No. 11

Western Region Technical Memorandum

SOME ELECTRICAL PROCESSES IN THE ATMOSPHERE

by

J. Latham

June 1966

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
U. S. WEATHER BUREAU

Western Region Technical Memoranda:

No. 1 "Some Notes on Probability Forecasting" by Edward D. Diemer

No. 2 "Climatological Precipitation Probabilities" compiled by Lucianne Miller

No. 3 "Western Region Pre- and Post-FP-3 Program" by Edward D. Diemer

No. 4 "Use of Meteorological Satellite Data"

No. 5 "Station Descriptions of Local Effects on Synoptic Weather Patterns" by Philip Williams, Jr.

No. 6 "Improvement of Forecast Wording and Format" by C. L. Glenn

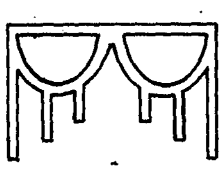
No. 7 "Final Report on Precipitation Probability Test Programs" by Edward D. Diemer

No. 8 "Interpreting the RAREP" by Herbert P. Benner

No. 9 "A Collection of Papers Related to the 1966 NMC Primitive-Equation Model"

No. 10 "Sonic Boom" by Loren Crow (6th Weather Wing, USAF, Pamphlet)

No. 11 "Some Electrical Processes in the Atmosphere" by J. Latham



A western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

SOME ELECTRICAL PROCESSES IN THE ATMOSPHERE

TABLE OF CONTENTS

Editor's Note:

This Technical Memorandum is a republication of an article by Dr. J. Latham, originally published in the April 1966 issue of "Weather", on processes that are responsible for the electrical phenomena found in thunderstorms and snowstorms.

Dr. Latham's article is published as a Technical Memorandum, with his kind permission, to make available to Western Region personnel some of the latest ideas and theories regarding the development of large electrical discharges in thunderstorms.

L. W. Snellman
Chief, Scientific Services

SOME ELECTRICAL PROCESSES IN THE ATMOSPHERE

By J. Latham*

National Center for Atmospheric Research, Boulder, Colorado

I - Introduction

Numerous electrical phenomena occur in the atmosphere. They range from extremely weak charging processes such as bubble-bursting at the surface of the oceans and condensation of cloud droplets on ions to the violent and spectacular electrical effects associated with volcanic eruptions and thunderstorms. Although it has been established that a multitude of physical mechanisms of charge transfer will operate in the atmosphere, very few of the observed electrical phenomena have been satisfactorily explained. The problems are particularly complicated in situations where water and ice coexist, as in large clouds. The difficulties of establishing the separate contributions to the observed electrification made by freezing, melting, splashing, bubbling, fragmentation, evaporation and collision, together with the influence of the prevailing electric fields in producing polarization of the hydrometeors and the distortion or disruption of water drops present almost insuperable problems of interpretation. The only solution appears to be the marriage of comprehensive laboratory investigations of each process, in which its efficacy is determined under all conceivable meteorological conditions, with equally thorough field studies in which the electrical properties are measured simultaneously with the values of all parameters which could be of significance. Little progress will be made while definite conclusions continue to be drawn from incomplete and often ambiguous data.

One charging mechanism which is explicable in terms of established physical effects is charge transfer associated with temperature gradients in ice, described by Latham and Mason (1961a). An assessment of the various conditions under which charge can be separated by means of this process was given by Latham (1965). It was shown that charge is transferred when temperature gradients exist within individual ice specimens, when specimens of different temperature are brought into transient contact, when ice specimens of equal temperature are rubbed together asymmetrically, and when ice evaporates. For ice containing only those contaminants found in natural rainwater the warmer ice becomes negatively charged and the colder ice positively charged. If uniform temperature-gradients exist along uniform specimens of ice the measured charge transfer is consistent with Mason's equations, but if the ice contains air bubbles, is non-uniform, or is impacted at velocities greater than

* On leave of absence from the Manchester College of Science and Technology.

about 10 cm sec^{-1}, the charge transfer is significantly greater than predicted by the theory.

