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Atmospheric Electrical Detection of Organized Convection

Airplane measurements of the vertical electric field have been used to infer atmospheric convection patterns.

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In the course of an airborne atmospheric electrical investigation over the eastern United States and the Bahamas, data were obtained suggesting that convective patterns were being detected. In this article I describe how the electric field measurements obtained during this study have been used to infer structural features of the earth's atmospheric boundary layer. This region, also called the "exchange layer" or the mixed layer, generally corresponds to the lower 1 or 2 kilometers of the atmosphere and is characterized by instability and overturning of the air mass.

The atmosphere near the ocean under convective windy conditions is organized into parallel horizontal rows of adjacent helical tubes lying on the sea surface. They are approximately aligned with the wind and extend to the top of the exchange layer (*1, 2*). Figure 1, adapted from Fleagle (*1*), depicts this structure. The study of these orderly mesoscale circulation patterns has been one of the major efforts during the BOMEX and GATE programs (*3*). In these extensive field experiments, arrays of ships and planes have been used to make concentrated measurements of the heat and moisture carried by the atmosphere from the sea into the air. Such convection measurements are of fundamental importance because the interactions between the ocean and the atmosphere have profound effects on the global weather patterns.

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Vertical air motions have been measured from aircraft with the use of inertial platforms and gust probes (*4*). Such instrumentation is complex and requires the use of large multiengine aircraft. In contrast, the instrumentation for the measurement of electric fields is cheap, lightweight, and small, and so a single-engine airplane can be used as the instrumentation platform (*5*).

Instrumentation on stationary platforms bound to the earth have inherent limitations for tracing air motions. Wind flow must carry the structural pattern of the wind field past the sensors. This is a relatively slow process and undesirable because the structure is changing in time and space. In addition, only the component parallel to the wind can be sampled—and only at the height of the sensor. With an airplane platform relatively rapid measurements can be made crosswind, parallel to the wind, or in any direction and at any height within the range of the aircraft.

The potential gradient [the potential gradient is numerically equivalent to the electric field but has the opposite sign (*6*)], which is determined by the distribution and amount of space charge in the atmosphere, can be measured from such an aircraft with an electrometer and two radioactive probe antennas (*5, 7*). In order to avoid measuring the electric field resulting from charge on the airframe, the probes were positioned in the same equipotential surface arising from aircraft charge and a differential solid-state electrometer was utilized to measure the voltage difference between them. The probes were positioned about 30 centimeters above and below the left wing tip.

Horizontal variations in the vertical electric field, measured in close proximity to the sea surface and above the top of the exchange layer over both land and ocean, seemed to indicate that convective patterns prevailed within the exchange layer. This particular convection pattern is of "cloud scale" (1 to 10 km) dimensions. Such a horizontal periodic organization of atmospheric space charge near the sea surface and in the vicinity of the top of the boundary layer probably results from variations in the air circulation patterns within the exchange region.

Related Past Measurements

It has long been recognized that the redistribution of space charge by convection causes many atmospheric electrical effects (*8*), and atmospheric electrical methods have been used to study meteorological phenomena. The magnitude of the eddy diffusion coefficient near the sea surface has been calculated from simultaneous measurements of space charge density and electric field (*9, 10*). This parameter is a measure of the ability of small air circulations to carry some property of the air, for example, moisture, from a region where its concentration is high to one where its concentration is low. Artificially produced unipolar space charge has been used to trace air transported by convection from close to the earth into fair-weather cumulus clouds (*11*). Large fluctuations and periodicities in electric field intensity have been noted in records obtained on land and sea, leading investigators to conclude that these effects were due to the drift of charged air parcels and turbulence (*12*). There has been at least one report on detection of well-defined horizontal electric field periodicities from a small aircraft flying within the exchange layer over land (*13*); however, in other reports on measurements of atmospheric electric parameters

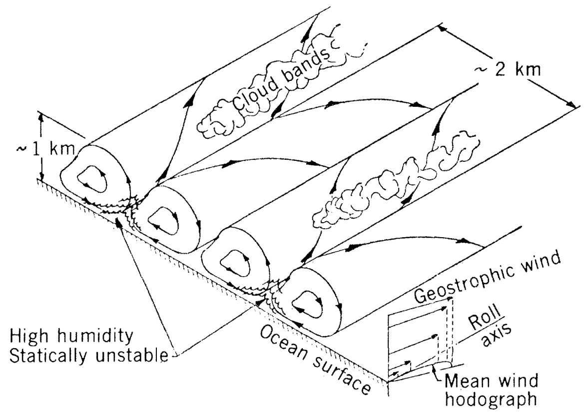


Fig. 1. Idealized flow in the maritime planetary boundary layer when roll vortices are present [from Fleagle (*1*)]. Cloud streets may form over regions of ascending air at every other interface between adjacent rolls. The layer of relatively moist air near the sea surface converges toward these regions and rises there in the ascending air flow; such regions were identified by periodic increases in humidity as the airplane crossed rising plumes near the sea surface (see Fig. 10).

made by an airplane within the exchange layer over the ocean, such observations are not mentioned (*14*). At altitudes above the exchange layer such periodicities have not been reported (*15*). With the use of a small airplane, however, which could fly down to the wave tops (following ocean swells, if necessary, to maintain a constant distance from the ocean) and obtain continuous straight-line measurements at any altitude within the aircraft's height range, variations of electric field intensity could be used to infer air motions within the exchange region.

