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THE POSSIBLE IMPORTANCE OF ELECTRICAL FORCES IN THE DEVELOPMENT OF SNOW CORNICES

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Abstract. Measurements were made of the vertical electric field strength around snow cornices on Bridger Ridge (2 590 m a.s.l.) in the Bridger Range, south-western Montana. The fields were considerably enhanced, owing to the exposed position of the cornices, but were nevertheless appreciably lower than those shown by Latham and Saunders (1970[b]) to be necessary in order to provide significant additional bonding when ice crystals collide with an ice surface. However, measurements made on Bridger Ridge and neighbouring Bangtail Ridge showed that the charges carried on snow crystals saltating over the surface of cornices were close to their limiting values.

Rough calculations indicated that pressure melting is unlikely to be of importance in the development of snow cornices formed from granular crystals, that frictional melting is probably significant only at fairly low temperatures and moderately high wind velocities, and that strong electrostatic forces between highly charged snow crystals saltating over the surface of a cornice may be sufficient to provide bonding where the crystal velocities are comparatively low.

Résumé. *Importance possible des phénomènes électriques dans le développement des corniches.* On a mesuré les champs électriques verticaux autour de corniches de neige sur le Bridger Ridge (altitude 2 590 m) dans la chaine de Bridger dans le Sud Ouest du Montana. Les champs étaient considérablement exagérées par la situation exposée des corniches, mais restèrent néanmoins sensiblement inférieurs aux valeurs qui sont nécessaires, comme l'ont montré Latham et Saunders (1970[b]), pour provoquer une liaison supplémentaire significative lorsque les cristaux de glace rencontrent la surface. Cependant des mesures faites sur le Bridger Ridge et au voisinage du Bangtail Ridge ont montré que les charges portées par les cristaux de neige en saltation sur la surface des corniches étaient tout près de leur valeur limite.

Des calculs approximatifs indiquent que la fusion par pression ne joue probablement pas un rôle important dans le développement des corniches de neige formées de cristaux sphériques, que la fusion par friction ne joue vraisemblablement un rôle significatif que par basses températures et par vitesses de vents élevées, et que les importantes forces électrostatiques entre les cristaux de neige en saltation fortement chargés sur la surface de la corniche peuvent suffir à expliquer leur fixation sur la face sous le vent de la crête principale, où les vitesses des cristaux sera comparativement faible.

Zusammenfassung. *Die mögliche Bedeutung elektrischer Kräfte bei der Entstehung von Wächten.* Messungen der vertikalen elektrischen Feldstärke wurden an Wächten am Bridger Ridge (2 590 m) in der Bridger Range, Südwest Montana, vorgenommen. Die Felder waren infolge der exponierten Lage der Wächten beträchtlich erhöht; sie waren aber trotzdem erheblich niedriger als solche, die nach Latham und Saunders (1970[b]) nötig sind, um beim Zusammentreffen von Eiskristallen mit einer Eisoberfläche merkliche zusätzliche Bindung zu bewirken. Dennoch zeigten die Messungen am Bridger Ridge und am benachbarten Bangtail Ridge, dass die Ladungen der über die Oberfläche der Wächten wirbelnden Schneekristalle nahe an ihren Grenzwerten lagen.

Überschlagsrechnungen zeigten, dass bei der Entstehung von Wächten aus körnigen Kristallen das Druckschmelzen wahrscheinlich keine wichtige Rolle spielt, dass das Schmelzen auf Grund von Reibung vermutlich nur bei tiefen Temperaturen und hohen Windgeschwindigkeiten bedeutsam ist und dass starke elektrostatische Kräfte zwischen hochaufgeladenen Schneekristallen, die über die Oberfläche dieser Wächten wirbeln, ausreichen können, um die Bindung an der leeseitigen Kante der Wächten herzustellen, wo die Geschwindigkeit der Kristalle verhältnismässig gering ist.

