electron attachment at least 200 times greater than air.

The actual volume of the electrically heated region is hard to estimate, but 10^{12} cm^3 is an upper limit of $\pi r^2_{crit} \times 1$ km, for E equal to or greater than 1 kv/cm.

Injection of 1 percent SF_6 or Freon-12 requires 10 tons (*15*) of electronegative gas, which is a large mass to inject rapidly adjacent to or inside the tornado, but is perhaps feasible from an airplane. Much larger quantities of borate are dropped on forest fires. It should be emphasized at this point that such measures as "bombing" every tornado with 10 tons of Freon-12 and dispersing the chaff are not advocated; instead the magnitude of the effort required to control tornadoes by what seems the best postulated means is estimated, which in turn may stimulate sufficient research to determine what is required. A large city such as Chicago that may be threatened with major (10^8 to 10^9 dollars) destruction by a tornado may be more inclined to contemplate such heroic measures upon that rare occasion.

It is also necessary to simultaneously provide another, less-destructive current path. This path could be another tornado not immediately threatening a major population center. Instead it is suggested that there is an optimum distribution of fine wire "chaff" (Fig. 1) that may be sufficiently effective to negate the requirement of the electronegative gas.

Kasemir and Weickmann (*16*) have been testing the use of shorter chaff (10 cm) in the region below electrified clouds. Once corona discharges occur in clear air, (from the chaff) the ion mean free path can be very long discharging the cloud-to-ground electric fields. Inside a cloud, the ions produced by the corona attach to water drops and become immobilized in roughly 10 m so that new ions must be produced to maintain the conductivity. Consequently, ions must be produced within each 10 m cube. The use of aluminum-coated fiber (designed to disintegrate rapidly) with a diameter of 10^{-3} cm and one length per 10 m cubed requires 2 kg of chaff per cubic kilometer of cloud. The multiple random interconnecting paths (10^4 per kilometer squared) should increase the conductivity within the cloud because of the corona from the ends as well as the interconnecting paths. The length of 10 m is chosen to be one or two mean free paths of an ion in a cloud before attachment to a cloud drop. The ionic conductivity will then apply between fibers with an ion drift velocity of μE approximately equal to 10^3 to 10^4 cm/sec, depending upon the local field. Since this drift velocity is comparable to the convective velocities, it should effectively short out the electrical generating mechanism throughout the entire cloud without initiating a few preferred channels of conduction and heat which otherwise would burn up the chaff.

Kasemir and Weickmann have experienced, in the past, difficulty in dispersing chaff 10 cm long without its balling or nesting. Extending this to 10 m is beyond the present technology, but the implication for the modification of electric field within clouds motivates the development.

Clearly, these considerations of tornado mechanisms and control are only an indication of the possibilities. Detailed measurements on the ground and from rockets flown through tornadoes are needed. Perhaps then a documented understanding can be reached.

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15. The total U.S. annual production of Freon-12 is estimated to be greater than 100,000 tons, the larger fraction of which is lost within the year [Earl V. Anderson, *Chem. Eng. News* **44**, 91 (1966)]. The additional atmospheric pollution from 10 tons for one disaster tornado per year is small. On the other hand, the effect upon the earth's total infrared emission could be major from less than 1 ton of a stable ideal infrared absorbing gas. Present Freon gases do not cause sufficient infrared absorption to be of concern.
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19 June 1967; revised 9 August 1967

Electric Currents Accompanying Tornado Activity

Abstract. *Measurements of the magnetic field and earth current in the vicinity of a tornado show large steplike deflections coincident with the touching down of the funnel. Calculations with a simple current model indicate that a minimum current of several hundred amperes must be postulated to account for the observed deflection in magnetic field. The existence of a steady current of 225 amperes for a period of about 10 minutes provides joule heat at the rate of approximately 10^{10} joules per second, and involves a total charge transfer of 135,000 coulombs. The calculations imply that a tornado is electrically equivalent to several hundred isolated thunderstorm cells active simultaneously.*

The origin of the high-energy density in a tornado is intriguing. Because the event is relatively rare and obtaining pertinent measurements is difficult, progress in our understanding of the source of energy that can accelerate air to near sonic velocities has come slowly. Vonnegut (*1*) has calculated that the atmosphere, operating as a perfect heat engine, would have to provide temperature contrasts between air masses of a minimum of 70°C in order to produce and sustain the near sonic velocities accompanying the tornado. As a possible source of concentrated energy, he suggests that electric currents in the cloud and down the funnel can provide joule heat in the required amounts.