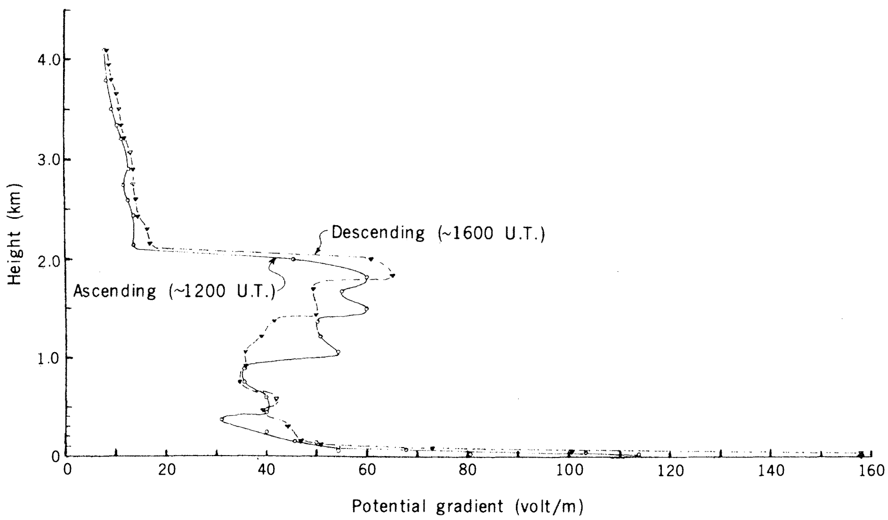


Fig. 2. Potential gradient soundings over the ocean (13 July 1971, 40 km south of Nantucket) depicting positive space charge layers close to the water and at the inversion.

Space Charge Layers

In a turbulent atmosphere there is generally little space charge from natural causes; more than 1 elementary charge per cubic centimeter (e/cm^3) was seldom encountered over land during the day (*16*). However, there are two source regions of space charge that could be utilized to establish the electric field variations associated with the measurements reported here. Close to the sea there is a layer of positive space charge which occurs because of (i) the breaking of bubbles (*17*) and (ii) the electrode effect (*6*, p. 42; *18*). At the top of the exchange layer [the top of this volume is frequently marked by a temperature inversion (*19*)] a positive space charge layer exists because of the discontinuity in conductivity between the air

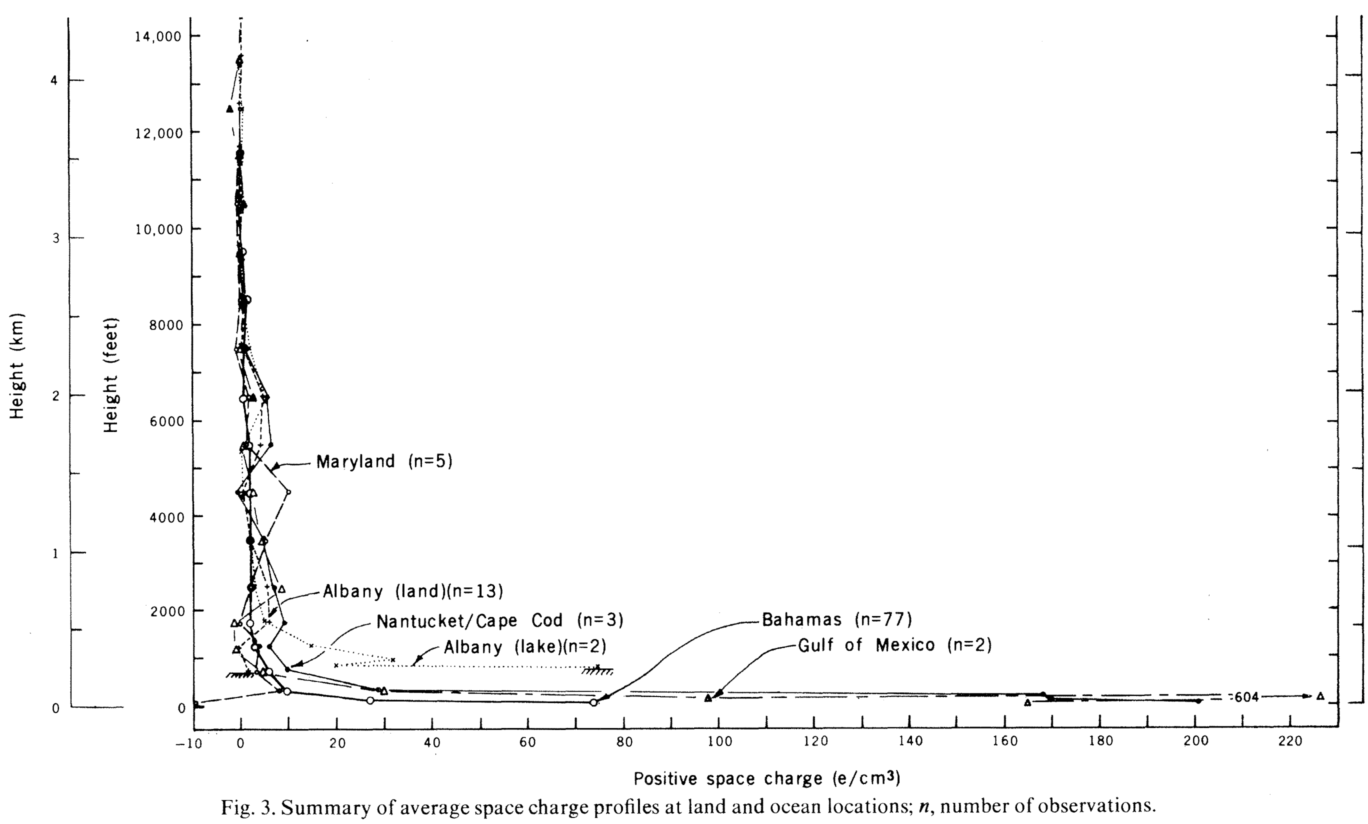


Fig. 3. Summary of average space charge profiles at land and ocean locations; *n*, number of observations.

masses above and below the inversion in the presence of the air-earth conduction current (*16*).