Introduction

The peculiar nature of snow deposition in the leading edge of ridge-top cornices has attracted the curiosity of scientists and mountaineers for some time. A cornice is simply a wedge-like projection of snow formed by wind deposition to the lee of a ridge line or slope inflection. Studies by Montagne and others (1968) have confirmed many earlier observations that the most common method for such horizontal extension of the cornice roof is by the interlocking of crystal appendages of stellar snow. Entirely unexpected, however, were observations that cornice growth may be brought about by the adhesion not only of stellar types but of granular or plate-like snow particles as well. That these particles actually extend horizontally into space in the lee of the edge is all the more peculiar. This paper explains some of the possible mechanisms involved in granular snow adhesion and emphasizes that electrical forces may be of importance in this process.

Under some circumstances snow grains have been observed to halt randomly near or on the leading edge during momentary calm intervals. This is one known and effective way to explain part of the cornice accretion problem. However, the random halt method does not apply when winds are steady nor does it bear on the question of horizontal projection of particles from the lee edge, both of which processes are known to occur.

Studies by Nakaya and Matsumoto (1953, 1954), Hosler and others (1957), Hosler and Hallgren (1961), and others have demonstrated conclusively that adhesion of ice to ice occurs at temperatures below those at which pressure melting is likely to be effective. These workers found that adhesion is a sensitive function of temperature, surface contamination and relative humidity. Hosler and his co-workers concluded that their results were explicable in terms of the "liquid-like layer" hypothesis propounded in elementary form by Faraday (1860) and developed by Weyl (1951). From considerations of minimum surface free energy Weyl proposed a reorientation of molecules in and near the surface of an ice specimen and that the thickness of the disordered layer will decrease with decreasing temperature and relative humidity. Circumstantial support for Weyl's hypothesis is provided by the experiments of Jellinek (1961) and the theoretical studies of Fletcher (1962), who calculated that the reorientation of water molecules in an ice surface near 0°C extends in an exponentially decreasing manner for about 10 molecular layers below the surface before achieving the bulk ice lattice arrangement, and that the theoretical relationship between the thickness of the distorted layer and temperature is similar to that between sticking force and temperature, measured by Hosler and others. However, although the "liquid-film" hypothesis offers an explanation for several experimentally determined properties of ice, these phenomena can also be explained in terms of well established physical effects. Experiments by Kingery (1960) and Kuroiwa (1961) indicated that surface and volume diffusion of ice molecules were primarily responsible for the sintering of ice, but a comprehensive theoretical and experimental study by Hobbs and Mason (1964), supported by the low-temperature investigations of Hobbs (1965), established that the dominant mechanism operative during the sintering of ice spheres in air at atmospheric pressure is evaporation of material from the surface of the spheres and condensation on to the concave region of the ice bridge growing between them.

The instantaneous bonding of ice crystals on the tip of the leading edge of a snow cornice or during the growth of snow flakes by means of aggregation may be a consequence of several processes. If the crystals possess an elaborate structure, initial binding may be produced simply by mechanical interlocking, reinforced as time progresses by a relatively slow sintering process. However, this explanation cannot be applicable to the rapid adhesion of smooth, granular crystals. In this case the bonding may result from the refreezing of a layer of liquid water produced by frictional contact of the crystals. It is also possible that pressure melting may be of importance at temperatures close to 0°C. An alternative explanation is that the adhesion process is a consequence of electrical forces. This proposition is supported by several lines of evidence. Latham and Saunders (1967) showed that over a wide range of temperature and relative humidity the force required to separate a pair of ice spheres increased rapidly with increasing electric field strength. The increased adhesion was not accompanied by an increase in the rate of growth of the ice bridge between the two spheres and is explicable in terms of Davis's (1964) calculations of the purely electrostatic forces between two spheres situated in an electric field. In addition, Latham and Saunders (1964, 1970[b]) have shown that the collection efficiencies of ice spheres for small ice crystals increased rapidly with increasing electric field strength above about 20 kV m^{-1} at all temperatures from 0°C to -37°C.

The objective of the studies described in this paper was to determine whether electrical forces may contribute to the development of snow cornices. Because of the exposed position of the great majority of cornices the electric field at their surfaces may be much greater than that in their immediate environment and, particularly during a snow-storm where fields may be extremely large, may achieve sufficient magnitude to promote or accentuate cornice development. In addition, snow crystals saltating over the surface of a cornice roof may become extremely highly charged by means of asymmetric rubbing (Latham and Stow, 1967) before being incorporated into the upper edge of the lee face.