II - The Electrification of Snowstorms

The electrical effects associated with blizzards were first studied in detail by Simpson (1921) who found that, in general, the blowing of snow was accompanied by a large increase in the normal positive potential gradient of the atmosphere close to the ground. These observations have subsequently been confirmed by other workers. Laboratory experiments in which the conditions existing in a snowstorm were simulated, and in which snow was disrupted by means of an air jet, or allowed to make violent impact with a snow block, showed that appreciable electrification was produced; charge was measured in the air, on the blown snow particles, and on the snow block. A detailed analysis by Latham and Stow (1965a) of this field and laboratory work showed that despite the erratic and often contradictory results, it is possible to discern a pattern in the electrification which is explicable qualitatively in terms of the temperature-gradient theory. According to their interpretation the measured charging was produced primarily by the frictional rubbing of snowflakes with the snow surface over which it was blown and the fragmentation of delicate snowflakes whose extremities were colder than their interiors because of evaporation.

In order to determine experimentally whether temperature differences are an important factor in producing the electrification of snowstorms Latham and Stow assembled the apparatus shown in Fig. I inside a refrigerator, the temperature of which was maintained at -20°C. An air jet whose velocity could be varied from 0-30 m sec^{-1} was directed on to the lower portion of a pyramid of snow residing on a copper tray. The temperature of the jet could be varied over the range 0°C to $\pm$ 40°C, thus enabling temperature differences of up to $\pm$ 20°C to be created between the base and the summit of the snow surface exposed to the air stream; these were measured by means of suitably located fine insulated thermocouples. Blown snow particles were collected in a large copper vessel; and in order to measure the electrical effects produced, the tray and the collector were both connected to electrometers in series with pen recorders. It was possible to distinguish from the records between the charges carried by tiny snow fragments blown into the collector and the charges residing upon the blown snow particles of much larger size. As the volume of the refrigerator was too small for accurate measurements to be made of the charge carried by the air, these experiments could indicate only whether qualitative consistency existed between the observed electrical effects and the temperature-gradient theory.

The experiments showed that the sign of the charge on the blown ice fragments was dependent upon the sign of the temperature difference between the air jet and the summit of the snow pyramid. When the jet was colder than the snow the fragments were negatively charged; when it was warmer the fragments were positively charged. The larger blown-snow particles always acquired a positive charge which was unrelated to the temperature gradient along the surface of the snow pyramid. Greater disruption and associated charging were found to accompany an increase in the velocity of the air jet.

These charging observations are explicable qualitatively in terms of the temperature-gradient theory. The air stream produced a temperature-gradient along the windward surface of the snow pyramid. The base acquired the temperature of the jet while the summit temperature remained close to -20°C. Therefore, according to the theory, when the jet is colder than the snow the summit will become negatively charged, and when fragments are blown from it they will carry away some of this charge; when the jet is warmer than the snow the fragments will be positively charged. In the case of the large particles the changing is attributable to asymmetric rubbing between a multitude of tiny ice fragments and the larger particles, which have greater rubbing area, are therefore cooler than the fragments, and consequently acquire positive charge, as was observed.

Temperature gradients, therefore, appear to be of prime importance in producing the charge transfer which accompanies the blowing of snow. However, in order to determine whether the qualitative agreement between the temperature-gradient theory and the electrical observations is reinforced quantitatively, it will be necessary to make measurements of the space-charged density of the air in the vicinity of the blowing snow, and of the charge carried by individual snow particles. An attempt to perform such experiments is presently being made inside a large cold room in Manchester.