Examples of such space charge layers are seen in Fig. 2, a maritime potential gradient sounding obtained near Nantucket when thick haze was present below a strong inversion. Poisson's equation can be used to calculate the space charge density in a horizontal air layer from the variation in the vertical potential gradient with height (*6*, p. 24; *20*). Calculations based on this equation indicate that the average charge density was $+45$ e/cm^3 in the lowest 100 meters over the ocean and was $+15$ e/cm^3 in an air layer 160 m thick at the inversion level. By comparison, the average charge density within the exchange layer (between 100 m and 2 km) was -0.3 e/cm^3, whereas above the inversion (from 2 to 4 km) the average charge density was $+0.2$ e/cm^3. The value near the ocean is representative of many measurements that I have made, and the value at the inversion is typical of conditions at a sharp inversion with thick haze in the exchange region (*21*).

Figure 3 is a linear plot of a comparison of the variation of space charge with height over land and sea as computed from potential gradient soundings during this research program. Over the ocean and a large lake a positive space charge layer was almost always recorded in the lowest 150 m of the atmosphere. Over land an accumulation of positive space charge can be seen near the inversion level when haze is present in the exchange region. The distribution of space charge obtained over Maryland under such conditions, seen in Fig. 3 as an accumulation of positive space charge near the top of the exchange layer, illustrates this effect.

In Fig. 4, a semilogarithmic plot, the Bahamas data are stratified according to the presence or absence of whitecaps. The mean charge density in the height range from 5 to 15 m was $+129$ e/cm^3 for the calm days as compared with $+64$ e/cm^3 for the days with whitecaps. These data support the idea that space charge near the sea is due primarily to the electrode effect (*22*).

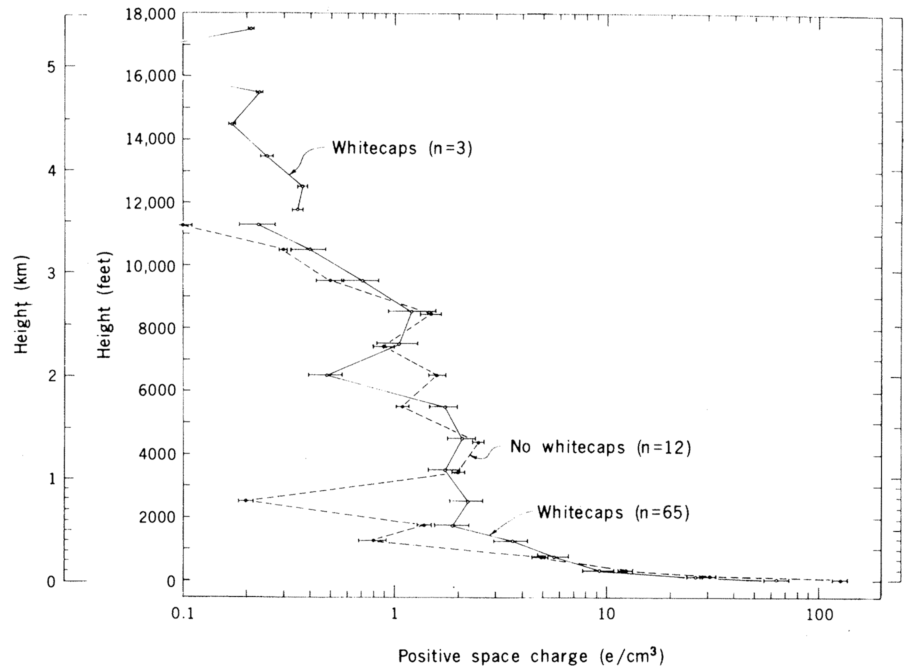


Fig. 4. Summary of average space charge profiles for all soundings off the Bahamas separated according to the presence or absence of whitecaps; the error bar represents 1 standard deviation.

Electrical Structure near the Sea

Figure 5 is a record of the vertical potential gradient as the aircraft made a sequence of passes at constant height (at 5, 46, and 150 m) over the ocean east of Eleuthera Island in the Bahamas on 19 December 1971. The surface wind was east-northeast at 10 to 20 m/sec (estimated). The sea was very rough with waves approximately 6 m high riding on large swells, and there were many whitecaps and much sea spray. These passes were made under broken clouds arranged in cloud streets with bases at about 800 m. With the plane at a height of 5 m flying parallel to the wind, the trace shows more randomness than when flying crosswind. Parallel to the wind the average spacing between periodic maxima is 3.3 km; crosswind the average spacing is 2.0 km. The average potential gradient at a height of 5 m is 177 volts per meter.

With the aircraft at 46 m flying parallel to the wind, peaks in the potential gradient are seen, but the periodicity is not clearly defined. The corresponding crosswind data indicate an average spacing between maxima of 2.3 km. The average electric field intensity at 46 m is 157 volt/m, which corresponds to an average space charge density of $+27$ e/cm^3 in the air layer from 5 to 46 m.