FIELD MEASUREMENTS

Measurements of the variation of vertical electric field strength around snow cornices on the Bridger Ridge (2 590 m a.s.l.) in south-western Montana were made during March 1969 using a conventional polonium probe technique, in which the current flowing along a high resistance located between the point of ionization and earth was amplified and recorded by

Fig. 1. View northward along Bridger Ridge showing cornice research area, Bridger Range, Montana. Structures are used for cornice control by redirecting wind.

means of a microammeter. The instrument was battery-driven. Fields of all magnitudes encountered could be measured to within ±10 V m^{-1}. The distance between the polonium probe and the earthed case of the instrument was 0.6 m. A simple modification to the instrument, which could be speedily effected, permitted the charge on snow crystals entering a shielded copper can to be measured to within ±0.3 pC. This version of the instrument was used at Bridger Ridge and also at neighbouring Bangtail Ridge (2 690 m. a.s.l.) to measure the charges on crystals saltating along cornice surfaces. A general view of Bridger Ridge is presented in Figure 1. Figure 2 shows a typical cornice on the ridge.

Fig. 2. Typical snow cornice on Bridger Ridge on which the studies were conducted.

Measurements were made at Bridger Ridge of the vertical electric field strength over the roofs of several cornices as a function of the distance from their summits. The results for three cornices are presented in Table I. Cornice 1 was in a slight dip in the ridge, cornice 2 was approximately 4 m higher and more prominent and cornice 3, although slightly higher than cornice 2 was not quite so steeply inclined. The average inclinations of the three cornice roofs with the vertical were about 72°, 65° and 70° respectively. The majority of measurements were made when the temperature lay in the range −0.5 to +1.0°C and the wind, which was gusty, varied in speed from about 0 to 15 m s^{-1}. The wind speed was measured using a hand anemometer. It is extremely unlikely that the slight variations in temperature and wind velocity which were observed during these experiments significantly affected the field-strength measurements.

TABLE I. THE ELECTRIC FIELD STRENGTH E AT VARIOUS DISTANCES D FROM THE SUMMIT OF THREE CORNICES ON BRIDGER RIDGE

Cornice 1	D m	3.5	2.4	1.3	0.3
	E V m^{-1}	130	155	220	350
Cornice 2	D m	5.3	4.0	2.4	1.3
	E V m^{-1}	115	160	260	480
Cornice 3	D m	4.4	2.4	1.3	0.3
	E V m^{-1}	150	220	300	460

Table I shows that for all three cornices the vertical field strength E increased rapidly with decreasing distance from the summit. In addition, E is seen to increase with the prominence and steepness of the cornice roof. However the maximum value of E measured, 480 V m^{-1} close to the summit of cornice 2, is about two orders of magnitude below the minimum required, in the experiments of Latham and Saunders, to produce a significant increase in the degree of aggregation.

Rough measurements of the charges carried on snow crystals blown across the cornice roof were made in the following manner. The shielded cylindrical collecting vessel connected to the portable electrometer was held a few centimetres above the snow surface with its axis parallel to the wind direction. Crystals were collected over an interval which was short in comparison with the time-constant of the electrometer. The total charge collected in this interval was measured by the instrument. When the concentrations of snow crystals were low the charge per crystal was estimated after the total charge had been measured by emptying the crystals from the collecting vessel onto a sheet of black velvet, counting them and measuring their average dimensions by means of a graduated eyepiece. When high fluxes of crystals were passing over the cornice roof, the numbers of particles collected were considerable, and it was more accurate to determine their number by measuring the volume of water produced by melting the total mass of collected crystals. In a typical experiment, conducted at Bangtail Ridge with a snow surface temperature of −1.5°C and an air temperature of −1°C, the total measured charge was −97 pC when about 240 granular snow crystals of average dimension about 400 μm were collected. The average charge per crystal was therefore about −0.4 pC which is close to the value deduced by Latham and Stow (1967) of the maximum charge that can be carried on an ice crystal of irregular shape. This finding suggests that the great majority of ice crystals carried a charge of the same sign (negative) produced by a common charging mechanism, probably asymmetric rubbing (Reynolds and others, 1957; Latham, 1963). Although the determination of individual charges on snow crystals saltating along the cornice roof is accurate only to a factor of about two the results of all the charge measurements agree to confirm that the charges on the blown particles were extremely high, and close to the limiting value. This conclusion is not surprising since the measurements of Reynolds and others (1957), Latham and Miller (1965) and others have shown that a single frictional contact between ice specimens can result in the transfer of very large charges. In the case of saltation, therefore, these charges will rapidly accumulate to achieve limiting values.

