The electrostatic force in blowing snow
by David Scott Schmidt

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering
Montana State University

Abstract:
In blizzards and sand storms, wind transport of particles is associated with separation of electrostatic charge. Moving particles develop charge of sign opposite the electrostatic charge on stationary surface particles. This electrification produces forces, in addition to the gravitational and fluid friction forces, that determine trajectories for particles being transported in saltation. Evaluating electrostatic forces requires the electric field strength very near the saltation surface and charge-to-mass ratios for the moving particles.

Measurements in a blizzard provide an electric field profile, with measured fields as high as 30 kV m-1 measured at the 4-cm height. Reversal of charge sign on samples of saltation particles collected in a blizzard indicates a mixture of positive and negative particles in transport. This result points out the need for measurements of charge on individual particles, and an apparatus designed to make these measurements is detailed. Using measured charge-to-mass ratio for individual saltation particles (Schmidt et al., 1998) of +72 mC kg-1 and -208 mC kg'1 we estimate electrostatic forces as large as the gravitational force on some saltating particles. Including forces of this magnitude in the equations of motion for saltating particles shows saltation trajectories altered as much as 60% from those for uncharged particles.

These results show that the electrostatic force has a significant effect on the saltation process which brings up questions about the effects of the electrostatic force on the transfer of momentum from the atmospheric boundary layer to the planetary surface and wind transport of particles by suspension in the atmosphere.

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APPROVAL

of a thesis submitted by

David Scott Schmidt

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 13 JAN 99

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ABSTRACT

In blizzards and sand storms, wind transport of particles is associated with separation of electrostatic charge. Moving particles develop charge of sign opposite the electrostatic charge on stationary surface particles. This electrification produces forces, in addition to the gravitational and fluid friction forces, that determine trajectories for particles being transported in saltation. Evaluating electrostatic forces requires the electric field strength very near the saltation surface and charge-to-mass ratios for the moving particles.

Measurements in a blizzard provide an electric field profile, with measured fields as high as 30 kV m^{-1} measured at the 4-cm height. Reversal of charge sign on samples of saltation particles collected in a blizzard indicates a mixture of positive and negative particles in transport. This result points out the need for measurements of charge on individual particles, and an apparatus designed to make these measurements is detailed. Using measured charge-to-mass ratio for individual saltation particles (Schmidt et al., 1998) of +72 mC kg^{-1} and -208 mC kg^{-1} we estimate electrostatic forces as large as the gravitational force on some saltating particles. Including forces of this magnitude in the equations of motion for saltating particles shows saltation trajectories altered as much as 60% from those for uncharged particles.

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CHAPTER ONE

INTRODUCTION

Wind is an incredibly powerful force capable of moving vast quantities of snow during blizzards. Deposition of wind-blown snow forms large drifts that hamper winter travel in many regions of the world. Billions of dollars are spent annually in an effort to keep roads and railways clear of drifting snow. In mountainous regions, cornices and wind-deposited snow in the lee of ridges trigger avalanches that damage structures and transport systems. Effective control of this natural phenomenon requires a better understanding of the physical processes that govern the transport of snow.

Wind transports snow by three mechanisms. Particles roll along the surface in a process termed creep. This mechanism occurs in light winds and accounts for very little transport. Strong winds eject particles from the surface in a mode of transport called saltation. Particles in saltation bounce along the surface, rebounding to heights typically within 10 cm of the surface. Most of the transport during blowing snow storms moves in saltation. In the third transport mode, known as suspension, particles travel without impact, at heights that may extend several hundred meters in polar storms. Saltating particles are the source for suspended transport, therefore understanding saltation is essential to controlling blowing snow.

The Saltation Process In Blowing Snow

In describing the motion of sand particles in water, Gilbert (1914) used the word saltation, to describe the hopping motion of sand particles near the flow bed. Later, Bagnold (1941) showed that this same mechanism occurred in wind-blown sand, and Kobayashi (1972) first photographed saltation occurring in drifting snow.

Saltation of snow in air occurs when wind across a snow surface exceeds a threshold speed above which particles are dislodged and ejected into the flow. Once dislodged, the snow particles bounce along the boundary, within a few centimeters of the surface. Photographs show the particles are often rounded by abrasion, with equivalent spherical diameters ranging from 0.1 to 0.5 mm (Schmidt, 1981). Kobayashi (1972) estimated trajectory lengths as large as 1 m in moderate drifting, with mean lengths between 0.1 and 0.3 m for wind speeds of 10 m s^{-1} at 1 m height.

