dal. This is similar to the findings of Flaig and Beutelspacher using electron microscopy (*3*).

In order to obtain more definitive knowledge about the size and shape of sodium humate molecules a homodisperse system must be obtained. Small-angle x-ray scattering offers a more specific means of characterizing humic acid preparations than others previously used.

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Tornadoes: Mechanism and Control

Abstract. *If electrical energy is invoked to account for the high velocity of tornadoes, hydrodynamics restricts the possible mechanisms of energy exchange. In particular, the vortex is driven by a line sink of electrically heated air that must extend at least 5 kilometers high. In those rare cases where heroic measures may be justified to protect a city in the path of a major tornado, some possible control measures are discussed in terms of the electrical heating mechanism.*

The possibility that the energy source of tornadoes is primarily electrical has been suggested independently by several authors, the most convincing analysis being given by Vonnegut (*1*). As he points out, this suggestion was made by Lucretius (*2*), but the more modern argument for an electrical energy mechanism is that purely hydrodynamic motion cannot adequately account for the very high wind speeds (close to Mach 1) derivable from the maximum available geostatic pressure potential of 0.1 atm. Abdullah (*3*) showed theoretically how a line sink in the atmosphere leads to an adiabatic vortex of constant angular momentum whose minimum critical radius is limited where the tangential air velocity reaches the speed of sound. Lewis and Perkins (*4*) showed how the observed pressure field around a tornado is entirely consistent with a frictionless vortex of specific, constant angular momentum ($\Omega_0 = \omega R^2$) of approximately 7.5×10^7 cm^2/sec. This corresponds to the very small and reasonable ambient wind sheer of $\pm$ 4.8 km/hour, 5 km either side of the tornado. The difficulty arises in explaining the line sink where the ratio of axial pressure to ambient pressure is at least 1 : 2 when the maximum adiabatic pressure difference (including latent heat of condensation) is less than 0.1 atm ($\Delta T \simeq 30°$C) from ground to the base of the tropopause. This pressure difference is the maximum pressure differential of the sink that can occur, provided the axial flow inside the vortex is frictionless from ground to the tropopause and provided that no mechanism for upgrading the specific energy is operating. This latter point concerning a mechanism for upgrading the specific energy content is analogous to the statement that no known hydrodynamic flow pattern allows one to create the equivalent of a jet engine operating stationary with respect to the atmosphere and with no mechanical moving parts. Mechanical (or electrical) leverage is always required to create a higher specific energy region from a lower specific energy source. The implication for a tornado is that a higher specific energy source than the adiabatic differential is necessary to give rise to the inferred line sink of 0.5 to 1 atm.

The presence of dramatic electrical effects associated with tornadoes has been reviewed (*5*). However, the magnetometer measurements discussed by Brook (*6*) is the first strong evidence that the electrical energy involved is as large as the hydrodynamic dissipation. If we assume the pressure of the line sink is 0.5 atm and that the axial flow is one-half of sonic, C_o, within the critical radius defined by a tangential velocity of sound speed and the observed angular momentum of Lewis and Perkins, then

$$r_{crit} = \Omega_o / C_o = 25 \text{ m} \qquad (1)$$

$$\text{Power} = P\,A\,U \simeq 2 \times 10^{10} \text{ watts} \qquad (2)$$

where the pressure, P, equals 0.5 atm; the area, A, equals $\pi\,(r_{crit})^2$ which about equals 2×10^7 cm^2; and the axial velocity, U, equals 1.6×10^4 cm/sec. As discussed by Brook, the magnetic field disturbance corresponds to several hundred amperes. At the mean potential difference of a thunderstorm cloud of 10^8 volts, this accounts for the observed tornado dissipation of 2×10^{10} watts. Rossow (*7*) suggested that this electrical energy is coupled to the vortex by a sheered horizontal current flow, and that this sheered stress furnishes the required angular momentum.

As it has already been pointed out, the ambient wind sheer is more than adequate to supply the required angular momentum; second, the observed large currents discussed by Brook are vertical, as expected from the energy source of updraft convection, rather than horizontal; third, the very low viscosity assumed by Rossow of ηt (turbulent) of about 0.1 ηl (laminar) for a Reynolds number of 5×10^9 is unrealistically small. A better assumption for a quasistatically stable vortex is a viscosity such that the vortex decays in 50 to 100 revolutions. If this condition is used in Rossow's equations, the tangential vortex velocity, V, is limited such that

$$\rho_{air}\, V^2/2 \simeq E^2/8\pi. \qquad (3)$$

Indeed, any electrostatic configuration of acceleration is limited to condition 3 unless a mechanical constraint is imposed that results in a mechanical leverage. If electrostatic acceleration alone is used to create the axial line sink, then the pressure difference between the critical radius, r_{crit}, and outside at infinite radius is limited to

