of including many harmonics, have been verified by numerical integrations of the complete equations (Béland, 1976). The authors are presently engaged in performing a more complete investigation of the fully nonlinear Rossby wave critical layer.

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REFERENCES

Béland, M., 1976: Numerical study of the non-linear Rossby wave critical level development. *J. Atmos. Sci.*, **33**, 000–000.

Benney, D., and R. E. Bergeron, 1969: A new class of nonlinear waves in parallel flows. *Stud. Appl. Math.*, **48**, 181–204.

Davis, R. E., 1969: On the high Reynolds number of flow over a wavy boundary. *J. Fluid Mech.*, **36**, part 2, 337–346.

Dickinson, R. E., 1970: Development of a Rossby wave critical level. *J. Atmos. Sci.*, **27**, 627–633.

Geisler, J. E., and R. E. Dickinson, 1974: Numerical study on an interacting Rossby wave and barotropic zonal flow near a critical level. *J. Atmos. Sci.*, **31**, 946–955.

Lin, C. C., 1958: On the instability of laminar flow and the transition to turbulence. *Proc. Boundary Layer Research Symposium*, Freiburg/BR, 26–29 August, 1957, H. Gortler, Ed., 144–160.

Comments on "The Role of Electric Forces in Charge Separation by Falling Precipitation in Thunderclouds"

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Kamra (1970, 1975) has used simple mathematical models to set the upper limits of cloud electrification by several gravitational mechanisms of charge separation. In his latest model, he requires that the size of the cloud particles, the number of cloud particles, the size of the precipitation particles, the number of precipitation particles, the charge per cloud particle and the charge per precipitation particle do not change with time. He has assumed that the cloud has already developed precipitation-sized particles and that the particles have acquired charges before he begins the computations, presuming that these assumptions will not affect the maximum value of the electric field that can be attained.

In his earlier paper he allowed the charges on the particles to vary with the electric field to approximate the effect of polarization charging. In either case an estimate of the maximum attainable electric field was atttained through an integration of Maxwell's differential equation for the growth of the electric field due to the contributing currents. As a result of these calculations, Kamra (1975) has concluded that electrification of clouds by any mechanism involving precipitation can only be effective as a secondary mechanism. Within the limitations of the models used, this conclusion appears valid. However, we have recently refined this treatment to allow for expected variations in particle sizes and numbers as well as charge sizes and numbers in a reasonably complete, interactive, stochastic model (Scott and Levin, 1975). Our model considers the electrical forces on all the particles and their altered fall velocities, the recombination of charge due to capture processes, the redistribution of charge during bouncing collisions, and the efficiency of contact and the contact angle.

Results from our model indicate field growth to over 4 kV cm^{-1} in realistic growth times even with precipitation rates well below 1 cm h^{-1} (Levin and Scott, 1975). Such fields are in agreement with most measurements of electric field strengths in thunderclouds (Winn and Moore, 1971, 1972; Gunn, 1954). One must point out that all the models to date only address themselves to average fields in the cloud and it is possible that lightning is triggered by higher fields that exist for short times due to inhomogenities in the cloud electrical structure. Such inhomogenities cannot be predicted by infinite cloud models since the field is averaged; full two-dimensional or even three-dimensional models are needed to resolve them. However, the electric fields reported are also electronically averaged and/or sufficiently removed from the charge centers that they effectively measure averaged values. In addition, radar measurements are averaged over large vertical and horizontal dimensions, so it is not surprising that the theoretical results are somewhat in agreement with the data (Levin and Scott, 1975).

Surprisingly, with the polarization charging mechanism, one often obtains larger electric fields with a diminished effectiveness of the charging mechanism. This effect is contrary to normal thinking and is, perhaps, our major criticism of Kamra's (1970, 1975) theoretical treatment of electrical charging by precipitation mechanisms. The interactions between electrical charge generation and precipitation formation are highly nonlinear and cannot be treated by simple linearized equations. These mechanisms are self-governing because a very effective particle-charging mechanism will quickly create charged particles that become suspended relative to one another in the electric field, terminating further field growth or precipitation formation. As a result, the most effective charging mechanism does not necessarily produce the largest electric field.

Simply put, if the particles are small and have acquired only insignificant charges, the levitating effect is small. Alternatively, when the particles have accumulated large charges, they may have grown to such large sizes that the electrical forces cannot overcome the gravitational forces. Depending on the rate of particle growth relative to the rate of charge and field development the levitation effect may occur early at a low field when the particles are relatively small or, alternatively, after a long time when the field is higher and the particles are large. However, if the particles grow large enough while gathering charge Q at a relatively slow rate, levitation will not occur and the particles will continue to fall at velocity V. Hence the field growth, which is proportional to the term ΣQV, will continue. Kamra (1970, 1975) did not consider these counteracting effects since he did not follow the charging of the particles from the onset of particle growth.

This nonlinearity of the processes leads to the situation where one is not concerned with optimizing the efficiency of charging to obtain the largest electric field. In fact, optimization as done by Kamra (1970, 1975) may give a best estimate of the *minimum* field that can be obtained. This applies to the laboratory experiments of Kamra and Vonnegut (1971) as well (see Levin and Scott, 1975). Nonetheless, in agreement with Kamra's (1975) paper, we feel that the mechanisms he considered in that paper (the splintering of drops and ice crystal/hailstone collisions) do not have the appropriate dependence on size and field to allow significant contribution to the electrification of thunderclouds. This does not, however, rule out other gravitational mechanisms, and (as mentioned) polarization charging is a particularly powerful one.

REFERENCES

Gunn, R., 1954: Electric field regeneration in thunderstorms. *J. Meteor.*, **11**, 130–138.

Kamra, A. K., 1970: Effect of electric field on charge separation by falling precipitation mechanism in thunderclouds. *J. Atmos. Sci.*, **27**, 1182–1185.

——, 1975: The role of electrical forces in charge separation by falling precipitation in thunderclouds. *J. Atmos. Sci.*, **32**, 143–157.

——, and B. Vonnegut, 1971: A laboratory investigation of the effect of particle collisions on the generation of electric fields in thunderstorms. *J. Atmos. Sci.*, **28**, 640–644.

Levin, Z., and W. D. Scott, 1975: Polarization charging may produce a large electric field before the radar echo maximum. *J. Geophys. Res.*, **80**, 3918–3923.

Scott, W. D., and Z. Levin, 1974: Stochastic rain development in an electrified cloud. *Preprints Conf. Cloud Physics*, Tucson, Ariz., Amer. Meteor. Soc., 377–382.

——, and ——, 1975: A stochastic electrical model of an infinite cloud: Charge generation and precipitation development. *J. Atmos. Sci.*, **32**, 1814–1828.

Winn, W. P., and C. B. Moore, 1971: Electrical field measurements in thunderclouds using instrumented rockets. *J. Geophys. Res.*, **76**, 5003–5017.

——, and ——, 1972: Reply (to Freier). *J. Geophys. Res.*, **77**, 506–508.

Reply

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One major reason for the controversy during the last few years over the question of the dominating mechanism of thunderstorm electrification has been a tendency to reach final conclusions about the efficiency of some particular mechanism in the absence of sufficient data on the electrical and dynamical nature of the cloud. Experimental data available at present on such factors as the particle charge densities, electric