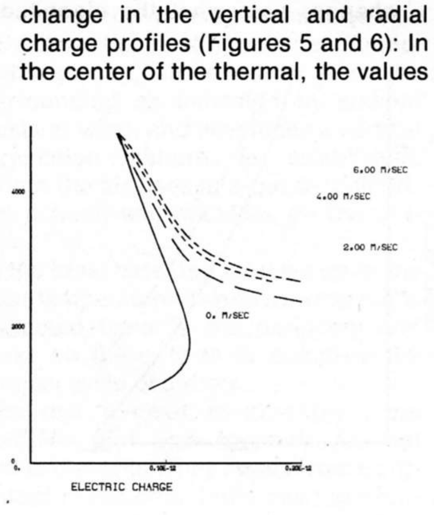

FIGURE 3
THE ELECTRIC CHARGE IN THE CENTER OF A THERMAL
AS FUNCTION OF ALTITUDE
(M=51,N=21,DZ=100,DR=200,MN=4)
SEQUENCE OF SUBROUTINES CALLED:
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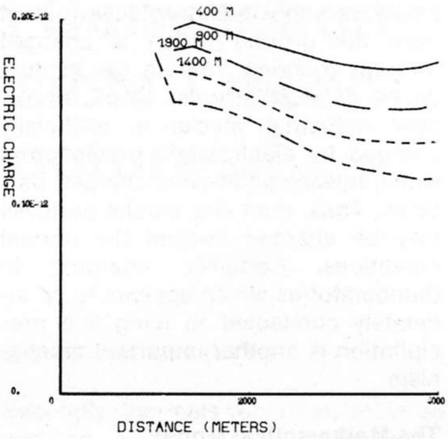

FIGURE 4
THE ELECTRIC CHARGE OF A THERMAL AS FUNCTION
OF RADIAL DISTANCE
(M=51,N=21,DZ=100,DR=200,MN=4)
SEQUENCE OF SUBROUTINES CALLED:
AIR DUST CHARGE WIND RELAX CHARGE
PLOTQC PLOTQR

decrease from already negative near the ground through a minimum, then increase with reversal of sign to maximum positive values. (Note: A priori generation of negative charges due to friction had been assumed). Towards still higher altitude, the charge distribution decreases again approaching clear air values at the top of the thermal.

Radially, some kind of wave pattern is observed, with an increase from negative values through a maximum, and again a decrease towards the periphery.

The overall charge distribution as a function of altitude and radial distance is shown in Figure 7, where lines of equal charge are drawn similar to isobars on weather charts.

In case of a linear dependence on the wind velocity, we observe a strong doughnut-shaped maximum at the periphery; while a second, less pro-

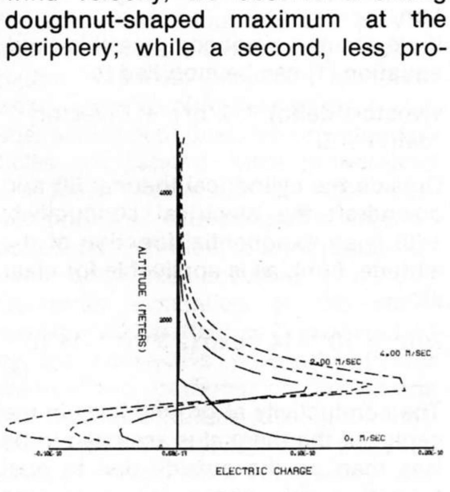

FIGURE 5
THE ELECTRIC CHARGE IN THE CENTER OF A THERMAL
AS FUNCTION OF ALTITUDE
(M=51,N=21,DZ=100,DR=200,MN=4)
SEQUENCE OF SUBROUTINES CALLED:
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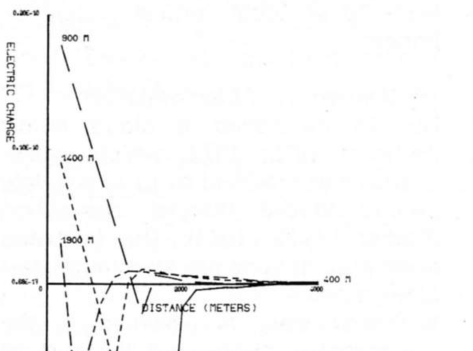
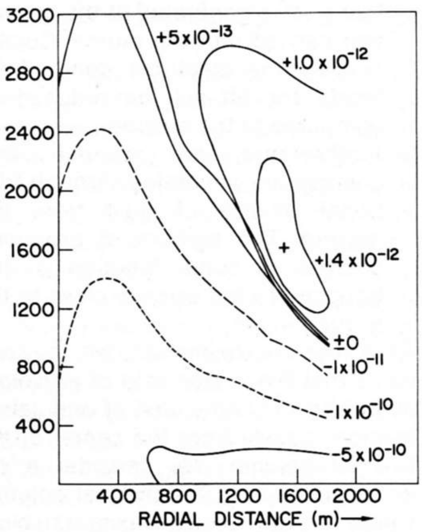