$$\Delta P = \int_{r_{crit}}^{R} E_r\, q\, dr \qquad (4)$$

where q is the charge density, E_r is the radial field, and R is an outer maximum radius less than the length of the vortex. If the distribution of q is such as to give the maximum possible field, that is, a constant field, limited by breakdown, then

$$q = (q_0/r), E_r = 4\pi q_0, \text{ a constant}$$

and

$$\Delta P = (E^2_{crit}/2\pi) \ln (R/r_{crit}). \quad (5)$$

This is an upper limit to the repulsive pressure difference from a distribution of charge of only one sign. To create a line sink both positive and negative charge must occur concentrically, and the resulting pressure difference will be less because the volume integral of $E^2/8\pi$ will be less.

The centrifugal pressure in a frictionless vortex can be obtained by integrating the body force up to the radius, r_{crit}, with constant angular momentum outside and a constant angular velocity inside. The pressure difference becomes

$$\Delta P = \int_{r_{crit}}^{R} (V^2/r) \rho \, dr \simeq \rho V^2_{crit}. \quad (6)$$

The radial velocity is neglected, and it is assumed that $R \gg r_{crit}$, and ρ is a constant; therefore, for electrostatic acceleration in either the case with tangential acceleration suggested by Rossow or by radial acceleration into a charged vortex core, the maximum pressure difference from inside to outside the vortex is limited to

$$\Delta P \simeq 4 (E^2_{crit}/8\pi) \ln (R/r_{crit}) \simeq \rho V^2_{crit}. \quad (7)$$

The maximum electric field is limited by electrical breakdown to less than 20 kv/cm, which gives a maximum ΔP equal to or less than 8×10^3 dyne/cm^2 or 0.008 atm. Vonnegut repeatedly emphasized that the observed wind velocity corresponds to nearly the speed of sound and by Eq. 6, requires ΔP to approximately equal 0.5 to 1 atm. One is forced to consider electrical heating of the atmosphere in the core of the tornado as the source of the line sink, as suggested by Vonnegut.

The efficiency of conversion of heat to kinetic energy depends upon the expansion ratio of the gas. The simplest conversion process envisaged is just the buoyancy of the hot gas of the core expanding up the vortex tube to the height, h, where h is determined by the viscous relaxation length of the vortex ($h \simeq 100$ to $200\ r_{crit} \simeq 2.5$ to 5 km). For a scale height of 7 km, this gives a maximum pressure difference of, at most, 0.5 atm for infinite temperature and, therefore, requires a large temperature increase such that $(\Delta T + T)/T$ is at least 2 to obtain the required pressure differential. However, once heating within the vortex is assumed, then the mass distribution differs from the adiabatic solution of Abdullah or the constant density case of Eq. 6. The hydrostatic equation $dP/dr = -\rho V_0{}^2 R^2/r^3$ when integrated for temperature vortex (*8*) and a radius ratio $r_{crit}/R \ll 1$ gives

$$P/P_0 = \exp [-\gamma/2 \, (V/C_0)^2] \quad (8a)$$

and

$$\Delta P = P_0 \{1 - \exp [-\gamma/2 \, (V/C_0)^2]\}. \quad (8b)$$

The critical radius condition of Abdullah is avoided, and the flow field is highly stable and inviscid. Equation 8b gives a significantly smaller pressure drop than the adiabatic case ($V = C_0$ when $\Delta P = 0.5$ atm), and in the case of a superheated vortex, even less pressure difference for a given velocity. The superheat reduces the gas density and, therefore, the contribution to the pressure integral (*6*). As a consequence, a pressure differential of 0.5 atm with heating of the central vortex region to 2 T_0, ρ equals $\rho_0/4$, gives a maximum tangential velocity of 1.2 C_0, where C_0 is the ambient sound speed at infinite radius. The electrical energy input should be more than adequate to give this heating as outlined in Eqs. 1 and 2, since the isothermal vortex is highly stable and, therefore, has a larger decay time. Wilkins (*9*) investigated the effects of heating a vortex in response to the suggestion of enhanced stabilization (*10*) and concluded that heat slowed down the maximum vortex velocity. This is to be expected for a vortex with a constant sink rate determined by a fixed blower speed, as he had in his experiment. In the case of an electrically heated tornado, heat increases the available pressure difference due to buoyancy from ground to tropopause. It also reduces the turbulent viscosity drag by increasing the stability of the centrifugally stratified atmosphere of the vortex as it does for a gravitationally stratified atmosphere. As a consequence, the available sink per unit length is increased, and a higher velocity occurs.