DISCUSSION

Three possible mechanisms by which smooth granular snow crystals may adhere on a cornice are pressure melting or frictional melting followed by regelation and electrostatic bonding. Although insufficient evidence is available to establish categorically which of these mechanisms may be responsible for the development of snow cornices, each one of them may be assessed, to a certain extent, in quantitative terms.

Both the pressure melting and the frictional heating mechanisms involve the formation of a film of water which subsequently refreezes. These mechanisms can be important only if the time of contact of a saltating crystal with the snow surface exceeds the time required for the liquid film to freeze. In order to assess the significance of this mechanism we consider the simplified case of a cubical snow crystal of side L and density ρ carried over the cornice surface, with which it makes repeated contacts, in an air stream moving with velocity U. The temperature in degrees Celsius of the air-stream and the snow surface is assumed to be T. We also assume that each sliding contact with the cornice surface produces a film of water of length L and thickness X. It can easily be shown that for any reasonable value of saltation length this water film will freeze in the interval between successive collisions, except at temperatures very close to 0°C. The work of Hallett (1964) and Macklin and Ryan (1965) showed that the velocity of propagation V (in m s^{-1}) of ice dendrites through supercooled water can be expressed approximately by means of the equation

$$V \approx 10^{-3}\,T^2. \tag{1}$$

The time τ for ice to propagate through the water film formed by friction or pressure melting is given, therefore, by

$$\tau \approx X/V = 1000X/T^2. \tag{2}$$

The time of contact t of a point on the snow crystal with the cornice surface can be expressed roughly by the equation

$$t \approx L/U \tag{3}$$

so that the condition for bonding, namely that $t < \tau$, can be re-expressed as

$$U > LT^2/1000X. \tag{4}$$

The quantitative requirements imposed by this condition are presented, for different values of the film thickness X, and the degree of supercooling T, in Table II. It is seen that at temperatures close to 0°C bonding is unlikely to occur except at quite low wind velocities because of the slow rate of freezing of ice. If we assume that snow particles will not be carried over the cornice surface at velocities below about 1 m s^{-1} we see from the Table that bonding will not occur unless the temperature is at least below about -1°C.

TABLE II. THE WIND SPEED U WHICH CANNOT BE EXCEEDED AT A TEMPERATURE T IF REFREEZING OF A WATER LAYER OF THICKNESS X IS TO OCCUR ($L = 5 \times 10^{-4}$ m) U m s^{-1}

X μm	$T = -0.1$°C	$T = -1$°C	$T = -3$°C	$T = -5$°C	$T = -8$°C
10	5×10^{-4}	5×10^{-2}	0.45	1.3	3.2
1	5×10^{-3}	5×10^{-1}	4.5	13	32

X μm	$T = -10$°C	$T = -15$°C	$T = -20$°C	$T = -25$°C
10	5	11.0	20	32
1	50	110	200	320

The importance of pressure-melting in cornice development can now be estimated. If a cubical snow crystal of side L, velocity U and density ρ loses almost all of its kinetic energy during an impact with the surface of a cornice its loss of momentum will be about $\rho L^3 U$. If this occurs over an interaction time of about L/U the force produced at the impact points will be

$$h = \rho L^2 U^2 \tag{5}$$

If the area of contact A is equal to ωL^2 then the corresponding pressure p produced by the impact over this region is given by

$$p = h/A = \rho U^2/\omega. \tag{6}$$

The reduction ΔT of the melting point with increasing pressure is given approximately by the equation

$$\Delta T = 8\times 10^{-8} p. \tag{7}$$

It follows from Equations (6) and (7), therefore, that the reduction ΔT in the melting point of ice when a snow crystal impinges against a snow surface is given approximately by