The restitution coefficient of an ice sphere bouncing on an ice block ranges from 0.6 to 0.9 as temperature decreases from -5 to -20 C, (Kobayashi, 1972). As a result, impacts of saltating snow are sufficient to fracture ice bonds holding surface grains (Schmidt, 1980) and impact energy may be transferred to several new particle trajectories. This rebounding of particles on the surface transfers significant momentum from the atmosphere to the planetary boundary

(Kikuchi, 1981), and results in a drag on the wind that is reflected in the vertical velocity profile (Maeno et al. 1979).

Whether it be snow or sand particles in air, sediment in a river bed, or sand in a density current on the ocean floor, the equations that describe saltation are of similar form. Particle rebound from elastic impact with surface particles to follow long, low trajectories in response to forces of fluid drag and gravitation. Using a high-speed camera to photograph trajectories of saltating glass spheres in a wind tunnel, White and Schultz (1977) found trajectories were higher and longer than predicted from equations involving only fluid drag and gravitational forces. They improved agreement with the observed trajectories by adding Magnus lift to the theoretical equations. However, matching measured trajectories by the addition of Magnus effect required large spin rates, in the range of 100 to 300 revolutions per second. Another force that could add or subtract lift is the electrostatic force that develops due to frictional rubbing between the particles and surface as they saltate.

A charged particle, moving in an electric field, is subject to an electrostatic force. The magnitude of the force is equal to the product of the electric field and the charge on the particle. The force acts along the electric field vector, in the direction determined by the sign of the particle charge. The purpose of the research presented in the following thesis was to measure the electrostatic force in blowing snow and analyze its effect on particle saltation trajectories. Equations of motion for a saltating sphere subject to an electrostatic force are developed. Measurements of the electric field during a blizzard as well as particle charge are presented. Finally, the equations of motion are solved, using this experimental data, showing the effects of electrification on saltation.

CHAPTER TWO

ELECTRIFICATION OF BLOWING SNOW

The Electrostatic Force

Two charges q and Q, separated by a distance r, experience a Coulomb force defined by

$$\mathbf{F} = \frac{qQ}{4\pi\varepsilon r^2}\mathbf{r}\,. \tag{2.1}$$

Here, $4\pi\varepsilon$ is a proportionality constant, with ε being the free permittivity of space. This force acts over a distance and is therefore a field force associated with an electric field analogous to the gravitational force and field that results from the separation of mass. By definition the electric field is the force on Q per unit test charge q so that

$$\mathbf{E} \equiv \left(\frac{\mathbf{F}}{q}\right) = \frac{Q}{4\pi\varepsilon r^2}\mathbf{r} \tag{2.2}$$

Equation (2.2) is known as Coulomb's Law. Equations (2.1) and (2.2) allow us to state that the force on charge q due to the electric field **E** is

$$\mathbf{F} = q\mathbf{E}\,. \tag{2.3}$$

The electric potential Φ of a unit charge in an electric field is defined by the work necessary to move the charge from $r = \infty$ to $r = r_o$ against the electric field so that

$$\Phi = \int_{\infty}^{r_o} \frac{Q}{4\pi\varepsilon r^2} \mathbf{r} \cdot d\mathbf{r} \tag{2.4}$$

or, conversely,

$$\mathbf{E} = -\nabla\Phi \,. \tag{2.5}$$

For any vector field we can define a flux through a surface. For the electric field **E** the electric flux through some surface S is

$$f = \int \mathbf{E} \cdot d\mathbf{S} \,. \tag{2.6}$$

Using Coulomb's Law we can write

$$\mathbf{E} \cdot d\mathbf{S} = \frac{Q}{4\pi\varepsilon r^2} \mathbf{r} \cdot d\mathbf{S} \,. \tag{2.7}$$

The dot product $\mathbf{r} \cdot d\mathbf{S}$ is the projected area element on the surface of a sphere of radius r. In spherical coordinates this is given by

$$\mathbf{r} \cdot d\mathbf{S} = (rd\theta)(r\sin\theta d\phi) = r^2 d\Omega \tag{2.8}$$

where $d\Omega$ is often referred to as the differential solid angle. The integral of $d\Omega$ over a closed surface is 4π so that combining equations (2.7) and (2.8) gives

$$\oint \mathbf{E} \cdot d\mathbf{S} = \frac{Q}{\varepsilon} \,. \tag{2.9}$$

Equation (2.9) for a single point charge generalizes, by the superposition principle, to the net charge density ρ(r) inside the surface

$$\oint \mathbf{E} \cdot d\mathbf{S} = \frac{\rho}{\varepsilon}. \qquad (2.10)$$

Using the divergence theorem (2.10) can be rewritten as

$$\int (\nabla \cdot \mathbf{E}) dV = -\int (\nabla^2 \Phi) dV = \frac{\rho}{\varepsilon}. \qquad (2.11)$$

Since the choice of volume is arbitrary this result must not depend on the volume integration but rather the integrand, implying

$$\nabla^2 \Phi = -\frac{\rho}{\varepsilon}, \qquad (2.12)$$

which is Poisson's Equation.

