A Brief Review of Snowdrifting Research

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The blowing-snow phenomenon is described, and practical procedures for controlling deposition of windblown snow are reviewed. Field methods are given for measuring velocity, particle concentration, mass flux, particle size, and their distributions with respect to height. The analysis of steady-state wind transport over a plane surface is outlined, and difficulties in extending the treatment to cover complex flow perturbations are stressed. Wind tunnel studies are reviewed, and modeling criteria for snowdrift simulation are given. Suggestions for future work include semi-empirical model and prototype studies for short-term benefits, and extension of fundamental analyses and field observations for progress over the long term.

Without delving too far into antiquity, it is safe to say that research on windblown snow and snowdrift control began at least a century ago. However, research efforts during this period have been sporadic and progress has been slow.

Basic control measures such as snow fences and shelter belts evolved without systematic research effort, but a significant improvement in understanding came with Finney's pioneering wind tunnel studies, which provided results that still have not been superseded. Finney's simple techniques were followed in a number of subsequent studies, but in recent years professional hydrodynamicists have attempted to apply more rigorous modeling criteria. The latter efforts have undoubtedly clarified understanding of wind-tunnel modeling, but so far they do not appear to have produced practical results that are significantly better than those yielded by simpler studies. The reason for this is that there has been a tendency for wind tunnel specialists to be supplied with inaccurate information on the natural phenomenon.

More fundamental research on the phenomemon of snow transport by the wind made little headway until about 20 years ago, but there is now an appreciable amount of useful observational data and a fairly clear understanding of the processes involved. Steady-state snow transport across flat unobstructed surfaces can be treated analytically, but effects of flow perturbations on snow transport and deposition have received virtually no attention theoretically.

From the engineering point of view, present day needs are being met largely from long-established technology. Over the short term, improvements in control measures will have to be achieved by semi-empirical developments based on model tests and field tests, but in recent years attempts to refine modeling techniques have been frustrated by lack of reliable input data. It therefore seems imperative to blend together fundamental and technical investigations, which previously have tended to follow independent paths with a minimum of interaction.

This brief review is intended to outline present ideas on basic mechanisms of snow transport and to relate them to engineering research on snowdrift control measures. It includes a digest of data that might form a basis for the formulation of realistic modeling criteria. The review does not cover the most recent Russian references, which are not yet available in English translation.

SURFACE WINDS

As wind blows across flat ground, surface drag creates a velocity gradient normal to the surface. When wind speed is a few m/sec turbulence begins to develop, and when it exceeds 10 m/sec turbulence is usually fully developed.

With strong winds and the neutral stratification typical for snowfields, there is a logarithmic relationship between wind velocity u and height above ground z, at least in the lower layers where blowing snow occurs.

$$u = (u_*/k) \ln(z/z_0) \tag{1}$$

where u_* is a parameter termed the "friction velocity" (typically 3 to 4 percent of the wind velocity at 10-m height, u_{10}), k is von Karman's constant (≈0.4), and z_0 is a surface roughness parameter (~0.1 to 1.0 mm for typical snowfield conditions). With strong winds, typical snow surfaces are aerodynamically rough (no laminar sublayer). When field measurements of u are plotted against log z, the intercept and slope give z_0 and u_* respectively.

The eddy viscosity, or momentum exchange coefficient for turbulent mixing, K, can be expressed as:

$$K = k\, u_*\, z \tag{2}$$

SNOW PARTICLES

Freshly precipitated snow crystals vary widely in size, shape, and mass according to the weather conditions prevailing during their nucleation and fall. By contrast, snow particles picked up from the surface, or maintained in turbulent suspension by strong winds, tend to be simple equant particles whose sizes are controlled within fairly narrow limits by the wind characteristics. For present purposes, interest centers on size, mass, and fall velocity of airborne snow particles.