$$\Delta T = \frac{8\times 10^{-8}\rho U^2}{\omega}. \tag{8}$$

Inserting into Equation (8) a value of $\omega = 0.1$, which was shown by Latham and Mason (1961) and Latham (1963) to be reasonably accurate at temperatures close to 0°C, it follows that the temperature reduction will be about 7×10^{-4}°C, 0.07°C and 7°C at velocities U of 1 m s^{-1}, 10 m s^{-1} and 100 m s^{-1} respectively. More detailed computations of ΔT are presented in Table III. Comparison of Tables II and III shows that a significant decrease in the melting point can be produced only with high-velocity impacts, but that time is available to permit refreezing only if the collisions occur at low velocities. Despite the crudity of these calculations it is nevertheless apparent that pressure melting is unlikely to be important in the development of cornices formed from granular snow crystals.

Table III. The reduction of melting point ΔT produced by the impacts of a snow crystal with a cornice at velocity U

U	m s^{-1}	0.1	1	5	20	100
ΔT	°C	7×10^{-6}	7×10^{-4}	4×10^{-2}	0.3	7

In order to assess the importance of frictional melting in cornice development we assume that a fraction f of the initial kinetic energy of a snow crystal is converted on impact into heat which produces, by melting, a film of water of length L, width W and thickness X.

The heat produced is given by

$$Q = 0.5\rho L^3 U^2 f. \tag{9}$$

If this heat is communicated entirely to the portion of the snow crystal, of mass $LWX\rho$, which may be melted by the frictional contact, the heat balance equation reads

$$LWXF\rho - LWXCT\rho \approx 0.5L^3U^2f\rho \tag{10}$$

where C is the specific heat of ice and F is the latent heat of fusion. Writing $W = \omega L$, and rearranging, we obtain

$$X = \frac{0.5U^2Lf}{\omega(F-CT)} \tag{11}$$

where X is the thickness of the water layer produced by the sliding of a snow crystal over a cornice surface at a velocity U and temperature T. Solutions of this equation for $L = 5\times 10^{-4}$ m, $\omega = 0.1$, $f = 0.1$, $C = 2.1\times 10^3$ J kg^{-1} deg^{-1}, $F = 3.3\times 10^5$ J kg^{-1} and various values of U and T are presented in Table IV. The table shows that the thickness of the water film increases rapidly with increasing impact velocity but is quite insensitive to variations of temperature. This latter conclusion is a consequence of the fact that much more heat is required to effect the change of phase than to elevate the temperature of the ice to the melting point. Table IV also shows that sufficient melting to produce adhesion on refreezing is unlikely to occur for velocities below about 30 m s^{-1}. It follows from Table II, therefore, that frictional heating is unlikely to produce permanent bonding at temperatures warmer than about −8°C, although it may be of importance at lower temperatures. This threshold temperature is actually probably somewhat lower than −8°C since the snow-particle velocity is unlikely to be as great as the wind velocity, and therefore the heat created on impact will be less than that calculated. Some alleviation of this problem will occur at fairly high velocities and moderately low temperatures, in which case appreciable melting will occur and the refreezing will be extremely rapid.

TABLE IV. THE THICKNESS X OF A WATER LATER PRODUCED WHEN A SNOW CRYSTAL SLIDES OVER A CORNICE WITH A VELOCITY U AT A TEMPERATURE T. $L = 5\times 10^{-4}$ m

	T °C	X μm $U = 0.1$ m s^{-1}	$U = 1$ m s^{-1}	$U = 5$ m s^{-1}	$U = 20$ m s^{-1}	$U = 50$ m s^{-1}	$U = 100$ m s^{-1}
$f = 0.1$	0	7.6×10^{-6}	7.6×10^{-4}	1.9×10^{-2}	0.30	1.9	7.6
	−10	7.1×10^{-6}	7.1×10^{-4}	1.8×10^{-2}	0.28	1.8	7.1
	−20	6.7×10^{-6}	6.7×10^{-4}	1.7×10^{-2}	0.27	1.7	6.7