Electric Fields In The Atmospheric Boundary Layer

Electric fields result from a separation of positive and negative charge. During periods of fair weather, ionization of air by gamma radiation, both terrestrial and from space, creates an electric field in the atmosphere that decreases with height above the Earth's surface. This fair-weather field varies considerably over time and location, with the average fair-weather field 1 m above the Earth's surface being -120 V m^{-1}. The negative field vector points toward the Earth's center, indicating positive charge located over negative charge in the atmosphere (Iribarne and Cho, 1980).

During dust storms and blizzards, the field increases in magnitude and reverses direction in the region occupied by blowing particles (Schonland, 1953). Many observers have reported electrification of natural blowing snow. Simpson (1921), Sheppard (1937), Schaefer (1947), Pierce and Currie (1949), Barre (1953), and Magono and Sakurai (1963) all observed a considerable increase in the positive electric field gradient normal to the earth's surface during blowing and drifting snow events. This would indicate negative charge positioned over a positively charged surface. Assuming that the electric field E is a function of height alone, the relationship between electric field and charge density ρ is given by Poisson's equation

$$\frac{dE}{dz} = -\frac{\rho}{\varepsilon}, \tag{2.13}$$

where z is height above the surface. The charge density decreases rapidly with height as transported particle density decreases so that the electric field diminishes with increasing height through the transportation region. At some point a balance between atmospheric charge and surface charge must exist at which point the electric field is zero. The total electric field at any height h is found by separating variables and integrating expression (2.13) so that

$$E_h = \frac{1}{\varepsilon_0} \int_0^h \rho dz. \tag{2.14}$$

so that the electric field is simply a function of the charge density between the surface and any given height h.

The field strength at which the insulating properties of air breaks down and allows electrical discharge provides an upper limit, near 3000 kV m^{-1} [Iribarne and Cho, 1980]. Results of such discharges depend on the amount of charge separation. Effects range from unobserved point discharges (most likely the case for blowing sand or snow on Earth) to the legendary Saint Elmo's fire at the pointed end of ships' masts during storms at sea, and the spectacular display of lightning following separation of enormous quantities of charge in thunderstorms.

Charge Separation In Ice

Efforts to explain electrification in thunderstorms produced most of the knowledge on charge separation mechanisms in ice. Several theories explaining thunderstorm electrification have developed since the early 1940's, but at this point, the process is not entirely understood. Lightning is the result of charge separation in clouds extending above heights at which the air temperature is 0°C. The main thunderstorm dipole develops in the region of the cloud where temperatures are well below freezing. This lead early researchers to conclude that the ice phase, or transition to the ice phase was responsible for thunderstorm electrification. Workman and Reynolds (1950) showed that large charge separation results as aqueous solutions freeze. They associated this charge separation (termed the Workman-Reynolds effect) to migration of contaminants along concentration gradients between the solid and liquid phase. Reynolds et al. (1957) hypothesized that impacts of ice crystals with a graupel pellet would create a liquid film by pressure contact, producing charge separation during regelation.

Latham and Mason (1961) demonstrated that charge separation in ice resulted from temperature gradients. Hobbs (1974, p. 179) reviews the theory of this process, termed the thermoelectric effect. Concentrations of H^+ and OH^- ions increase as the temperature on an ice specimen increases. H^+ ions have greater mobility in the ice lattice than OH^- ions, therefore they migrate more rapidly along a concentration gradient. When a temperature gradient in the ice produces an ionic concentration gradient, H^+ ions move more rapidly to colder regions. The process develops a potential difference across uniform pure ice of (2.3±0.3) mV for each degree C of temperature difference (Hobbs, 1974).

Latham and Mason (1961) extended this theory to two separate ice specimens. When two pieces of ice, at different temperatures, were brought into contact for a short period of time (10^{-3} s) and then separated, the warmer piece of ice acquired a negative charge while the cooler piece became positively charged.