Measurements on freshly precipitated snow particles by Nakaya and Terada (33), still generally accepted, given the following values for terminal fall velocity w: spatial dendrites, 57 cm/sec; plane dendrites, 31 cm/sec; "powder snow," 50 cm/sec; w is independent of size in all 3 cases. For needle crystals, w increased from ≈20 to ≈70 cm/sec as length increased from 1 to 2 mm. For graupel, w increased from ≈120 to ≈260 cm/sec as size increased from 1.5 to 5 mm, and rimed crystals fell at ≈100 cm/sec. Generally higher values of w were found for very small crystals by Mellor (31): spatial dendrites 0.2 to 1.0 mm, 70 to 90 cm/sec; plane dendrites ≤ 1 mm, 45 to 100 cm/sec; needle crystals 0.5 to 2 mm, 50 to 100 cm/sec; rimed crystals 0.2 to 1 mm, 50 to 105 cm/sec; w tends to increase with size in the last 2 cases. (The Japanese results were for particles falling through an enclosure, whereas Mellor's results were for particles falling en masse in open air.)

Fall velocities of snowflakes (aggregations of crystals) measured by Magono (27) were in the range 80 to 240 cm/sec, with w tending to increase as size increased from 0.2 to 4.5 cm. Langleben (23) related w (cm/sec) for a snowflake to the diameter of the water drop formed by melting it d (cm).

$$w = C_1 d^a \tag{3}$$

where a = 0.31 and C_1 ranges from 160 to 234 for different types of snow. Litvinov (26) obtained results indicating a ≈0.16 and C_1 equal to 87 and 115. For small snowflakes (≈1 cm) Mellor (31) found w mainly in the range 70 to 140 cm/sec; a frequency distribution showed $70 \leq w \leq 80$ cm/sec to be most common for typical midwinter snowfalls at Hanover, New Hampshire.

Nakaya and Terada (33) related the mass of a snow crystal m (mg) to its maximum linear dimension d (mm).

$$m = C_2 d^a \tag{4}$$

where C_2 and a are respectively 0.0038 and 2 for plane dendrites, 0.027 and 2 for rimed plates and stellar dendrites, 0.010 and 2 for powder snow and spatial dendrites, 0.0029 and 1 for needles, and 0.065 and 3 for graupel. Other values of m for a variety of small crystals are given in Table 1.

TABLE 1

ESTIMATED PARTICLE MASS FOR FRESH SNOW

Snow Type and Size (mm)	Approximate Mean Particle Mass (g)
Spatial dendrite, 0.3 diameter	1.47×10^{-5}
Spatial dendrite, 0.2 to 0.5 diameter	5.5×10^{-6}
Spatial dendrite, 0.8 diameter	4.29×10^{-5}
Rimed grains, 0.2 diameter	7.99×10^{-6}
Rimed grains, 0.1 to 0.7	7.63×10^{-6}
Spatial dendrites, 0.5 diameter	3.07×10^{-5}
Rimed spatial dendrites, 1	4.52×10^{-5}
Rimed plane dendrites, 1 to 2	5.49×10^{-5}
Hexagonal "flowers" (plane dendrites with plates on arms), 1 diameter	2×10^{-6}
Stellar dendrites, 1	1.5×10^{-6}
Stellar dendrites, 1 to 2 diameter	5×10^{-6}
Needles, 2 long and 0 to 1 thick	1.4×10^{-5}

Particles picked up from the surface or particles falling into turbulent windstreams are reduced to simple equant forms by mechanical action and vapor diffusion; particle mass m is related to particle diameter d by

$$m = C_3 \rho_i d^3 \tag{5}$$

where $C_3 \sim 1$ and ρ_i is the density of ice (0.917 g/cm^3). Size selection is determined largely by upward eddy velocities in the turbulent windstream. Under typical strong wind conditions, mean particle size is $\approx$0.07 to 0.1 mm above 10-cm height (25, 8, 7) and somewhat larger in the lowest layers next to the surface. Size distribution of blown snow particles is discussed in detail by Budd (7) and a data summary is given by Mellor (30).

Terminal fall velocity (w, cm/sec) of equant snow particles from 0.1 to 1.5 mm effective diameter (d, mm) was measured by Mellor (29), who found:

$$w = C_4 d \tag{6}$$

where C_4 is 166, 191, and 223 for angular, subangular, and rounded particles respectively. Budd (7) estimated w for blown snow particles from empirical relationships for other atmospheric particles, taking C_4 = 388 for spherical particles and C_4 = 244 for irregularly shaped particles.

INTERACTION OF SNOW AND WIND

Snow can be moved horizontally by the wind in a number of ways.