The stabilization of electrical discharges in gaseous vortices is a well-known phenomenon. The low density in the center of the vortex leads to a natural higher conductivity and an axial current path with lower specific heat. In a tornado, an additional effect takes place that enhances this stability. The mobility of ions in clear air of 1 cm^2 sec^{-1} volt^{-1} is such that the

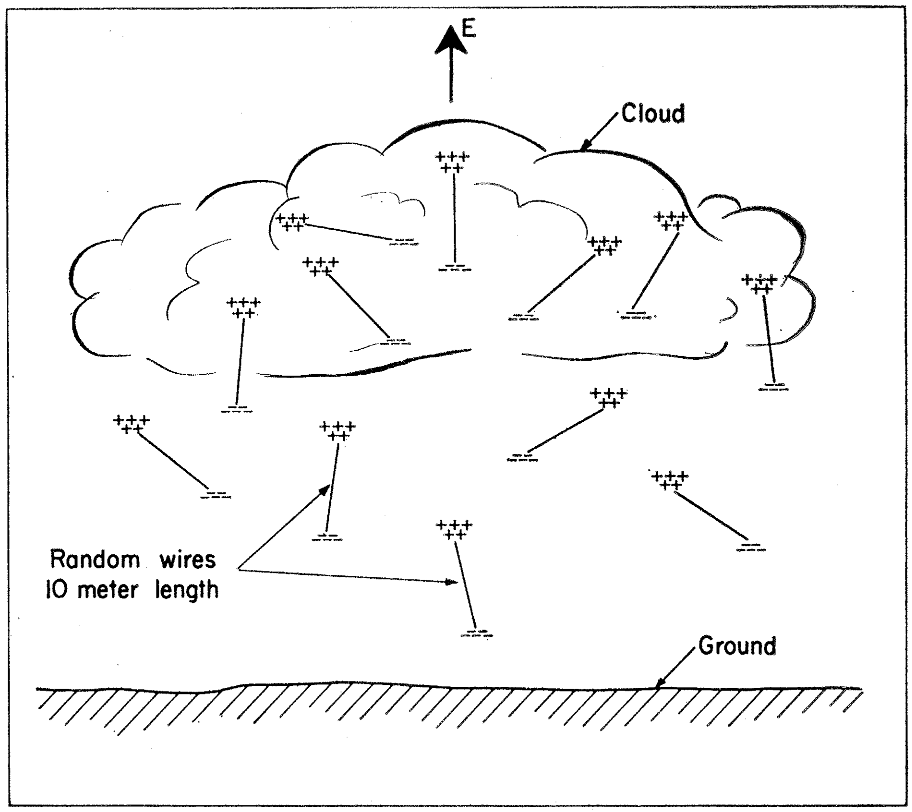

Fig. 1. The cloud becomes a conductor of charge by the random distribution of short wires 10 m long whose mean separation of 10 m is of the order of the ion to cloud drop attachment free path.

charge motion is relatively fast (10^4 cm/sec) at the highest electric fields of atmospheric phenomena. The attachment of these ions to cloud or dust particles renders them immobile relative to the air mass. Hence, water-vapor clouds or dust clouds represent relative insulators in a conducting medium. Convection or turbulence can transport charge in these insulating media, but the resulting currents are only secondarily related to the fields and depend more strongly upon the fluid motions and stresses (*11*). The immobilization of the charge by water drops in a thunderstorm allows the relatively high fields to be established. A tornado vortex is strong enough to centrifuge these condensation drops (10-micron diameters) out of the central core (*12*), leaving a core not only of lower pressure but also devoid of charge immobilization nuclei. This is important for the understanding and possible control of tornadoes for two reasons. As already pointed out, the tornado vortex must extend a fair fraction of the distance from ground to the tropopause if even so extreme a mechanism as electrical heating is to result in near sonic velocities. Consequently, a major fraction of the tornado must extend within the cloud, and the latent heat of the water drawn into the vortex would reduce the electrical heating of the air. Although a small effect (10 percent) at tornado maximum, it nevertheless naturally affords a clear air path for initial electrical breakdown. In addition, any method of possible tornado modification that depends upon the addition of matter into the vortex to reduce possible heating mechanisms is restricted to matter more finely subdivided than 10 microns.