Tabor (1951) estimates a contact time between colliding particles on the order of 10^{-7} s. Gross (1982) shows that, theoretically, substantial charge can be transferred in this time span for pure ice-ice collisions and that transfer is enhanced with the introduction of impurities.

Electrification In Blizzards

From laboratory experiments on the electrification of wind-blown snow, Latham and Stow (1967) suggested three processes for charge separation, all involving the thermoelectric effect. In their discussion, the processes are: (1) crystal fragmentation, (2) asymmetric rubbing, and (3) transient contact of blown particles with the surface. Each is described below. They found contributions to electrification by the Workman-Reynolds effect, and by evaporation of ice, were minimal.

Process (1), crystal fragmentation, separates charge when a temperature gradient exists across the crystal. Such a gradient might exist when the temperature of the wind differs from the snow temperature below the surface. If the wind is warmer, the most exposed projections on the surface are warmed, and become negatively charged. If such a fragment breaks from the surface, it carries a net negative charge.

Asymmetric rubbing, process (2), refers to a difference in contact areas when two ice pieces rub together. If a small ice crystal slides along a larger ice surface, the contact area of the crystal remains small, while the area contacted on the surface increases with time. Greater frictional heating of the crystal results, and the warmer crystal gains a negative charge. Henry (1953) described charging of insulators by asymmetric rubbing, which was demonstrated with ice by Reynolds et al. (1957), and Latham (1963).

By process (3), if a temperature gradient exists over the areas of contact, charge will be transferred during the transient contact of a blown particle with the surface. If air flow is warmer than the surface, particles receive negative charge during contact, since surface particles have negatively charged extremities, as in process (1). Net charge on the surface becomes opposite in sign. The signs are reversed if colder air creates saltation across a warmer surface.

Latham and Stow (1967) based their conclusions upon measurements of charging as a function of particle concentration, wind speed, temperature difference between the air and snow surface, and relative humidity. In their experiment they found charging of wind blown particles to be a strong function of wind speed, with charge increasing approximately as wind speed squared. The temperature difference ΔT between the air jet used to transport saltation particles and the snow surface had a significant effect on particle charge, particularly charge sign. Here, ΔT is positive when air temperature is greater then surface temperature. Their results indicate that particle charging is a minimum when ΔT is zero. Saltating particles became more negatively charged when ΔT was positive. Saltation particle concentrations play a role in particle charging as a function of ΔT. During low level transport of 1 g s^{-1} the net charge measured on the blowing particles switched from positive to negative, opposite the change in sign of ΔT. When mass flux was increased to 10 g s^{-1} the net charge on the saltation particles remained negative for all ΔT, with the magnitude of the charge increasing as ΔT went from negative to positive. Measurements of the effects of relative humidity on particle charging were confounded by instrumentation problems in Latham and Stow's (1967) experiment. They were able to show, however, that electrification increased as relative humidity decreased. In wind tunnel experiments, Maeno et al. (1985) also measured electrification as a function of temperature and wind speed. They found charging of blowing particles increased as wind speed increased and air temperature decreased. Their measurements did not include differences in air and surface temperatures.

A fourth process Latham and Stow (1967) suggested, ionization of air by point discharge as highly charged particles rebound from the surface, depends on the amount of charge separation developed by the first three. Their hypothesis was based on measurements (Latham and Miller, 1965) showing increasing production of ions by point discharge as wind velocity increases. As Hobbs (1974) pointed out, the relative importance of these processes under natural conditions remained to be determined. Apparently this is still the case.

Other theories explain charge separation in thunderstorms without the thermoelectric effect. Scott and Levin (1970) describe polarization of ice particles by a potential gradient, which enhances charge separation during collisions with smaller ice crystals. The force associated with collision between particles, and roughness of the ice surfaces are also factors. Scott and Hobbs (1968) show that the sign of the charge acquired by an ice specimen from a collision depends on the shapes of the particles involved and that magnitudes of the acquired charge increases with increased impact velocities. Latham and Stow (1965) found that charge transfer associated with the thermoelectric effect could be greatly enhanced if the ice specimens are rough and if impact velocities are high. They attribute their results to the delicate nature of rough particle appendages and increased particle fragmentation with increasing impact forces.

In general, the results of Latham and Stow's (1967) experiments support the hypotheses of the thermoelectric effect as the charging mechanism for windblown particles, but also suggests a complicated relationship between the charge that develops on the particle and the environment the particle travels in.