Snowfall With Light Winds

When new snow is falling at 1 m/sec or less, wind speeds of a few m/sec impart appreciable horizontal travel, even when turbulent suspension is negligible. The horizontal mass flux q_H is related to vertical mass flux q_V (snowfall rate, accumulation rate), wind speed u, and particle fall velocity w by

$$q_H/q_V \approx u/w \tag{7}$$

Direction to the particle velocity vector is also given by u/w.

Turbulent Diffusion

In a fully turbulent boundary layer, snow particles can be held in suspension indefinitely, upward transport in turbulent eddies counteracting gravity settlement. The snow particles are small, well dispersed, and have low inertia, so that the problem can be approached from general turbulent diffusion theory.

By considering a wide turbulent flow across a long plane surface and by assuming that (a) steady-state conditions prevail (concentration at any level invariant with time) and (b) gradients of velocity and concentration along the flow direction are small compared with normal (vertical) gradients, the diffusion equation reduces to

$$vn - \epsilon_z(\partial n/\partial z) = 0 \tag{8}$$

where v is the component of particle velocity in the z (vertical) direction, n is particle concentration (mass of snow per unit volume of air) at height z, and ϵ_z is a mass transfer coefficient (eddy diffusivity) in the z-direction. If it is further assumed that (a) v is equal to snow particle fall velocity w and w is invariant with height z, (b) horizontal particle velocity is equal to wind velocity u (no "slip"), and (c) ϵ_z is equal to the eddy viscosity for turbulent winds K (Eq. 2), then the required solution of Eq. 8 is

$$n/n' = (z/z')^{-w/ku_*} \tag{9}$$

where the prime denotes a fixed reference level. It we substitute for u_* from Eq. 1, snow concentration n can be expressed in terms of wind speed u.

$$\ln(n/n') = -(w/k^2) \times \ln(z/z_0) \times \ln(z/z') \times (l/u) \tag{10}$$

Equation 9 is quite realistic when the reference height z′ is chosen at a low level, especially for strong wind conditions and for considerations of transport close to the surface. However, observations show w tends to increase with u, and also to decrease with increasing z; hence basic theory ought to be modified to account for nonuniform particle size (7, 8, 38). For present purposes the simple theory for uniform particle size is preferable, as it illustrates fundamental relationships without undue complication or much loss of reality.

The horizontal mass flux of snow q at any height z is

$$q = n\,u \tag{11}$$

and the rate of snow transport per unit width of the flow Q between 2 given levels z_1 and z_2 is

$$[Q]_{z_1}^{z_2} = \int_{z_1}^{z_2} n\,u\,dz \tag{12}$$

Saltation

The term saltation was used by Bagnold (1) to describe a transport mechanism for blown sand; particles were envisaged as bonding along the surface impelled by wind, elastic impacts with the surface causing particles to bounce and to dislodge other particles. Following early studies of saltation for snow (32, 16), Radok (38) applied Owen's saltation theory (37) to snow, using field data to define probable characteristics of the saltation layer. Trajectories of saltating snow particles were photographed by Oura et al. (1967).

The following picture emerges from Radok's analysis (38). Snow particles plucked from the surface by hydrodynamic forces stream along under gravitational and wind shear forces in a layer whose self-regulating thickness is governed only by the surface shear stress. Saltation is initiated at relatively low wind speeds, and the saltation layer is maintained even when turbulent diffusion develops with increasing wind speed. Snow concentration in the saltation layer remains of the same order of magnitude, irrespective of wind speed. Deposition and erosion take place by vertical flux through the saltation layer, but are not directly controlled by saltation. The saltation layer affects the airflow above it as would fixed roughness elements of comparable height; its effective roughness tends to decrease with increasing wind speed as a consequence of its upper boundary becoming more diffuse due to increased particle flux.

Threshold conditions for onset and maintenance of saltation, determined by the surface shear stress, may be defined in terms of a dimensionless group $\gamma = (\rho_a u_*^2/\rho_p g\,d)$, where ρ_a and ρ_p are densities of air and particles respectively and d is particle diameter. Saltation over a loose surface is initiated when $\gamma \approx 10^{-2}$, and ceases when $\gamma \approx 0.0064$; free-stream velocities corresponding to these values are $\approx$2.5 and $\approx$2.0 m/sec respectively when d = 0.1 mm. When $\gamma > 1.0$, all particles of size d will be carried into suspension. Thickness of the saltation layer is $\sim(u_*^2/2g)$, and concentration stays roughly constant at the same order as the fluid density ($\sim 10^3$ g/m^3). Thus the mass flux of the saltation layer is proportional to u_*^3. Radok found the saltation layer thickness increasing from $27z_0$ to $113z_0$ as u_{10} increased from 5 to 20 m/sec; the height of fixed roughness elements is commonly found to be $20z_0$ to $30z_0$.