The suspension of a small drop in a vortex flow field depends upon the balance of the Stokes drag of the slow, inward radial flow being balanced by the centrifugal acceleration. If Stokes law for the frictional drag is used and the line sink is such that the radial flow is 1/200 of the tangential flow at r_{crit} (that is, a vortex 100 radii long), then the drop size, δ, suspended at r_{crit} becomes

$$\delta = 2\, r_{crit}\, (4\pi\, \Delta\rho\, \Omega_0^2/9\, \eta\, \Phi_0)^{-\frac{1}{2}} \text{ cm,} \qquad (9)$$

where $\Delta\rho$ is the density difference and equals 1; η is the viscosity of air; Ω_o, the specific angular momentum, and Φ_o, the inward radial flow per unit length. If Ω_o equals 7.5×10^7 cm^2/sec, as measured by Lewis and Perkins, and Φ_o equals $\pi\Omega_o/100$ or 2.2×10^6 cm^3/sec^{-1} cm^{-1} for the length 100 r, then δ equals 12 microns in diameter. Since this is the mean size of the condensation drops, most of the cloud drops and almost all dust will be centrifuged out of the vortex core. (Heavy debris entering the bottom of the vortex at the axis should be lifted several diameters before being flung out.) The small fraction of smaller-sized drops reaching a smaller radius will be evaporated by the electrical heat flux, which is much larger than the latent heat required. Consequently, the core of the vortex should be free of charge immobilizing nuclei, and the fact that observers have reported "seeing" inside the funnel is indicative that no cloud or dust is suspended. It is here that the largest effect can possibly be made on the electrical mechanism of vortex heating by the addition of both an electronegative gas (*9*) and charge immobilizing nuclei. Decreasing the mobility of the charge carriers should increase the electrical heating mechanism for a constant current source, but the simultaneous creation of a parallel, less destructive, current path will be suggested later. The transfer of current to this path can be enhanced by increasing the resistance (decreasing the mobility of the current carriers) within the core of the tornado.

The presumed discharge current may be either an arc or glow discharge. If the discharge is an arc, the electrical heating is difficult to explain if the measured current of several hundred amperes and the maximum assumed vortex length of 5 km are used. Typical arc resistances for 200-amp atmospheric arcs result in a gradient of several tens of volts per centimeter (*13*), giving a heating of less than 2×10^9 watts—an order of magnitude less than required. If it is assumed that there is a glow discharge and that the current is distributed approximately uniformly across the vortex, then the current density, J, becomes

$$J = I/\text{area} = 10^{-5} \text{ amp/cm}^2.$$

To show that the current is carried by electrons, we prove that the assumption to the contrary is false. If it is assumed that the electrons are rapidly attached as negative ions, and that the mobility of positive and negative charge carrers μ equals 1 cm^2 sec^{-1} volt^{-1} (*13*), then for an electric field typical of thunderstorms of 1 kv/cm, ambipolar diffusion results in a charge density, n_i

$$n_i = J/2\, \mu E = 3 \times 10^{10} \text{ ion/cm}^3$$

For an ion-ion recombination coefficient, α, of 1×10^{-6} cm^3/sec in heated air, the ion lifetime, τ_i, becomes

$$\tau_i = 1/n_i\, \alpha = 3 \times 10^{-5} \text{ second}$$

giving an ion mean free path, λ_i, of

$$\lambda_i = \mu E \tau_i = 3 \times 10^{-2} \text{ cm.}$$

The electron attachment coefficient in air for E of 1000 volt/cm, atmospheric pressure and temperature less than 400°C is approximately 5 per centimeter (*13*), giving a mean free path of 0.2 cm or ten times further than the ions. Therefore, the assumption that the current carriers were positive and negative ions only is false, and the current must be carried primarily by electrons.

The electron mobility is 100 so that the electron charge density becomes

$$n_e = 3 \times 10^8/\text{cm}^3.$$

In small-size corona discharges, maintenance of this electron density requires a higher electric field of about 10 kv/cm at P equal to 0.5 atm and T approximately equal to 400°C, but the properties of discharges as large as 50 m in diameter will be different because of the photon reabsorption, in which case, the electric field may be as small as 1 kv.

The control of the electrical heating mechanism of a tornado requires primarily the shorting of the electrical energy to the ground by another less harmful path, as Vonnegut and Rossow suggested. However, the suggestion of Rossow (*7*) was based upon the distribution of continuous wires in the cloud shorting the charge to the ground. Experiments attempting this in thunderstorms have met with only partial success (*14*), presumably because the cloud itself is an insulating medium and will support large internal fields without breaking down to the wires.

The tornado, on the other hand, is a relatively good conductor because of the lower central pressure, the electron conduction, and freedom from charge immobilizing nuclei. To attain a reasonable possibility of shorting the charge to the ground, the tornado resistivity must be increased so that the potential between the cloud and ground increases. To increase this resistivity by severalfold, one must add an electronegative gas as well as a fine aerosol of smoke particles, which have a major effect upon the corona conductivity of air. As reviewed in Brown, Freon-12 and CF_3SF_5 or SF_6 have an 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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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