III - The Electrification of Thunderstorms

There are two processes by which the temperature-gradient mechanism could be responsible for the creation of the main dipole of a typical thunderstorm, with positive charge located above negative charge and both charge centres situated at temperatures below 0°C. The first process involves the freezing and fragmentation of supercooled droplets as they are collected by soft hail pellets. When a water drop supercooled to a temperature T degrees below 0°C is nucleated a fraction T/80 of the drop freezes immediately, often in the form of a shell of ice surrounding a liquid interior. Any subsequent freezing and associated expansion generates immense pressures in the ice shell, which often shatters, ejecting many small ice fragments, primarily from the exterior of the shell. However, during the freezing of the drop a radial temperature gradient exists in the ice shell, with the exterior surface, at a temperature close to that of the environment of the drop, being colder than the water-ice interface forming the inner surface of the ice shell. According to the temperature-gradient theory the outer surface has a net positive charge part of which could be carried away on the ejected ice fragments, leaving a compensating negative charge on the residual frozen drop which, inside a thundercloud, would be frozen on to a soft hail pellet. Gravitational separation of the positively charged ice crystals and the heavier negative pellets of soft hail would therefore confer the observed positive polarity on the thundercloud. Latham and Mason (1961b) simulated this process in the laboratory and determined that appreciable charging occurred over a wide range of temperature, droplet diameter, and impact velocity. They concluded that the average charge per freezing droplet was consistent with Mason's equations and that this process could generate charge inside a thunderstorm at a rate of about I coulomb km^{-3} min^{-1}, which is the value calculated by Mason (1953) for the minimum rate at which any tenable mechanism of thunderstorm electrification must generate charge. However, electrical activity corresponding to a charging rate of about one hundred times this initial value has been observed occasionally, and some recent experiments by Stott and Hutchinson (1965) have shown that the charging produced by the freezing and fragmentation of individual supercooled drops is often significantly different from the predictions of Mason's equations.

The second process by which the temperature-gradient effect can create charges within thunderclouds involves the rebounding collision between ice crystals and much larger pellets of soft hail growing by the accretion of super-cooled droplets which freeze on to the pellets and warm their surfaces by the associated evolution of latent heat. The colder ice crystals acquire positive charge on collision with the pellets and gravitational separation of the crystals and the negatively charged pellets therefore confers the observed positive polarity on the thundercloud. Reynolds, Brook and Gourley (1957) deduced from some laboratory experiments that the average charge per crystal-hailstone collision would be about 5×10^{-4} esu and that this process could therefore easily generate charge inside thunderclouds at the required rate. However, Latham and Mason inferred from their laboratory experiments that a typical value for the charge transfer per collision was 5×10^{-9} esu which is consistent with Mason's equations but which, if applicable to thunderstorms could generate charge at only an insignificant rate. However, Latham and Stow (1965b) demonstrated that the charge transfer associated with temperature gradients in ice increases markedly with increasing impact velocity and irregularity of the ice specimens and concluded that the enormous discrepancies between these two sets of investigations is probably a consequence of the fact that in the experiments of Latham and Mason no droplets were present and ice crystals made glancing contact with a smooth hailstone; whereas in the experiments of Reynolds, Brook and Gourley the simulated hailstone had a highly irregular surface structure owing to the presence of supercooled droplets in its vicinity and ice crystals impacted against it with extreme violence; their experiments were therefore more representative of the conditions existing inside a thundercloud than those of Latham and Mason. However, the experiments of Latham and Stow were confined to large ice specimens impacting at velocities much lower than those with which ice crystals and soft hail pellets collide in the atmosphere, so Latham and Miller (1965) performed some experiments in Yellowstone Park to determine whether these enhancement processes were still operative under conditions which corresponded more closely to those occurring inside thunderclouds.

An ice-coated sphere was suspended from an insulating fibre and was whirled through a stream of steadily-falling natural ice crystals. Any charge acquired by this artificial hailstone was then measured by lowering it into an induction can connected to an electrometer. The surface structure of the hailstone could be varied by spraying it with supercooled droplets, formed by means of an atomizer. An average value for the velocity of impact could be calculated from the length of the fibre and the revolution rate, and an approximate value for the charge per collision could be computed from the number of revolutions, the radius of the hailstone, the dimensions of the ice crystals and the precipitation rate, which remained roughly constant over a period of several hours, thus facilitating the acquisition of unambiguous results.

Fig. 2 shows that when a smooth ice sphere made collisions with snow crystals it acquired a positive charge, the magnitude of which increased markedly with an increase in impact velocity. The positive charging is explicable qualitatively in terms of the temperature-gradient mechanism because asymmetric rubbing causes the crystals, of diameter about 1 millimetre, to become warmer at the points of contact than the smooth hailstone, which therefore acquires the observed positive charge.