The parallel and crosswind measurements at 150 m show no obvious periodicities, although statistical techniques might bring them out. The average field intensity at this level is 136 volt/m, and thus the average space charge density in the region from 46 to 150 m is $+11$ e/cm^3.

A sounding of the potential gradient obtained at about the time and place where the data of Fig. 5 were obtained is presented in Fig. 6. Plotted points represent values at the indicated heights. When

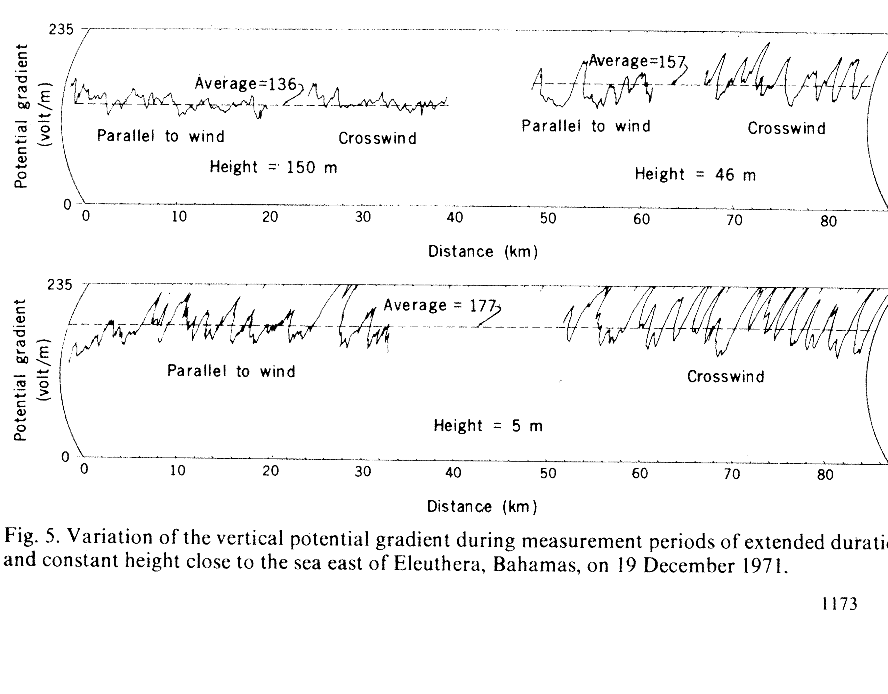
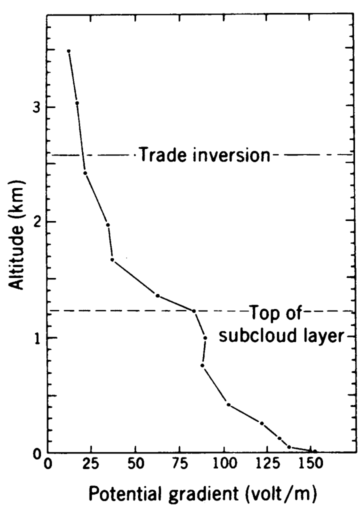


Fig. 5. Variation of the vertical potential gradient during measurement periods of extended duration and constant height close to the sea east of Eleuthera, Bahamas, on 19 December 1971.

discontinuities in the slope of the sounding line occur, values are given at such points (for example, 1.2 km). The discontinuity in the slope of the potential gradient at 1.2 km corresponds to the top of the "subcloud layer," a homogeneously mixed region in such a maritime tropical atmosphere (*23*). The position of the "trade inversion," placed at 2.6 km, was determined by a strong temperature inversion at this height. The lack of a discontinuity in the potential gradient sounding at this level, the normal condition at an inversion, is attributed to clean air in the "cloud layer" between the top of the subcloud layer and the trade inversion. Disparities between values of the potential gradient at comparable altitudes in Figs. 5 and 6 are due to the appreciable spatial and temporal variations that exist in such a regime.



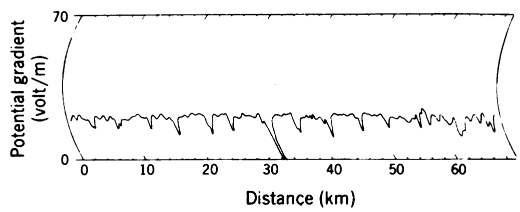


Fig. 6 (left). Potential gradient profile at about the time and place where the data in Fig. 5 were obtained. Fig. 7 (above). Variation of the vertical potential gradient at constant altitude above an inversion over Salisbury, Maryland, on 13 December 1971.

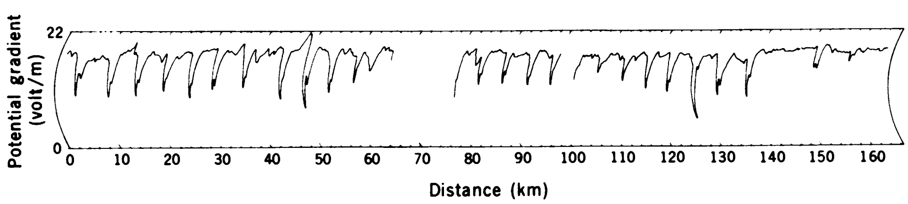


Fig. 8. Variation of the vertical potential gradient at constant altitude above the trade wind inversion crossing the Gulf Stream on 14 December 1971.

Fig. 9. Cloud streets along the east coast of Eleuthera, Bahamas, suggesting the convection pattern in the subcloud layer.