Equations for Saltation in an Electrostatic Field

In this section, we add electrostatic forces from equation (2.3) to the equations for saltating motion developed by White (1975), as presented in White and Shultz (1977). Forces acting on the moving particle include lift forces, fluid drag forces, and gravitational force $m_p\mathbf{g}$, where m_p is the mass of the particle and $\mathbf{g}$ is gravitational acceleration. The additional electrostatic force is $q\mathbf{E}$, where q denotes particle charge, and $\mathbf{E}$ is the electric field. Following notation in White and Shultz (1977), the horizontal, vertical, and rotational components of motion for a charged particle saltating in an electric field are

$$m_p \ddot{x} = L\left(\frac{\dot{y}}{V_r}\right) - D\left(\frac{\dot{x}-u}{V_r}\right) + E_x q, \qquad (2.15)$$

$$m_p \ddot{y} = -L\left(\frac{\dot{x}-u}{V_r}\right) - D\left(\frac{\dot{y}}{V_r}\right) - m_p g + E_y q, \qquad (2.16)$$

$$I_p \ddot{\theta} = M. \tag{2.17}$$

Here u is the velocity of the fluid (assumed to be traveling in the horizontal direction) which is a function of height y above the surface. I_p is the particle's moment of inertia, and $\ddot{\theta}$ is the particle's angular acceleration. E_x and E_y are the horizontal and vertical components of the electric field, and V_r is the velocity of the particle relative to the fluid flow. Its magnitude is

$$V_r = [(\dot{x} - u)^2 + (\dot{y})^2]^{1/2}. \tag{2.18}$$

Drag force D resulting from this relative velocity opposes motion of the particle and is expressed in terms of the drag coefficient C_d, as

$$D = \frac{1}{2} C_d A_p \rho V_r^2, \tag{2.19}$$

where A_p is the cross-section area of the particle, and ρ is the density of the fluid.

In the atmospheric boundary layer, the strong velocity gradient near the surface produces a pressure difference between the top and bottom of the particle, resulting in a lift force. This velocity gradient also produces a moment, causing the particle to spin, adding additional lift by Magnus effect. Total lift force on the particle is

$$L = \frac{1}{8} \pi d^3 \rho V_r (\dot{\theta} - \frac{1}{2} \frac{\partial u}{\partial y}), \tag{2.20}$$

where the lift force is coupled to the moment of the particle through the angular velocity $\dot{\theta}$ (defined as positive for clock-wise rotations) and d is particle diameter. The moment is

$$M = \pi\mu d^3(\dot{\theta} - \frac{1}{2}\frac{\partial u}{\partial y}), \tag{2.21}$$

with μ denoting fluid viscosity. We note that these equations describe the saltation trajectory for a sphere and are only an approximation to the trajectories of saltating sand and snow particles. The electrostatic charge is assumed to be uniformly distributed over the particle surface.

Electrostatic Force on Saltating Particles

Solving the equation for a charged saltation particle requires measurements of the particle charge and the electric field in the saltation region (typically 0 - 10 cm above the saltation surface). At the onset of this project measurements of average particle charge-to-mass ratios were available, however measurements of the electric field close to the saltation surface were lacking.

Several researchers have measured particle charge. Latham and Montagne (1970) measured average charge-to-mass ratios of -10 $\mu C\ kg^{-1}$ for snow blowing across a cornice. Wishart (1970) measured average charge-to-mass ratios as high as -50 $\mu C\ kg^{-1}$ in Antarctic drifting. Maeno et al (1985) showed that negative charge also develops on snow particles saltating in a wind tunnel. The charge on surface particles varied from -0.01 μC kg^{-1} to +0.03 μC kg^{-1}. These magnitudes were near those of the saltating particles, and sign changes appeared to coincide with local deposition and erosion areas on the surface. These researchers attributed lower charge-to-mass ratios, compared to those seen in natural blowing snow by Latham and Montagne (1970) and Wishart (1970), to the short fetch distance of their wind tunnel.

As will be shown, measurements made by Schmidt and Schmidt (1992) indicate average particle charge-to-mass ratios significantly underestimate actual particle charge. Nevertheless, these average values could be used as an estimate of particle charge. Solution of the saltation equations was still confounded by lack of electric field measurements. Latham and Montagne (1970) measured the field in the region 30-100 cm above the surface and found it varied significantly with height. In an effort to evaluate the effects of electrification on saltation, Schmidt and Dent (1993) proposed a theoretical model based on Latham and Montagne's (1970) data at distances far from the surface and the electric field due to a bed of charged ice spheres for the near-surface field.