Fig. 3 shows that the negative charge acquired by the rimed spheres on exposure to the crystal stream increased markedly with increasing velocity and surface roughness of the spheres. The magnitude of the charge acquired by a sphere possessing a high degree of surface irregularity is seen to be about ten times greater than that acquired by a smooth sphere colliding at the same velocity with an identical cloud of snow crystals. The negative charging of the spheres is explicable qualitatively in terms of the temperature-gradient theory and can be attributed to asymmetric rubbing between the crystals and the irregular surface of the spheres, formed by the freezing of supercooled droplets of diameter between 10 and 90 microns; in this case the surfaces of the spheres have a smaller rubbing area than the snow crystals and therefore become warmer than the crystals and acquire negative charge, in agreement with the theory.

The influence of the surface structure in determining the sign of the charge on the hailstone, produced by asymmetric rubbing with ice crystals, is illustrated in Fig. 4. The magnitude of the average charge per collision between an ice crystal impacting with a velocity of 8 m sec^{-1} against an artificial hailstone of irregular surface structure, which is representative of the situation occurring inside thunderstorms, was 10^{-3} esu. This value for the average charge per collision is in good agreement with that measured in the experiments of Reynolds, Brook and Gourley and is several orders of magnitude greater than predicted by Mason's equations. However, in view of the described rapid increase of charge transfer with increasing impact velocity and surface irregularity it appears that the enhancement of the measured values above the theoretical predictions can be ascribed solely to these two processes, and that the results of the experiments of Reynolds, Brook and Gourley are explicable in terms of a modified temperature-gradient theory.

The theory of charge transfer associated with temperature gradients in ice therefore provides the physical basis of two theories of thunderstorm electrification, the droplet shattering process described by Latham and Mason, which can generate charge inside a thundercloud at the required minimum rate, and the ice crystal-soft hailstone collision process propounded by Reynolds, Brook and Gourley, which can generate charge at a slightly higher rate. The two processes acting in conjunction produce appreciable negative charging of soft-hail pellets over a wide range of temperature, pellet radius, and supercooled droplet diameter as shown in Fig. 5. However, these processes are probably not primarily responsible for the immense lightning activity of the giant electrical storms which have occasionally been reported.

It is aesthetically unsatisfactory to postulate more than one explanation for thunderstorm electrification, just as it was difficult several years ago to accept two mechanisms of rain formation, but it should perhaps be remembered that the noun "thunderstorm" merely defines a cloud which, at some stage in its history, produces lightning. A thunderstorm can develop in many different ways according to its geographical and topographical location and the particular time and season during which it evolves. Its dynamical and physical characteristics vary immensely as it grows from a small water cloud—which often possesses significant electrical properties—to a huge precipitating cumulonimbus. In fact, it appears that many charging mechanisms will be operative inside thunderclouds, although there are probably not more than three or four processes which provide almost all of the electrification of the great majority of thunderstorms; one of these processes will preponderate at a specific stage in the lifetime of a particular cloud, while another may be dominant at a different stage, or in another cloud.

The thunderstorm is a vital, dynamic and extremely complex phenomenon, whose labyrinthine interactions and spatial and temporal idiosyncracies bemuse the investigator who presumes to unravel its secrets. However, the problems are susceptible to modern research techniques, and painstaking studies involved are willing to accept that the exceptions may, on occasion, be the rule.

IV - Acknowledgment

The author is deeply grateful to Dr. V. J. Schaefer for the invitation to participate in the 1965 Yellowstone Field Research Expedition.