Electrical Structure near the Inversion

Cloud scale periodicity in the electrical records has also been observed in another discrete atmospheric region—near the top of the exchange layer. Periodic decreases in the intensity of the vertical electric field were recorded when the aircraft was flying above the inversion over land and sea.

The land data, shown in Fig. 7, were obtained near Salisbury, Maryland, on 13 December 1971. The aircraft was flying south at an altitude of 2.6 km in clear air about 100 m above a thick layer of haze with a sharply delineated upper boundary marking the inversion level. No clouds were present above or below the inversion, and no structure was visible in the region of haze. The spacing between the periodic decreases averaged 4.8 km. It may be significant that at the time of this measurement the aircraft was crossing under a low and strong west-to-east jet stream.

The sea data, shown in Fig. 8, were obtained on 14 December 1971 at an altitude of 3.4 km while the aircraft was flying over the Gulf Stream from Miami across Bimini and on eastward over the northern tip of Andros Island. The periodic decreases seen in Fig. 8 are about 5 km apart. Towering cumulus clouds covered 2/10 of the sky with their bases near 1 km and their tops at about 3 km. They were not aligned in cloud streets as viewed from the aircraft, although such patterns might have been evident if viewed from higher altitudes. The top of the exchange layer, as inferred by the characteristic decrease in potential gradient with height passing through the inversion, was at about 2.5 km. There was some haze below the inversion. The surface wind was east at 7 m/sec, and the wind at the flight level was light. The surface air temperature was 26°C, and there were whitecaps. An interesting feature of this record is the W-shaped notch near the minima in most of the periodic decreases.

On 14 March 1972 an attempt was made to replicate these measurements over the same flight path. The Gulf Stream was repeatedly traversed over a height range from 5 m to 3.4 km, but no periodicity was observed in the electrical record, even though 3/10 of the sky had cumulus clouds and some were arranged in isolated cloud streets. There were no whitecaps, the surface air temperature was 20°C, and the wind was light.

Discussion

These data imply that, given a sufficiently large vertical gradient of space charge density in the exchange layer, organized convection can be detected from aircraft with electric field instrumentation. The mechanism probably involves the redistribution of naturally occurring atmospheric space charge by convective circulation patterns.

Periodicities in crosswind records of the potential gradient measured close to the sea and near the top of the exchange layer can be explained in terms of the atmospheric circulation model of parallel horizontal roll vortices filling the exchange layer (*1, 2, 19, 24*), as illustrated in Fig. 1. In this model, adjacent roll vortices, aligned approximately with the wind, rotate in opposite directions. Thus, successive vertical interfaces between adjoining tubular cells are regions of alternately ascending and descending air. Horizontal convergence of air near the sea would carry space charge to the regions of ascent. As the aircraft crosses these interfaces at low altitude, the increased positive charge overhead is sensed as an anomalous rise in fair-weather potential gradient. The 2-km spacing between maxima in the crosswind runs seen in Fig. 5 implies a 1-km spacing between rolls in accordance with this model.

Peaks in the potential gradient record parallel to the wind also were observed, but they were less well defined and of different spacing than in the crosswind data. Cloud street pictures, which have been used to study organized convection, depict parallel rows of clouds. Spaced along the rows, the clouds resemble pearls on a string (*1, 2, 24, 25*). The cloud rows correspond to the rising air interfaces between roll vortices. Cloud periodicities along the rows indicate that regions of maximum vertical wind velocity are periodically spaced along the rows. Figure 9 is a photograph of cloud streets taken during the measuring program along the coast of Eleuthera. The ocean waves run crosswind, and the cloud rows are parallel to the wind. Under such conditions, periodically spaced regions of rising air would be encountered on a flight parallel to the wind or crosswind. Periodicity would also be expected if the convective pattern was arranged in polygonal Bénard cells, as discussed by Woodcock and Wyman (*26*). It is not understood why the measurement made parallel to the wind at a height of 5 m depicts more fine structure than the corresponding crosswind data (Fig. 5); this implies more randomness in vertical air motion along the wind by comparison with crosswind. Analysis of the BOMEX data gives the same result—less variance in the crosswind component than in the alongwind component (*27*).

In measurements near the ocean surface, periodicity in the electric field records could be observed only below 150 m and was most pronounced closest to the water.

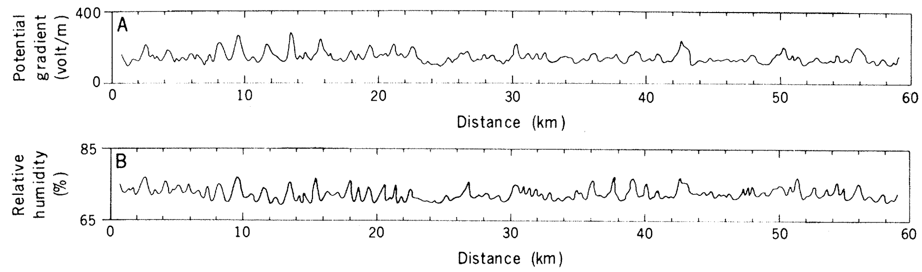


Fig. 10. Simultaneous records of the vertical potential gradient (A) and relative humidity (B) showing correlation. Data were obtained at an altitude of 16 m over the ocean off Eleuthera.

This does not mean that space charge plumes do not rise to higher levels, only that the signal became too small above that altitude. Several factors contribute to this effect: (i) loss of charge because of atmospheric conductivity; (ii) dilution of charge in the plume by entrainment of surrounding air; and (iii) reduction in the potential gradient that would occur as altitude increases going up a plume of space charge from the ocean until the electrical center is reached; that is, at the "electrical center of gravity" of a cloud of space charge the electric field intensity due to this charge is zero.