MEASURING WINDBLOWN SNOW

The prime object in measuring windblown snow is to measure concentration n, mass flux q, and velocity u as functions of height z, covering a representative range of free-stream wind speeds u_{10}.

Direct Methods

Direct methods measure horizontal mass flux q by extracting snow particles from a cross section of the airstream at a given height, the total catch for a timed period being weighed to find the mass passing unit cross section in unit time. Measurement of average wind speed u at the same height and time permits concentration n to be calculated. This method gives temporal means of q, n, and u rather than instantaneous values, which is preferable for a turbulent flow.

Several types of snow traps were evaluated by Budd et al. (8), who determined aerodynamic and collection efficiencies from wind tunnel tests and field tests. The simple trap shown in Figure 1 was found suitable for general field studies; its characteristics are such that the catch is about 10 percent too high, but in practice losses during handling and weighing tend to reduce this error.

Indirect Methods

Indirect methods for measuring snow concentration are based mainly on attenuation of electromagnetic radiation passing from a source to a detector through the snow-filled airstream. Visible light techniques seem to have developed furthest (45, 22, 14), but alpha, beta, and gamma radiations have been investigated (30). Although electromagnetic metering is highly attractive, reliable equipment for operational use is not yet available.

CONCENTRATION AND FLUX OF BLOWING SNOW

Reliable data on concentration and flux are rare. The only comprehensive program of field measurements by experienced investigators using thoroughly tested and calibrated gages appears to be a "third generation" study by Budd, Dingle, and Radok (8).

Concentration and Flux as Functions of Height

Simple turbulent diffusion theory (Eq. 9) gives a power relation between concentration (or density) n and height z. Substitution of appropriate values for w and u_*

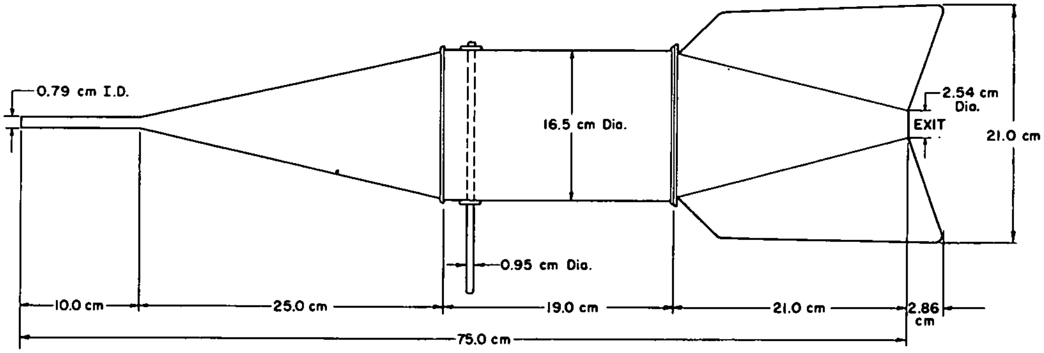

Figure 1. A simple trap for measuring concentration and horizontal flux of blowing snow. Several of the traps are mounted on a mast, with anemometers alongside, so as to give vertical profiles of n and q.