FIGURE 6
THE ELECTRIC CHARGE OF A THERMAL AS FUNCTION
OF RADIAL DISTANCE
(M=51,N=21,DZ=100,DR=200,MN=4)
SEQUENCE OF SUBROUTINES CALLED:
AIR DUST CHARGE GEN WIND RELAX CHARGE GEN PRINTE
PLOTQC PLOTQR



nounced maximum is located in the center of the thermal at around 3500 m altitude. (Note: rotational symmetry about the z-axis is assumed). As to be expected, the maximum of negative charges is located peripherally on the ground bulging upwards toward the center of the thermal. In the case of exponential velocity dependence, the charge distribution does not appear to be very different from the case of linear dependence, except that the strongest maximum of positive charge is located at some altitude in the center, while a second, smaller doughnut-shaped maximum is near the periphery on the ground, with bulging towards the center.

Similar in many respects to the charge distribution is the behaviour of the vertical extension of the atmospheric electric field.

Figure 8 represents a vertical sectional plot, where the electric field is plotted again as a function of altitude. Different curves represent different maximum vertical velocities: at 0 m/sec.

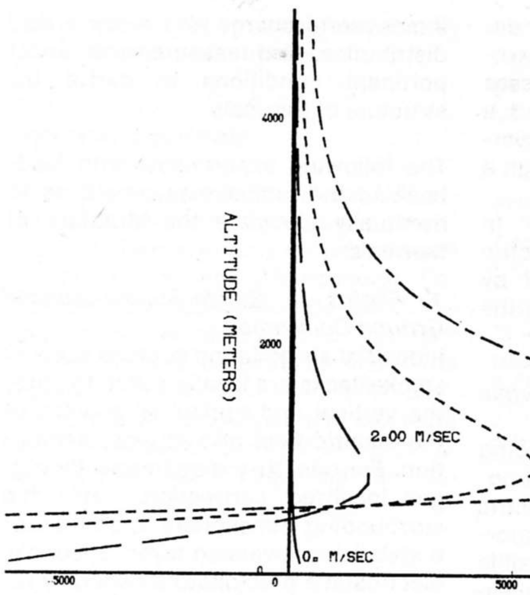


FIGURE 8
THE ELECTRIC FIELD IN THE CENTER OF A THERMAL
AS FUNCTION OF ALTITUDE
(M=51, N=21, DZ=100, DR=200, MN=4)
SEQUENCE OF SUBROUTINES CALLED:
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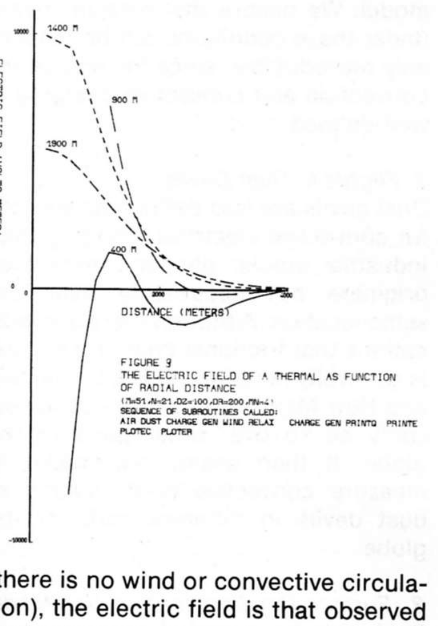


FIGURE 9
THE ELECTRIC FIELD OF A THERMAL AS FUNCTION
OF RADIAL DISTANCE
(M=51, N=21, DZ=100, DR=200, MN=4)
SEQUENCE OF SUBROUTINES CALLED:
AIR DUST CHARGE GEN WIND RELAX CHARGE GEN PRINTQ PRINTE
PLOTEC PLOTER

(there is no wind or convective circulation), the electric field is that observed under normal clear air conditions. It decreases exponentially with altitude. Increasing the simulated wind velocity from 0 to 2.4 and 6 m/sec. we obtain a drastic change in the curve: The electric field in the center of the thermal increases from strongly negative values close to the ground and reverses at some higher altitude, passing through the maximum. At still higher altitudes it decreases to the clear air values towards the boundary of our cylinder.