The spacing between rolls inferred from the potential gradient records near the ocean, about 1 km or a little more, is the same as that inferred from measurements of the vertical wind velocities from inertial platform instrumentation on aircraft in the lower portion of the atmosphere during the BOMEX program (*1, 27*). This indicates that both techniques have comparable sensitivities and that they record similar convective patterns near the sea surface. Since the top of the "subcloud layer" (in this case the mixed layer) during the atmospheric electrical observations (Figs. 5 and 6) was at 1.2 km, the horizontal roll spacing is what would be expected from the model of near circular roll vortices filling this region.

Because the vertical potential gradient measurements could only be used to infer organized convection (they were not recording air motion directly), I decided to make simultaneous measurements of the relative humidity and potential gradient close to the sea in order to determine if my interpretation of the electric field periodicities were correct. The moisture concentration is a discrete property of the local air mass, whereas potential gradient is caused by space charge remote from the measuring location. Figure 10 is a record obtained in February 1972 off Eleuthera where the data in Fig. 5 were taken. The aircraft flew at a height of 16 m since humidity fluctuations were more pronounced at this level than lower. Figure 10A depicts vertical potential gradient; Fig. 10B records relative humidity. High correlation exists between these parameters. The periodicity commonly observed in December was less evident in February, presumably because the atmosphere was more stable in the latter period. Nonperiodic convective plumes are indicated in Fig. 10. In February the sea temperature was 21°C and the air temperature just above the water was 23°C. These data confirm that the vertical potential gradient increases in the regions of rising air near the sea. The transverse motion of air close to the water brought relatively humid air to the regions of ascent, making the plumes more humid than the surrounding air at the same level. This is depicted in Fig. 1.

I postulate that the periodic decreases in potential gradient observed as the aircraft flew above the inversion occur as the plane crosses over accumulations of positive space charge organized by air circulations. These charge accumulations may be located where ascending plumes, carrying positive charge from below, reach the inversion. An alternate possibility is the rearrangement of space charge accumulated at the inversion because of the conductivity discontinuity by horizontal convergence of air near the inversion and downdrafts. With maxima 5 km apart, the data in Figs. 7 and 8 indicate a 2.5-km spacing between roll vortices. Since the inversion in both cases was at about 2.5 km, these measurements are in agreement with the model of roll vortices filling the atmospheric boundary layer.

The measurements described here represent an example of the remote-sensing capability of electric field instrumentation. With inertial platform instrumentation it would not be possible to sense air motions within the exchange region when the aircraft was flying above the inversion.

The most pronounced periodicities observed so far with the electric field instrumentation are those shown in Fig. 8. It is significant that this record was obtained while the plane was flying across the Gulf Stream. In December, when these data were taken, the Gulf Stream between Bimini and Florida and the shallow waters east of Bimini to Andros Island would have been as warm or warmer than the air, a necessary condition for the formation of roll vortices according to Woodcock (*24*). The periodicity ended when the aircraft came over deeper and cooler waters east of Andros. The lack of periodic decreases in February over the same Gulf Stream region implies the absence of organized convection because of a more stable atmosphere. In addition, the winds did not favor the formation of roll vortices in February. Woodcock (*24*) found that a minimum wind velocity of 7 m/sec was necessary for the formation of such vortices; Kuettner (*2*) has indicated that wind shear is necessary for the formation of roll vortices. These conditions existed during the December measurements.

The W-shaped notches near the minima of the periodic decreases in Fig. 8 provoke speculation. They may be indicative of charge concentrations in the eddies formed on both sides of the plumes at the inversion similar to the concentration of smoke in a smoke ring. The circulation pattern would resemble a vortex-ring model of convective updrafts (*28*) in cross section. Similar W-shaped potential gradient signatures have been observed in flights over and under artifically charged developing cumulus clouds (*11*).

Summary and Future Plans

Relatively simple atmospheric electrical instrumentation carried on a small aircraft constitutes a flexible and sensitive system for detecting organized convection. Data can be obtained close to the sea surface, and low-velocity flight enhances the spatial resolution. With a slow-flying airplane or powered glider, it may be possible to trace the circulation of individual convection cells and to investigate the trajectory of air which forms cumulus clouds, one of the major unsolved problems in tropical meteorology. Since space charge near the ocean surface was found on some days to be organized on a horizontal scale equivalent to the cumulus cloud scale, this suggests that some of the air which forms maritime cumulus clouds may come from within a few meters of the ocean and that atmospheric electrical instrumentation may have the potential for tracing air from the sea surface to the clouds.

Although the atmospheric electrical instrumentation technique described here cannot be used for direct measurement of air velocity, it may be possible to develop a model that can be used to calculate air velocities from electric field data. Even though with the technique described here it is not possible to make direct measurements of wind velocity, airborne electric field records can provide useful information about convection by delineating patterns in the wind field and structural features of thermals (rising bodies of relatively warm air) and by making possible the remote detection of thermals (*29*).

Future plans include attempting to trace interfaces between adjacent roll vortices from the sea surface through the depth of the mixed layer (i) by flying the aircraft parallel to the wind so as to nullify the horizontal electric field (measured between wing-tip probes) while ascending and descending along the interface between adjacent roll vortices and (ii) by measuring vertical and horizontal potential gradient variations at different flight levels (*30*).