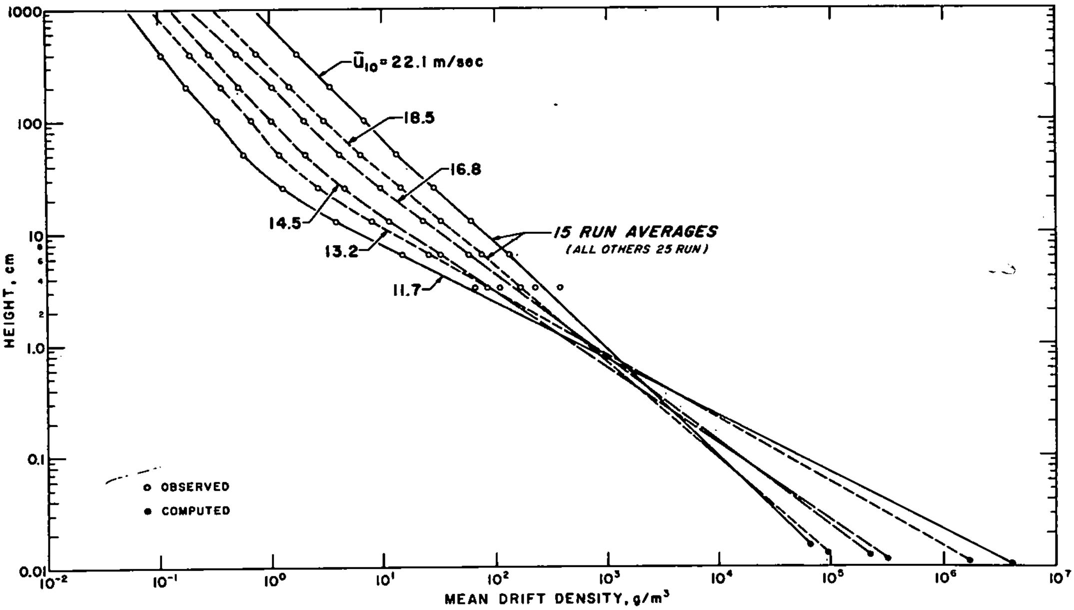

Figure 2. Vertical profiles of mean drift density, or concentration, for a range of wind speeds (8).

indicates that for strong winds the exponent is ≈-1. Field data (Fig. 2) confirm this prediction for u_{10} ≈20 m/sec, but for lower wind speeds n changes more rapidly with z for z < 50 cm. The measured profiles converge at z ≈ 1 cm, giving n ≈10^3 g/m^3 for all wind speeds, in agreement with saltation theory.

Field data show a similar power relation between flux q and height z in strong winds, with a corresponding trend to more rapid change of q with z at low levels in gentler winds. Because u can be expressed as a power of z, with an exponent ≈1/7 for neutral stability, simple theory (Eq. 9) predicts that q (= nu) will be proportional to a power of z.

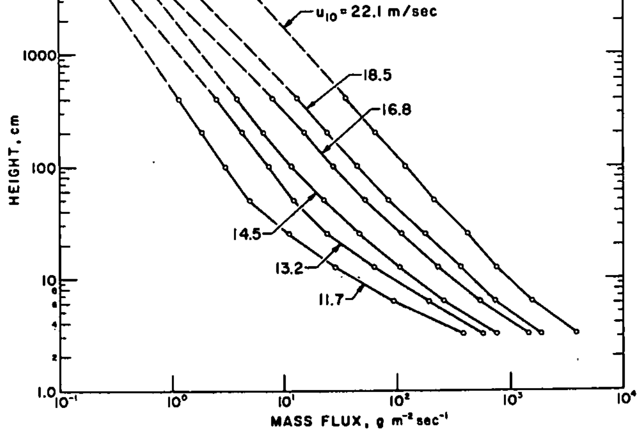

Figure 3. Vertical profiles of mean horizontal mass flux for a range of wind speeds (8).

Concentration and Flux as Functions of Wind Speed

Equation 10 predicts a linear relation between log n and 1/u for a given value of z, provided that w and z_0 are invariant with u. Extensive field data by Budd et al. (8) were quite well represented by such a relation (Fig. 3); lines fitted to their data are shown in Figure 4, which shows representative values of n as a function of u with z as parameter. It may be noted that n becomes less dependent on u as z drops below 10 cm. Because (1/u) ln (z/z_0) is proportional to $1/u_{10}$, a similar relationship between n and u_{10} can be expected; Figure 5 shows data bands for n as a function of u_{10} using results from 3 different stations.