Vonnegut and Weyer (*2*) have presented a summary account of visual and photographic evidence from nocturnal tornadoes indicating that tornadoes are quite often accompanied by unusual electrical activity. If electric currents of unusual duration and magnitude do accompany tornado activity, their presence should be detectable by magnetic instruments such as have been used to measure the long continuing currents in lightning (see *3*).

I now report a measurement of perturbations in the magenetic field and in the telluric currents taken in the vicinity of a tornado. The data in Fig. 1 were obtained by Mr. Geoffrey Boucher at the Geophysical Observatory of the Jersey Production Research Company near Tulsa, Oklahoma on 27 May 1962. The charts have been aligned to coincide at 10:15 p.m. C.S.T. (0415 U.T.). (The reader will note that the time scales are not the same for the various records.) According to eye-witnesses interviewed by Mr. Boucher, a tornado touched down briefly at 10:15 p.m. (0415 U.T.) 9.6 km west of the laboratory.

The most striking feature of Fig. 1 is the large rapid deflection in the record of the horizontal earth current at precisely 0415 U.T. Coincident with this deflection is a large, sudden shift in the magnetic field, particularly the horizontal (*H*) component, with smaller deflections in the declination (*D*) and in the vertical component *Z*. The coincident, step-like deflections on all of the records in Fig. 1 strongly suggest that the disturbance originated from a common source. We believe that the source of the disturbance was the tornado that was seen to touch down at precisely the time at which the deflections occurred.

To calculate the current needed to produce the magnetic field deflection registered by the magnetometer, one first assumes a model consisting of a vertical line current extending from ground to a height of 10 km, and an image current of equal length in the earth. Thus,

$$B = \mu_0 I / 2\sqrt{2}\pi R$$

in mks units, where B is the magnetic induction, I the current, and R the distance from the instrument to the current source. Solving for I and converting to more convenient units, one gets I equal to 7.07 RB amp, where R is now the distance in kilometers and B is in gammas. In this case, R equals 9.6 km, and B equals about 15 gamma, yielding an I of about 1000 amp.

In the simple analysis given above, I have deliberately used a value for B which underestimates the peak current by perhaps a factor of 2. The reason for doing so is evident from a close examination of the H trace at 0415 U.T. The intensity of the trace is extremely weak at this time, a fact which, from my experience with magnetograph measurements in thunderstorms, is indicative of a high rate of lightning flash activity. I feel that an average rather than a peak value for the current is more representative of the actual situation.

In considering a vertical line current I have assumed that the charge is stored in the dimension of cloud which is small compared to the length of the vertical channel. For a more realistic model one must assume the charge to be distributed over a large volume of cloud, as judged from the duration of the telluric and magnetic deflections. For example, when the duration of the magnetic effects on the record is estimated to be between 5 and 10 minutes, the amount of charge transferred to earth would have exceeded 300,000 coulombs. Thus, the assumption that the charge moves only along a vertical path is unrealistic. Lightning discharges consisting of multiple strokes have been observed to bridge adjacent cells and extend horizontally for many miles in the cloud, yet the individual strokes travel to earth along the same vertical channel (*4*).

This mechanism essentially funnels electrical energy stored in a large volume into a single concentrated region. On the basis of the above and choosing the extreme case (minimum current needed to produce a given magnetic field) one must revise the model to consist of a 20-km long horizontal line current 6 km high in the cloud joining a 6-km vertical current to the earth. The magnetometer is assumed to be 10 km from the vertical current and directly under the midpoint of the horizontal cloud current. The line current distribution in the cloud now requires that there be an