The experiments of Latham and Saunders (1967, 1970[b]) showed that the increased adhesion between a pair of ice specimens in the presence of electrical forces is not associated with an increase in the rate of growth of a linking ice bridge but is a consequence of the purely electrostatic forces between them. The possible importance of electrical effects in cornice development can therefore be estimated roughly in the following manner. Davis (1964) showed that the electrostatic force A on a conducting sphere of radius R_2 and charge Q_2 separated by a distance S from a sphere of radius R_1 and charge Q_1 in an electric field of strength E inclined at an angle θ with the line of centres of the spheres is given by the equation

$$A = R_2^2E^2(B_1\cos^2\theta + B_2\sin^2\theta) + E\cos\theta(B_3Q_1 + B_4Q_2) + R_2^{-2}(B_5Q_1^2 + B_6Q_1Q_2 + \\ + B_7Q_2^2) + EQ_2\cos\theta \tag{12}$$

where the force coefficients B_1 to B_7 possess values which are dependent upon S/R_2 and R_1/R_2. In the case of cornice development, the experiments described in the preceding section showed that whereas the charges on the blowing snow crystals were very high the electric fields, although enhanced in the region of a cornice, were extremely weak and could not affect the collection process. All the terms involving E in Equation (12) can therefore be eliminated and we can also assume that the cornice surface is uncharged, i.e. $Q_1 = 0$. Writing $R_2 = L/2$ and incorporating the factor γ, determined experimentally by Latham and Saunders (1970[a]), which represents the modification to Davis's equation resulting from the fact that the electrostatic forces between irregularly shaped ice crystals are different from those between spheres, Equation (12) can be rewritten as

$$A \approx 4\gamma B_7 Q/L^2 \tag{13}$$

where Q $(= Q_2)$ is the charge on the blowing snow crystal.

Latham and Stow (1967) inferred from their laboratory studies of snow-storm electrification that the maximum charge Q in picocoulombs that can be located on an ice crystal of dimension L is given approximately by the equation

$$Q \approx 10^{-5}L^2. \tag{14}$$

Since the experiments at Bridger Ridge and Bangtail Ridge showed that the charges on snow crystals saltating over cornice roofs were very close to the maximum values, the above expression for Q can be inserted into Equation (13) thus yielding

$$A \approx 4\times 10^{-5}\gamma B_7. \tag{15}$$

Latham and Saunders showed that the factor γ was essentially constant for a particular configuration over a wide range of separations S. A typical value for γ is 3. The work done W_E against attractive electrostatic forces when a snow crystals of charge Q is removed to infinity from an initial minimum separation S_0 from the uncharged surface of a cornice is therefore given by

$$W_E \approx \frac{10^{-5}\gamma}{\pi\epsilon_0}\int_{S_0}^{\infty} B_7\,\mathrm{d}S \tag{16}$$

where ϵ_0 is the permittivity of free space. Using the values of B_7 derived from the tables of Davis and taking $S_0 \approx 1\ \mu$m (Latham and Saunders, 1967) Equation (16) gives $W_E \approx 10^{-9}$ J.

Electrostatic forces may be expected to influence bonding if the electrostatic energy W_E is of the same order as the kinetic energy of a snow crystal, which, with $L = 5\times10^{-4}$ m, is given by $W_K \approx 6\times10^{-8}U^2$. W_E exceeds W_K when $U < c.\ 0.1$ m s^{-1} and is equal to 0.1 W_K when $U \approx 0.3$ m s^{-1}. This extremely rough argument suggests that electrostatic forces will be of no significance at high velocities, when crystals are being blown over the roof of a cornice at velocities close to U, but that at velocities below about 0.3 m s^{-1}, such as may occur on the lee side of the leading edge, they may be important. This argument is consistent with the fact that snow crystal collection occurs on the sheltered accretion face of a cornice during its development. However, it is not so easy to explain how electrostatic forces can promote growth on the leading edge of the cornice, where the wind velocities are generally considerably in excess of 0.3 m s^{-1}. It is possible that windshear may provide conditions suitable for electrostatic bonding, and further alleviation of the problem may result from the fact that the snow-particle velocities may be considerably less than the wind speed. However, the preceding arguments, although providing a reasonable circumstantial case for the possible importance of electrical forces in the development of cornices formed from granular snow crystals, cannot be regarded as definitive, and the problem requires considerable further study.

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