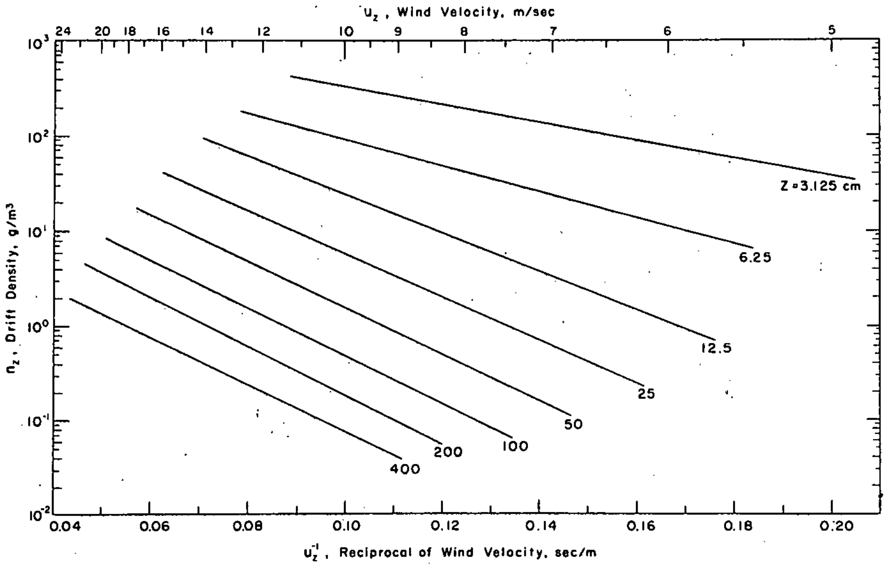

Figure 4. Observed relationships between mean drift density, or concentration, and wind speed for a range of heights. Data points have been omitted for clarity (8).

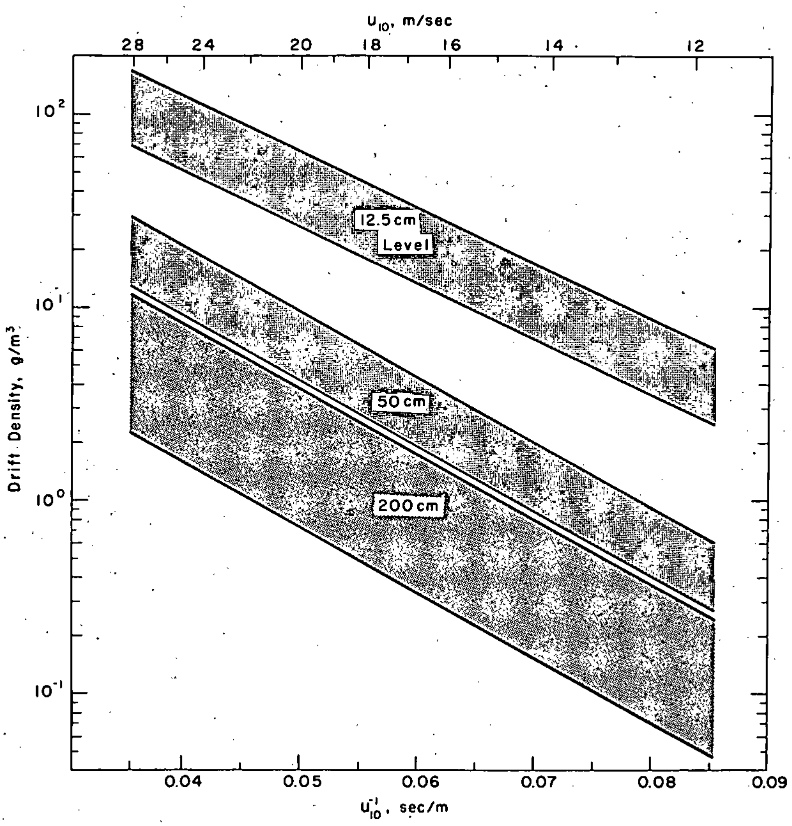

Figure 5. Data bands covering relationships between drift density (concentration) and wind speed at various heights, as observed at 3 different stations (8).

More empirically, there are good linear correlations between log n and log u_{10}, and between log q and log u_{10}, which indicate that, for $z \geq 50$ cm, n is approximately proportional to u_{10}^6 and q is approximately proportional to u_{10}^7. These simple relationships emphasize the very strong dependence of n and q on u.