The sensitivity of atmospheric electrical instrumentation to the top of the mixed layer and structure within it can be used to explore another important problem in boundary layer convection—why convective cloud cover and oceanic rainfall are greater at night than during the day (*31*).

Workers in atmospheric electricity have long recognized that their domain is strongly controlled by turbulence in the lower atmosphere, and many have believed that the most effective use of atmospheric electrical techniques to assist meteorological research would be in studying exchange processes. Reiter [see (*8*)] effectively extended atmospheric electrical studies of boundary layer phenomena through a height range by mounting instruments on cable cars traveling between the valley floor and mountain tops in the Alps. The airborne measurements described here extend this approach. Relating the electrical structure of the atmosphere to its dynamic structure poses an interesting problem which may contribute to our understanding of the atmosphere.

References and Notes

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2. J. P. Kuettner, *Tellus* **23**, 404 (1971).
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5. B. Vonnegut, C. B. Moore, F. J. Mallahan, *ibid.* **66**, 2393 (1961).
6. J. A. Chalmers, *Atmospheric Electricity* (Pergamon, New York, ed. 2, 1967), pp. 22–24.
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8. Individual investigations, some of them related to the sunrise effect, solar eclipse observations, atmospheric electric "agitation" (noise), and the austausch generator, have been carried out by J. A. Chalmers, J. F. Clark, H. Israël, H. Kasemir, M. Kawano, J. H. Kraakevik, R. Reiter, and others; these investigations are reported in books by R. Reiter [*Felder, Ströme und Aerosol in der unteren Troposphäre* (Steinkopff, Darmstadt, 1964)] and H. Israël [*Atmospheric Electricity* (National Technical Information Service, Springfield, Va., 1973)]. Later experiments concerned with convective effects from solar eclipses are discussed by R. V. Anderson [*J. Atmos. Terrest. Phys.* **34**, 567 (19[illegible] R. V. Anderson and H. Dolezalek (*ibid.*, p. 561); and D. R. Lane-Smith and R. Markson [*Proc. 5th Int. Conf. Atmos. Electr.* (Garmisch-Partenkirchen, Germany, 1974), in press].
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12. Inspection of the original data of the extended ocean measurements made on board the R.V. *Carnegie* does not show this effect; the time resolution of these data is not fine enough. The first reported observations are probably those of S. Ruttenberg and R. E. Holzer [*Proc. Conf. Atmos. Electr.. AFCRC Geophys. Res. Pap. 42* (1955), p. 107] R. Mühleisen [*Arch. Meteorol. Geophys. Bioklimatol. Ser. A* **12**, 435 (1962); *Problems of Atmospheric and Space Electricity* (Elsevier, New York, 1965), p. 26]. More detailed and extended observations were made by R. Mühleisen ["*Meteor" Forschungsergeb. Reihe B* **2**, 57 (1968); *Ann. Meteorol. Neue Folge* **4**, 102 (1969)].
13. Flying in an aircraft within the exchange layer over land while trailing a long wire connected to an electrometer, D. A. Kohl [*J. Geophys. Res.* **73**, 1913 (1968)] detected horizontal variations and periodicities in the horizontal electric field. From these he deduced the separation of space charge centers, probably associated with thermals, as well as a measure of turbulence.
14. No periodicities of this kind are mentioned in the reports of atmospheric electrical measurements obtained on flights over the ocean by investigators at the Naval Research Laboratory in the 1950's [J. F. Clark, *J. Geophys. Res.* **62**, 617 (1957); *Recent Advances in Atmospheric Electricity* (Pergamon, New York, 1958), pp. 61–73; J. H. Kraakevik, *J. Geophys. Res.* **63**, 161 (1958); *Recent Advances in Atmospheric Electricity* (Pergamon, New York, 1958), pp. 75–88; ——— and J. F. Clark, *Trans. Am. Geophys. Union* **39**, 827 (1958)] possibly for the following reasons. Since a large multi-engine aircraft was utilized, it could not be flown safely close to the sea. Thus data were not obtained during periods of extended duration at constant altitude next to the water. Above the exchange layer, where the potential gradient becomes relatively small, it was necessary for the Naval Research Laboratory aircraft to bank in order to measure vertical potential gradient because of the sensitivity limitation of the field mills employed [see J. F. Clark, *J. Geophys. Res.* **62**, 617 (1957)]. This precluded straight-line continuous measurements.
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18. The electrode effect is an accumulation of charge in the atmosphere near the surface of a conductor (the earth) in the presence of a conduction current. It occurs because the solid earth is not a source of ions. Near the earth's surface, in the presence of the fair-weather electric field, negative ions drift upward but are not replaced from below, while a continuous flow of positive ions descends from the atmosphere above through the volume. The net result is an accumulation of positive space charge in this region.
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20. This equation as applicable for computing space charge from measurements of the vertical potential gradient at two levels is:

$$\rho = -E_0 \frac{\delta E_z}{\delta_z}$$

where ρ is the net space charge density (in coulombs per cubic meter), E_0 is the permittivity of free space = 8.85×10^{-12} farad/m, E_Z is the vertical potential gradient (in volts per meter), and z is the vertical direction coordinate (in meters). This equation reduces to

$$\rho = -55.2 \frac{\Delta E_z}{\Delta z}$$

where ρ is the net space charge density (in elementary charges per cubic centimeter), ΔE_Z is the change in the vertical potential gradient (in volts per meter), and Δz is the change in height (in meters).