Horizontal cross sections at varying altitudes indicate that the field may either increase from negative or positive values through a maximum and then decrease toward the periphery of the cylindrical area reaching eventually clear air values, or, at higher altitudes may just decrease from a maximum in the center of the thermal (Figure 9).

The Model and the Actual Structure of Thermals

(A) Model Predictions of Convective Electrification and Preliminary Experiments

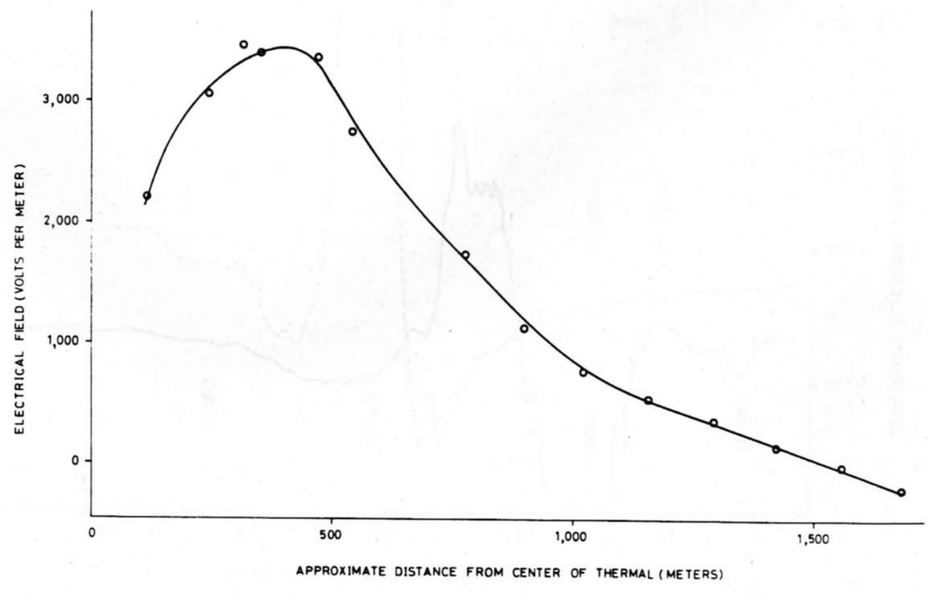
System simulation is only justifiable, if eventually correlations in the real world are found. Thus, we should use the theoretical results, try to predict the future behaviour of the real system, and finally, compare these predictions with experiments.

The most pertinent way to check our results with reality is to use an appropriate instrument platform equipped with measuring devices to determine the parameters in question: An airplane or better yet a sailplane is such an instrument platform. In particular, the latter is designed to take advantage of vertical air motions, it rides and thrives on convective currents.

1. With proper instrumentation such as a variometer compensated for total energy, one can measure directly the vertical wind component while climbing in the center of the thermal lift. Electric field probes and similar devices will be capable of determining the changes in the electric field during the ascent.

2. Flying radially outbound from the center of the thermal towards the boundary, we should find either an increase or a decrease of the field and/or charge distribution depending on the altitude of flight. At some altitude we should experience field reversal which can be rather abrupt depending on the strength of the electric field.

3. Experimental measurements close to the isoline of zero electric field should indicate a fast reversal of the field depending on the direction and altitude of flight during measurements, because the isoline is tilted upward towards the center of the thermal.