Based on measurements of surface particle charge made in a wind tunnel (Maeno et al.,1985), the ice spheres were assumed to have a charge-to-mass ratio equal but opposite to that measured for blowing snow particles. The electric field above a bed of ice spheres, made up from rings of spheres arranged in closest packing, was computed as a function of height above the bed by treating each sphere as a point charge and applying Coulomb's Law. Contributions to the field decreases rapidly as the radius of these rings increases, so that little was contributed beyond 10 rings, or the area covered by 61 bed spheres. This model allowed us to solve the saltation equations (2.15) - (2.21) using standard numerical techniques. The results predicted substantial changes in saltation trajectory lengths for charged particles compared to uncharged particles. These changes in trajectory lengths were consistent with observed trajectories.

Experimental evidence was obviously needed to verify the extent to which saltation is affected by electrification. Based on measurements made by Schmidt and Schmidt (1992), we questioned the validity of particle charge-to-mass ratios determined by measuring the average charge on a sample of blowing snow. Measurements of the electric field profile in the saltation region and the charge on individual particles became the focus of the research presented here. The remainder of this thesis details Schmidt and Schmidt's (1992) experiment. Measurements of the electric field profile in the saltation region are presented as well as measurements of the charge on individual blowing snow particles. Inclusion of this data in the saltation equations presented in the previous section leads to an analysis of the effects of the electrostatic force on the saltation process.

CHAPTER THREE

MEASUREMENTS OF THE ELECTRIC FIELD GRADIENT IN A BLIZZARD

Determining of the electric field profile in a blowing snowstorm requires a measuring device that can be placed close to the snow surface without affecting the measurements. In the past it was not possible to measure closer then 30 cm to the surface without disrupting the field (hence Latham and Montagne's 1970 measurements). Recent technologic advancements have resulted in electric field meters capable of making the needed near-field measurements. The meter used in this experiment was developed by the Jet Propulsion Laboratory (JPL) at the California Institute of Technology. The DC electric field probe is described in detail by Kirkam and Johnston (1989). The following is a description of the physics involved in its operation.

DC Electric Field Mill

The sensor is a cylindrical Fiberglass shell 25 mm in diameter and 33 mm long, rotating around the long axis. The cylinder is divided length-wise into two semi-cylinders of conductive paint, coating the outer surface of the shell, separated by a thin dielectric (Figure 1). The electric field induces a charge on the surface of the cylinder (figure 1). This induced charge is proportional to the field. An air turbine (from a dentist drill) rotates the probe using compressed nitrogen in place of air as the driving agent. As the cylinder rotates, the charge on the surface remains fixed with respect to the electric field, inducing an alternating current between two electrodes mounted 180 degrees from each other on the cylinder's surface. A hybrid microcircuit inside the shell amplifies the oscillating signal and converts it to an optical pulse train by means of a light emitting diode. The pulse train is transmitted by optical fiber to a receiver that demodulates and resolves the signal into horizontal and vertical components of the measured electric field. The sensor is electrically isolated from the receiver and supported by a 1-m long Fiberglass wand clamped to the vertical support tube of an adjustable camera tripod. A calibrated ten-turn potentiometer mounted on the tripod produces voltages proportional to the height of the probe above the snow surface. Output from the receiver was recorded using a Campbell Scientific data logger (Model CR21). Moving the probe to various heights and sampling at 1 min intervals for periods of 15 min gave an average vertical profile of electric field strength. We confirmed probe calibration

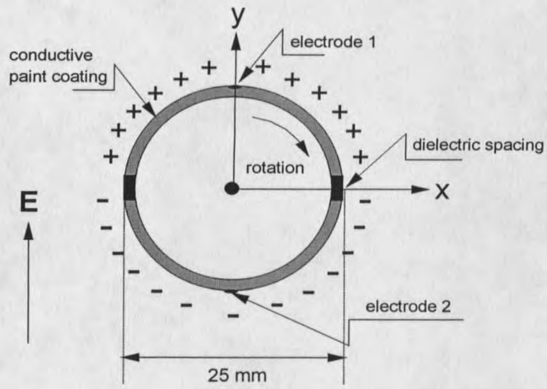

Figure 1: End view of electric field probe in an electric field. Charge is induced on simi-circular shells separated by a dielectric spacing. Rotation of the cylinder in the electric field results in the generation of a current between electrodes.

immediately after the measurements by centering it between two parallel, 50 cm square aluminum plates at 20 kV difference in potential.