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22. Figure 4 shows greater space charge near the sea on calm days than on windy days. On calm days, when there are no whitecaps, there is no contribution to space charge from the breaking of bubbles. In addition, on low-wind days the electrode effect is more pronounced since atmospheric mixing, in-

creasing with wind velocity, spreads space charge upward and lowers its density near the surface (*9*, *10*). That the space charge layer near the sea is due primarily to the electrode effect is consistent with the data obtained over a lake (Fig. 3). Here the space charge layer cannot be due to the bubbling mechanism since this produces negative space charge with fresh water [S. G. Gathman and W. A. Hoppel, *J. Geophys. Res.* **75**, 1041 (1970)]. Although the electrode effect appears to be the dominant mechanism on calm or low-wind days, the bubbling mechanism can contribute significantly to the positive space charge layer close to the ocean on windy days [(D. C. Blanchard, *J. Atmos. Sci.* **23**, 507 (1966)].
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30. Recently I have begun such measurements in flights over the Atlantic Ocean and the Gulf Stream off Virginia, utilizing new horizontal electric field instrumentation in addition to the original vertical field instrumentation. The vertical field measurements have indicated circulation patterns spaced 1 km apart, presumably roll vortices, at times when meteorological conditions favored their formation. The horizontal field records at low altitudes (5, 15, 50, and 150 m) generally were characterized by higher-frequency oscillations, thus suggesting that the aircraft was passing through rising air plumes spaced about 100 to 300 m apart as found over l: [J. Warner and J. W. Telford, *J. Atmos. Sci.* **20**, 313 (1(*ibid.* **24**, 374 (1967)]. The horizontal spacing increases with altitude, thus suggesting that smaller eddies merge into larger ones as the air rises. This has also been reported over land and discussed in the above references. The relatively closely spaced plumes were detected both on days when the 1-km circulation patterns have been detected (presumably roll vortices) as well as on days when these were not in evidence. The horizontal field measurements nicely complement the vertical field data in that each appears to be especially sensitive to a particular size of circulation pattern.
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32. I acknowledge the suggestions of D. Latham, University of Miami, regarding flight paths close to the ocean which were important in recording convection patterns in this regime. I thank D. Blanchard, B. Lettau, and B. Vonnegut, State University of New York at Albany, for valuable discussions during this research program; H. Dolezalek, Office of Naval Research, Washington, D.C., who provided extensive critical evaluation during preparation of the manuscript; B. Leary, airport manager, and the Pan American Airlines staff, Rock Sound International Airport, Eleuthera, for their help during field operations in the Bahamas; and D. Mitchell, Governor's Harbor, Eleuthera, who measured ocean temperatures. This research was supported in part by the Atmospheric Science Program, Office of Naval Research, under contracts N 00014-71-C-0156 and N 00014-74-C-0336.

Membrane Transport: Its Relation to Cellular Metabolic Rates

Glucose transport into animal cells is adapted to their metabolic rate and often controls rates of glucose use.

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It is a truism to say that the various activities of the cell membrane are functionally integrated with the metabolic and other properties of the cell. For example, the cell membrane must provide for access of metabolic substrates at rates consistent with the cell's metabolic activity. It is of interest, therefore, to consider how membrane transport processes in different types of tissues are related to metabolism and other cellular functions and how various factors modulating these functions find expression at the membrane transport level. We discuss here one example of such integration between membrane transport and intracellular events, the interaction between the transport of glucose and its metabolism in the tissues of vertebrates. This choice is justified by the importance of glucose for the animal organism and the extensive information available on its distribution and metabolism. Even though certain animal tissues may use noncarbohydrate substances preferentially (*1*), all of them are able to use glucose and some use it almost exclusively; this substrate is constantly available, and its concentration in the blood is kept remarkably stable. Also, as discussed below, carbohydrate metabolism is subject to control by metabolic, hormonal, and other factors.

Owing to its essentially lipid nature, the cell membrane represents an effective barrier to the passage of hydrophilic molecules, unless specific transport pathways exist. Thus, glucose enters human erythrocytes 10,000 times faster than calculated for diffusion across the lipid membrane layer (*2*). The membrane transport of glucose and related monosaccharides is characterized by saturation (Michaelis-Menten) kinetics, chemical specificity, and other features indicating that its transfer across the cell membrane involves transient interaction with a limited number of specific membrane constituents, commonly referred to as carriers (*2*–*4*). Several nonmetabolized analogs of glucose are available permitting study of membrane transport in isolation from any subsequent metabolic transformation. From the point of view of energy requirements, the sugar transport systems in the absorptive epithelia of the small intestine and the proximal tubule of the kidney may be described as active—that is, capable of moving the substrate against an electrochemical gradient and requiring metabolic energy for this function. In most other animal tissues sugar transport is by energy-independent facilitated diffusion which leads to equilibration of sugar across the membrane and mediates equally its rapid flux in and out of the cell. The net flux will depend on the substrate concentrations at the two faces of the membrane and on kinetic parameters reflecting the carrier's affinity for the substrate and its capacity. The latter embodies both the number of carriers and their "mobility" (or rate of reorientation) within the membrane (*5*). The kinetic constants expressing affinity and capacity vary widely for transport systems in different tissues. The chemical specificity of the facilitated diffusion systems for sugars appears to be very similar but differs from that of the active transport systems; in both groups, however, D-glucose is the preferred substrate (*2*). As shown below, in some tissues facilitated diffusion of sugars depends exclusively on the substrate concentrations and the fixed properties of the carrier. In other tissues, such as muscle and adipose tissue, the properties of the sugar carrier are variable and are con-

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