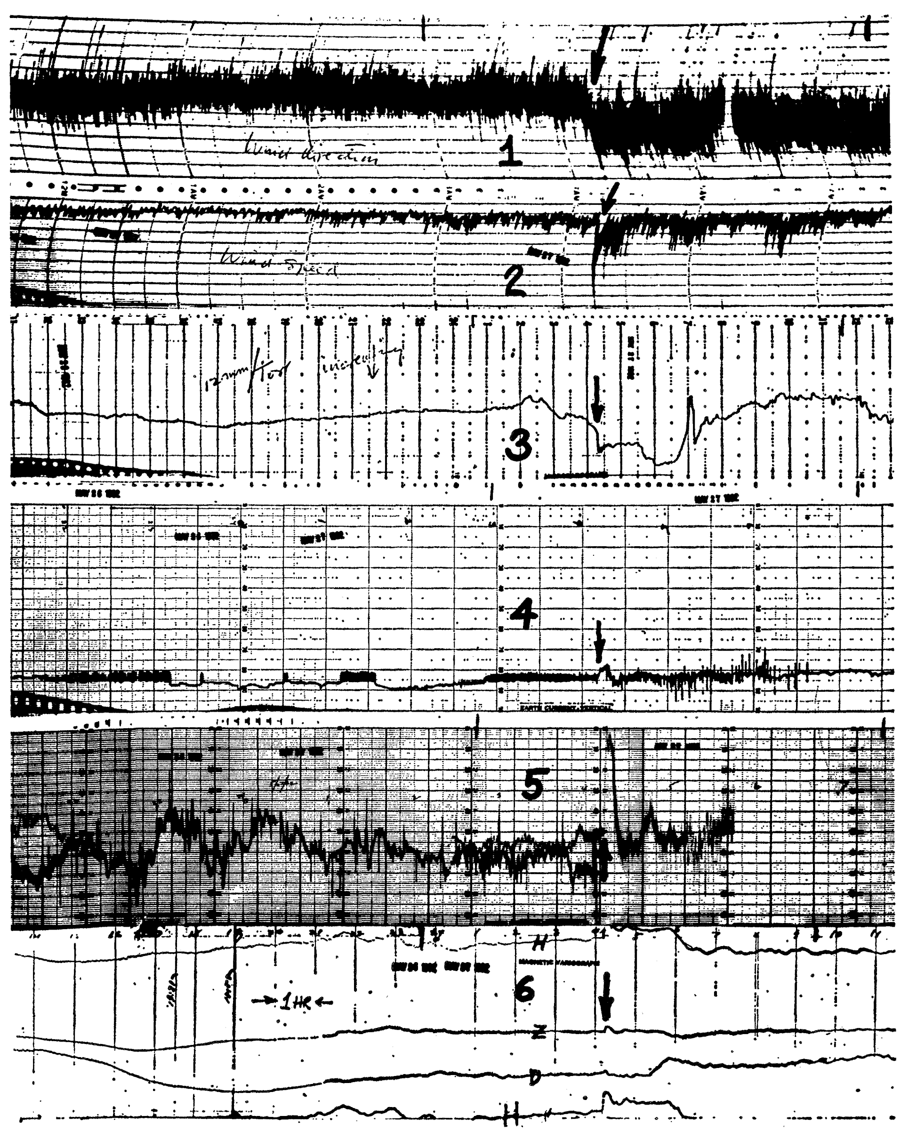

Fig. 1. Instrumental records obtained during the passage of a tornado 9.6 km west of the Geophysical Observatory of the Jersey Production Research Company, on 27 May 1962. The variables recorded are, from top to bottom (1) wind direction, (2) wind speed, (3) pressure, (4) vertical earth current, (5) two components of horizontal earth currents, and (6) magnetic variograph. The arrows indicate the time (0415 U.T.) at which the funnel was seen to touch down. Note that the time scales for the various charts are not the same. The record of the magnetic field has been darkened for reproduction.

areal return current under it on the surface of the earth. This requirement is satisfied if a horizontal image current 6 km below the surface is chosen. Thus, for a measured B of 15 gammas, I equals 225 amperes. This value represents the minimum current needed to produce the measured magnetic deflection. In the model chosen, B exhibits essentially $1/R$ dependence. In a ring-current model, for example, such as one might postulate to be rotating with the funnel, the magnetic field would vary at least as $1/R^2$, requiring the existence of much higher currents.

Whatever the model chosen to explain the magnetic effects, the existence of high currents of the order of hundreds of amperes is implied, and the energy involved is staggering. For example, if one extrapolates from the ordinary thunderstorm and chooses a value of 10^8 volts for the potential difference between cloud and ground, the electrical energy is calculated as being dissipated at a rate of 2.25×10^8 joules/second. Over a period of 5 minutes, approximately 7×10^{12} joules of energy will have been expended.