CONCENTRATION AND FLUX OF FALLING SNOW

When snow is falling in wind-free conditions, the vertical mass flux is given by the accumulation rate at the ground, which is easily measured by exposing a tray of known area for a timed interval and weighing. If mean particle fall velocity is known, mass concentration snow in the air can be found. Concentrations measured by the writer at Hanover, New Hampshire, range from approximately 0.01 to 0.7 g/m^3 as accumulation rate, or vertical flux, ranges from approximately 0.003 to 0.25 g-cm^2/hr.

REDUCTION OF VISIBILITY AND LIGHT TRANSMISSION BY FALLING AND BLOWING SNOW

Particles of falling or blowing snow scatter visible radiation, reducing light transmission and visibility. Detailed measurements by Budd et al. (8), which were in broad agreement with Liljequist's earlier results (24), gave a relation (Fig. 6) between visibility, or visual range, V(m) and snow concentration n (g/m^3).

$$V = 100/n \tag{13}$$

The foregoing figures showing n as a function of z and u can thus be reinterpreted to show V as a function of z and u by appropriate scale changes.

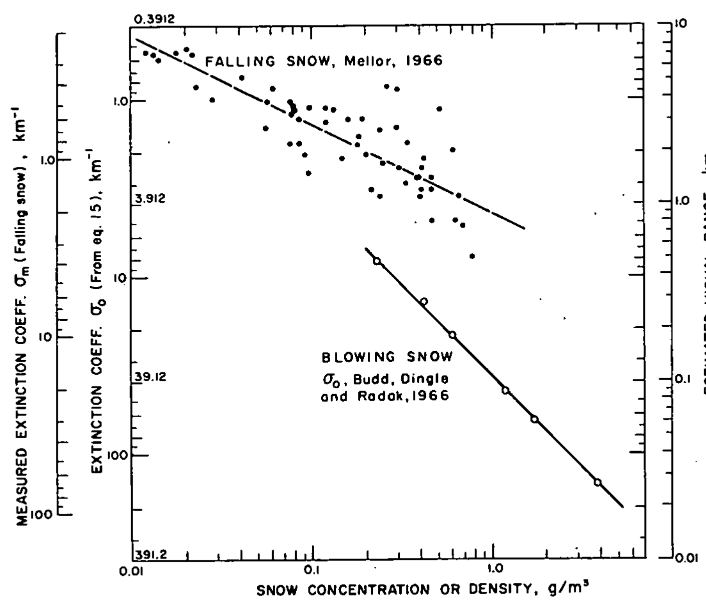

Figure 6. Visual range and extinction coefficient as functions of snow concentration for falling and blowing snow. The left scale gives an extinction coefficient σ_0 calculated on the assumption that liminal contrast is 0.02 and inherent target contrast is -1, and also gives a scale that corrects the data for falling snow in accordance with photometric control measurements.

Mellor (31) measured visibility through falling snow (Fig. 6) and gave an empirical relation between V(m) and snow accumulation rate A(g-cm²/hr):

$$V = 625\ A^{-0.42} \tag{14}$$

An extinction coefficient σ_O, which gives attenuation rates for transmitted light, can be estimated from visibility data by the relation

$$\sigma_O = 3.91/V \tag{15}$$

More detailed data summaries, together with relevant theory, are given by Mellor (30, 31).

SNOW DEPOSITION ON FLAT SURFACES

A variety of deposition-erosion patterns (ripples, waves, barchans, sastrugi, and dunes) form when snow blows across flat unobstructed terrain. Their general characteristics and dimensions are known, and their modes of formation are understood in broad terms (30), but there is little systematic quantitative information on details of formation. Detailed field research on these features might be valuable because, while they do not significantly affect the wind profile at higher levels during course of formation (8), they are intimately related to wind transport processes and particularly to saltation. Furthermore, because they undoubtedly reflect "wall" structures of the boundary layer, they may well yield information of broad significance.

Deposition-erosion features provide a means of assessing local wind directions and, to some extent, wind strengths. Large whaleback dunes are usually associated with strong winds blowing during major snowstorms, when much new snow is deposited. Ripples, barchans, and sharp-edged sastrugi commonly form when previously deposited snow is being redistributed by "dry" winds. Transverse features (ripples and waves) form in light winds, whereas longitudinal features (dunes and sastrugi) form in strong winds. Some observers have the impression that there is a positive correlation between the wind speed and the height, or length-width ratio, of sastrugi.