Harold Kirkam made a generous loan of the DC electric field meter to Montana State University for the winter of 1993-94 in order that its operation be tested in harsh blizzard environments. The probe worked exceptionally well in winter conditions and in January 1994 measurements were made of the electric field in the region .002-4 m above the snow surface during blizzard conditions.

The Experiment

On 6 January 1994, a mobile laboratory was moved to a location just south of the Cooper Cove interchange of Interstate Highway 80, 50 km west of Laramie, Wyoming, at 41 31' N, 106 05'W, 2360m elevation. Consistent west winds during drifting over nearly level terrain with short-grass vegetation make the site nearly ideal for such measurements. These conditions exist for approximately 1 km upwind of the measuring location, beyond which terrain becomes more rolling for about 3 km to the foot of the Medicine Bow Mountains. 10 cm of new snow provided light drifting due to moderate winds. At 2458 hours on 7 January the wind increased from around 4 m s^{-1} to 10 m s^{-1} and up.

Instruments

An anemometer with 19 cm diameter, 3-cup plastic rotors produced signals with frequency proportional to wind speed. A thermistor shielded with a plastic pipe 'T' connector produced voltages proportional to air temperatures.

Both the average wind speed and temperature measurements were made at a 1 m height. Relative humidity at 2 m height was sensed in an enclosure mounted on the side of the mobile lab, and screened with polyester filter fabric. The electric field probe was connected to the receiver unit, housed in the mobile lab, by 15m fiber-optic cables.

Procedure

Computers in the mobile lab accumulated data from runs of 1 hour duration for storage on magnetic disks. Measurements of average wind speed, temperature, and humidity, as well as probe height and horizontal and vertical electric field components were recorded every minute. The procedure was simply to set the probe at a given height for a period of 15 min. Each time the probe height was changed a manual measurement was taken and compared to the height reading given by the potentiometer to insure accuracy. A series of vertical profiles for electric field above the snow surface was measured in the period 0100 h to 0630 h.

Results

Measurements of electric field were averaged at each height interval. The measured electric field as a function of height is shown in figure 2. We fit a power-law profile to the data in order to facilitate evaluation of saltation trajectories. The theoretic model of the electric field immediately above a bed of charged spheres (Schmidt and Dent, 1993) was the basis for choosing the power-law fit.

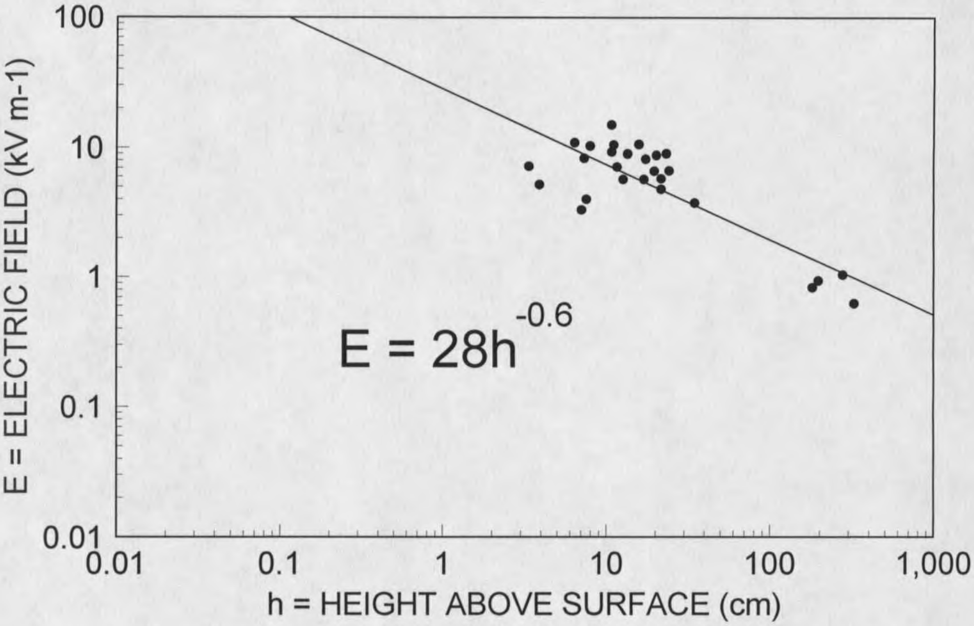

Figure 2: Electric field profile measured in blowing snow 7 Jan 94 using a DC electric field mill. Windspeed at the 1-m height averaged 12 m/s over the two hour measurement period. A power law fit to the data was used as an approximation for computational purposes based on a theoretical profile proposed by Schmidt and Dent (1993).