An average current of 225 amp must, at first sight, appear incredible. But long continuing currents in lightning from ordinary thunderstorms have been measured at greater than 400 amp for durations exceeding 1 second. An average thunderstorm, however, involves an equivalent steady current of about 1 amp. From the results based upon the assumed model, one can infer that a tornado is equivalent to several hundred thunderstorm cells active simultaneously.

A current of 225 amp flowing for 10 minutes involves a total charge of 135,000 coulombs, or about one-third of the total charge on the surface of the earth. The release of charge in this amount should be detectable anywhere on earth, provided that local effects in the atmospheric electric field are small. Electric field or air-earth current measurements several hundred miles from a tornado should show this effect if the currents inferred from the magnetic field measurements are as large as calculated. In support of this inference, Falconer and Schaefer (*5*) detected strong negative electric fields in Schenectady, N.Y. during the period of the Worcester tornado on 9 June 1953, when the sky was clear overhead and the tornado was 150 km distant.

Although this measurement represents only one observation, there may exist other records such as this one which have not been reported. My primary purpose in writing this note is to bring to the attention of scientists, especially those who live in areas of frequent tornado occurrence that reliable magnetic measurements made in the vicinity of tornadoes would be most helpful in establishing whether or not electrical effects are important in the energy budget of the tornado. It would be highly desirable to have an extended array of three component magnetometers. Data from such an array should make possible the construction of a reasonably consistent model of the distribution and magnitude of the large currents which seem to accompany a tornado.

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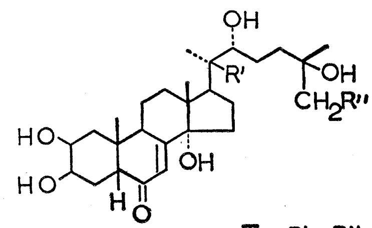
19 June 1967

Insect Hormones: Alpha Ecdysone and 20-Hydroxyecdysone in Bracken Fern

Abstract. *The two major molting hormones of insects, alpha ecdysone and 20-hydroxyecdysone, were isolated in crystalline form from dry pinnae of the bracken fern,* Pteridium aquilinum *(L.) Kuhn. Three unidentified substances with molting hormone activity were also detected. Bracken is the first plant found to contain both of the major insect ecdysones, and it is the first known plant source of alpha ecdysone.*

Three structurally related hormones, termed ecdysones, that regulate molting and metamorphosis in insects have been isolated and identified. Alpha ecdysone (*1*), the first molting hormone isolated, was shown by x-ray diffraction studies (*2*) and by syntheses (*3*) to be a compound of structure I. The 20-hydroxyecdysone of structure II has been isolated from insects (*4, 5*) and from crustacea (*6*), and a third hormone 20,26-dihydroxyecdysone of structure III was isolated (*7*) from the tobacco hornworm pupa, *Manduca sexta* (Johannson). The configurations at C-20 and C-22 in II and III remain to be established.



I, R′=R″=H
II, R′=OH; R″=H
III, R′=R″=OH

Reports that two Coniferophytes also yield similar or related steroids (*8, 9*) with molting hormone activity in extremely large quantities prompted us to examine certain more primitive plants. Ferns, which are widely distributed and relatively immune to insect attack (*10*), were considered ideal subjects for these studies.

During the winter in the vicinity of the laboratory, we observed stands of withered, but intact, bracken *Pteridium aquilinum* (L.) Kuhn. Crude extracts from the dry pinnae proved positive in the housefly assay (*11*), and the titer was greater than that found for 7-day-old tobacco hornworm pupae (*5*), the best insect source of the ecdysones yet reported.

A sufficient quantity of the dry bracken was collected in mid-January; the pinnae were separated from the plant and pulverized to a powder. The dry powder (4.0 kg) was blended once with 75 percent methanol (10 ml per gram) and then twice again with 5 ml per gram. The techniques used to isolate and purify the extracted, biologically active components were similar to those used to isolate the ecdysones from insect sources (*5*). The adsorption columns (*12*) were scaled to accommodate larger quantities of extractives, and fractions were monitored by ultraviolet spectroscopy and by bioassay.

The concentrate, after adsorption chromatography, was subjected to 37 transfers in a countercurrent distribution system consisting of cyclohexane,