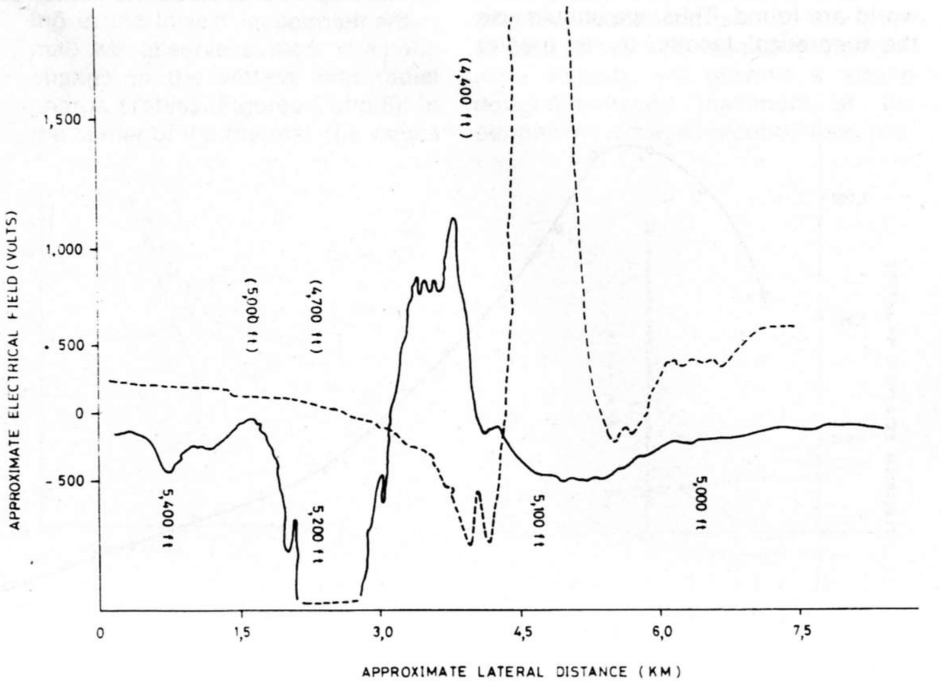


4. The maximum of charge is concentrated on the ground near the periphery where just velocity is at its maximum. This is reasonable, since our model assumes frictional production of charges of one polarity only.
5. Influence charges of opposite polarity are concentrated on top and in the surrounding sink areas of the convection.

Some time ago we obtained some preliminary results which are quite compatible with the theoretical observations. We made several flights with a high-performance sailplane over industrial smoke stacks in the United States.

It was mentioned before that smoke emanating from stacks is tagged by charged tracers due to electrostatic precipitators. In the case under investigation we found during climb in strong lift of generally more than 3 m/sec that the electric field reversed dramatically from strong negative values at lower altitudes, passed through a maximum and decreased back to values found in clear air. Also, flying outbound at an altitude of approximately 5000 feet, the field first increased and then decreased towards the areas of downdraft (Figure 10). Flying several passes through the thermal we observed a strong decrease in the field with reversal and subsequent increase through a maximum (Figure 11).

Similar conditions were found in strong dust devils, where electric charges were apparently created by frictional release of the dust from the ground.



(B) Implications to Possible Thermal Structure

We believe that better understanding of perturbations in the local atmospheric electric field and the electric charge distribution would be an important step in the assessment of possible structure of thermals. For one, excessive charging occurs during time of extreme convective processes such as experienced in cumulonimbus clouds. It appears to be intimately connected to the formation of incing and precipitation.

Dust storms and/or dust devils are generally charged too and we may use our correlations between model of the atmospheric charge and electric field distribution, and measurements under pertinent conditions to derive the structure of thermals.

The following experiments with feedback to the model may permit us to eventually elucidate the structure of thermals:

1. Flights in Single-Source-Induced Ground Convection

Industrial air pollution sources such as smokestacks are ideally suited to study the vertical and horizontal profiles of the electric field and charge distribution. For one, they may frequently trigger localized convection, while the surrounding atmosphere is still under a stabilizing inversion layer. Secondly, electrostatic precipitators generally required by air pollution legislation, will strongly charge the released smoke particles.

Once the convection is progressing, these charged particles will distribute in characteristic vertical and horizontal profiles which we hope will verify our model. We believe that measurements under these conditions will be reasonably reproducible, since the source for convection and convective charging is well-defined.

2. Flights in Dust Devils

Dust devils are less defined as sources for convective electrical charging than industrial smoke plumes, since they originate not necessarily over the same location. Although there are indications that frictional charging of dust is generally negative (at least in Illinois and New Mexico), this may not necessarily be so over other parts of the globe. It then seems reasonable to measure convective electrification of dust devils in different parts of the globe.

3. Further Development in the Model

So far we have considered a convection model which is relatively simple. We started, however, to work out the mathematical equations which take into account that thermals in general probably rotate around a central axis. Thus, the introduction of vortex simulation should result in characteristic three dimensional charge and electric field distributions which can be measured with proper instrumentation. Also, wind shear, and other than isolated thermals will be considered. Intuitively, we feel that by removing the arbitrary restriction of a singular circular pattern may prove that thermals organize in regular patterns which may verify the existence of thermal waves.

Acknowledgements

This paper was initiated at the University of Petroleum and Minerals, Dhahran. It is based in part on work begun at the Center for Atmospheric Research in Boulder, Colorado (USA). We appreciate the dedication of the staff of UPM's DPC department under the directorship of Mr. Ahmed Al-Sari. Without their competent help this work would not have come off the ground. We certainly like to thank the Administration of UPM, in general, and Dr. Herrera, Chairman of the Chemistry Department, in particular, for providing us with adequate time allowance to this research.

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