Discussion

The electric fields measured in this experiment were as much as 30 kV m^{-1} at a height of 4 cm as compared to the fair weather electric field of 0.06 kV m^{-1} measured at the same height. Electric fields measured in a blowing snow storm compare surprisingly well with the theoretic model developed by Schmidt and Dent (1993).

As expected by a review of the charging mechanisms for ice particles (Hobbs, 1974) the electric field measured here appears to be a strong function of blowing snow particle flux. Based on the results of Lathem and Stow (1967) temperature and humidity must also play a role in the charging of the blowing snow particles. For the measurements made here temperature and humidity remained constant.

CHAPTER FOUR

THE SIGN OF ELECTROSTATIC CHARGE ON BLOWING SNOW

Based on a review of the mechanics by which charge separation develops in drifting snow, it seems likely that during stronger wind gusts, eroded surface particles with positive charge mix with negatively charged saltating particles. If, at some point, eroded particles dominate the mixture, this should lead to a reversal in the sign of charging current generated by accumulating drift particles in a suitable measuring trap. This chapter describes an experiment to detect such reversals and shows that the average sign of the charge on drifting snow particles can indeed change from negative to positive during periods of strong wind gusts. This new evidence strongly supports past findings indicating that blowing snow particles acquire negative charges while surface particles become positively charged. These results raise questions about the validity of average particle charge-to-mass ratios determined by measuring the total charge on a sample of blowing snow and dividing by the sample mass.

The Experiment

Measurements in a blizzard in southeastern Wyoming, on 9 and 10 January 1988, provide data for an initial test of the hypothesis. The location is just south of the Cooper Cove interchange of Interstate Highway 80, 50 km west of Laramie, Wyoming, at 41 31' N, 106 05'W, 2360m elevation. This is the same location used by Schmidt and Dent (1994) in their experiment conducted 7 January 1994, reported in the previous chapter.

On 5 January 1988, a mobile laboratory was moved to the site. Electric power is available from a stub line that approaches from the northwest. Light snowfall with light north winds, during the evening of 5 January and all day on the 6th, added 10-15 cm of snow to old, hard snow dunes and drift features formed from a 60-cm snowfall, approximately 10 days earlier. Wind speed increased and drifting began about 1200 h on 7 January. Light snowfall and drifting continued throughout 8 January, during preparations for the electrostatic measurements. Interstate 80 was closed from Laramie west to Walcott Junction at 0950 h on 9 January, because of blowing and drifting snow. Measurements from two periods, 2100 h on the 9th to 0020 h on the 10th, and 0800 h to 1030 h on the 10th, are used in this thesis.

Instruments

Measurements included vertical profiles of average wind speed and temperature from 10 levels on a 10 m mast. A 2 m high pipe mast supported a wind vane and fast-response sensors of drift particle frequency, wind speed, and electric current generated by accumulating drift particles. An electronic barometer measured atmospheric pressure in the mobile laboratory. Relative humidity at 2 m height was sensed in an enclosure mounted on the side of the mobile lab, and screened with polyester filter fabric.

Anemometers with 19 cm diameter, 3-cup plastic rotors produced signals with frequency proportional to wind speed, for the 10 m profile. Two-thermistor networks shielded with plastic pipe 'T' connectors produced voltages proportional to air temperatures at each level on that tower. Tabler (1980) gives details of the vertical profiling system.

A heated-thermistor anemometer (Kurz Mdl 1440M-4) provided a fast-response voltage proportional to wind speed near 18 cm above the surface at the 2 m mast. Although this sensor iced over in heavy drifting during the last runs on 9 January, readings for most of the experiment compared well with averages from the wind profile.

To sense drift rate, a photoelectric device called a snow particle counter (SPC) generated pulses from shadows of drift particles breaking a light beam. The sensing window is approximately 25 mm long and 3 mm high, normal to the wind. Height of this sensor above the snow surface was near 18 cm throughout the experiment. Electronics in the mobile lab produced a voltage proportional to a 5 s running average of the frequency of these pulses. Schmidt (1977) details this system.

The device constructed to measure the charging current produced by drifting snow particles is a portable Faraday Cage (Figure 3), similar in principle to the design reported by Wishart and Radok (1967). Two cylinders of brass screen are held concentric by insulating plastic. Polyester filter fabric (50-micron