V - References

Latham, J.	1966	Weather, 21 (3), p. 79
Latham, J. and Mason, B. J.	1961a	Proc. Roy. Soc., A, 260, p. 523
	1961b	Ibid., A, 260, p. 537
Latham, J. and Miller, A. H.	1965	J. Atmos. Sci. (in Press)
Latham, J. and Stow, C. D.	1965a	J. Met. Soc. Japan, 43, p. 23
	1965b	Quart. J. R. Met. Soc. 91, p. 462
Mason, B. J.	1953	Tellus, 5, p. 446
Reynolds, S. E., Brook, M. and Gourley, M. F.	1957	J. Meteor., 14, p. 426
Simpson, G. C.	1921	Atmospheric Electricity. British Antarctic Exp. 1910-1913, I, Harrison and Sons, London
Stott, D. and Hutchinson, W. C. A.	1965	Quart. J. R. Met. Soc., 91, p. 80

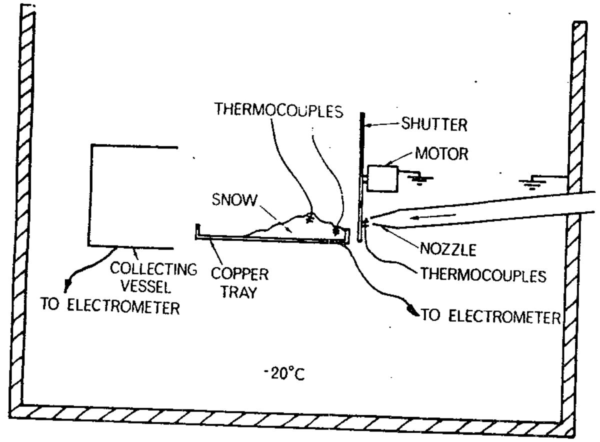


Fig. 1. Apparatus for measuring the electrification produced when snow is disrupted by an air jet

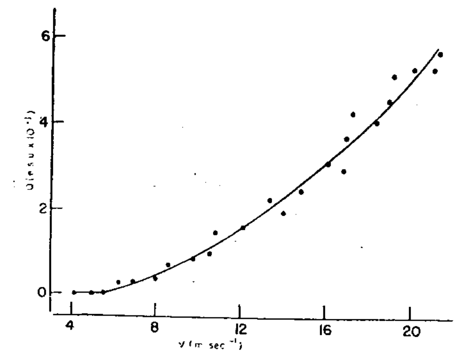


Fig. 2. The charge Q acquired by a smooth ice sphere exposed to a stream of snow crystals as a function of the velocity of impact V

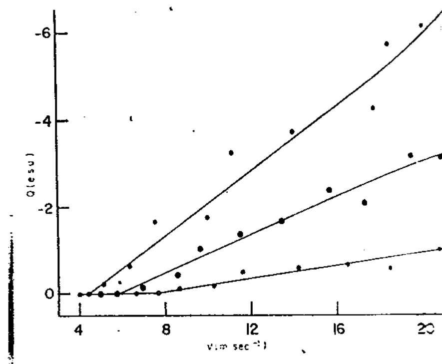


Fig. 3. The charge Q acquired by ice spheres of irregular surface structure exposed to a stream of snow crystals as a function of the velocity of impact V: (1) exceedingly irregular, (2) very irregular, (3) irregular surfacestructure

Fig. 4. Asymmetric rubbing with ice crystals confers (a) positive, (b) negative charge on a soft-hail pellet, according to its surface structure

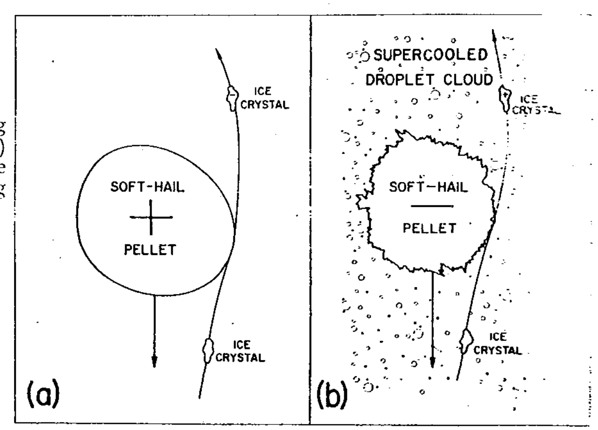


Fig. 5. The ranges of pellet radius r, supercooled droplet diameter D, and temperature T over which a growing pellet of soft hail acquires appreciable negative charge by means of (A) ice-crystal-hailstone collisions and (B) supercooled droplet shattering