FLOW PERTURBATION BY OBSTACLES AND SURFACE IRREGULARITIES

When a wind stream encounters obstacles or surface irregularities, boundary layer separation occurs, turbulent wakes are formed, and preferential deposition and erosion of snow take place. The general proportions and characteristics of eddy zones around typical obstacles are reasonably well known, although there does not appear to be any systematic compilation of such data for a wide range of obstacle types and wind speeds. Deposition and erosion in the vicinity of an obstacle are clearly related to local eddy patterns, and equilibrium, or "saturation," profiles of drifts and scours have been determined for some common obstacles. However, little is known quantitatively about the conditions controlling deposition and erosion, or about the rates at which they occur.

Thus, while flow perturbation by obstacles and irregularities lies at the heart of practical snowdrifting problems, it cannot be treated analytically at the present time. The alternative is to tackle the problem experimentally, either by field observations or by model tests (which might conceivably include analog models).

FIELD OBSERVATIONS ON PROTOTYPES OR LARGE MODELS

Field tests of prototype structures or large models, and field observations on existing structures and features, have provided invaluable information on the drifting characteristics of snow fences, shelter belts, embankments, cuts, buildings, and other structures. Field studies will continue to form an essential part of any balanced research effort (38), but it seems important to distinguish between engineering studies designed to give specific results for local conditions and more fundamental studies designed to provide basic data of broad applicability and control data for model studies.

For basic investigations, ideal test sites are flat, unobstructed areas subject to frequent and consistent occurrence of blowing snow, with a range of wind speeds. Ideally, the sites should be manned continuously. Open plains and frozen lake surfaces are obvious locations for testing, but perhaps the best research sites of all are found on polar snowfields. One advantage of a permanent (polar) snowfield is that tests can run until equilibrium drift profiles are attained, whereas in areas of seasonal snowfall drift accumulation may be terminated artificially. Another advantage of polar snowfields is that the dense snow can easily be formed (and stabilized) to make embankments and cuts. To reap full value from field tests, one should throughly monitor snow transport in the unperturbed flow along the lines developed by Budd et al. (8).

MODELING TECHNIQUES

Direct modeling of snowdrifting may be carried out by using (a) a wind tunnel with introduced solid particles, (b) a wind tunnel without aerosols, and (c) a water flume with introduced solid particles.

Wind Tunnel With Aerosols

Simple wind tunnel experiments using fine powders have yielded useful information on shapes and dimensions of drifts (11, 34, 6, 21). Less empirical experiments designed to provide quantitative information, including rates of deposition, call for more rigorous application of modeling criteria (15, 42, 20, 17, 39, 35, 36, 9). Odar's comprehensive consideration of relevant criteria (35, 36) provides a sound basis for preliminary design of experiments, although some revision in detail may be called for. However, because it is unlikely that all modeling criteria can be satisfied in full simultaneously, judicious selection of the most significant and attainable scaling factors is probably necessary. This selection, together with subsequent evaluation of scaling factors, should be made on the basis of reliable data for the natural phenomenon.

Some wind tunnel tests have been made using ice particles (40), but for most purposes the experimental complications do not appear commensurate with the potential advantages. However, it should be pointed out that snow has adhesion and sintering properties not normally found in many other powders; these characteristics allow snow deposits to form wind-resistant surfaces and to develop shapes (e.g., cornices) that are prohibited for cohesionless powders.

Wind Tunnels Without Aerosols

Use of wind tunnels without aerosols has been proposed as an alternative to direct modeling. Leaving aside simple procedures for defining eddy zones by smoke tracers, quantitative modeling with solid particles involves the following steps:

1. Flow past the structure has to be properly reproduced by satisfying appropriate modeling criteria, which call for geometric and kinematic similarity and scaling of surface roughness;
2. Guided by postulated criteria for deposition or erosion, measurements have to be made on the flow;
3. By using theoretical criteria for deposition, initial deposition rates have to be calculated from the flow measurements; and
4. The base surface of the model has to be reshaped in accordance with results of step 3, and the entire procedure repeated.

Alternatively, it may be possible to establish equilibrium drift profiles by omitting step 3 and warping the model's base surface until flow measurements indicate that stable conditions have been reached (9)

The prime problem is to establish the criteria governing deposition and erosion, and to develop the analytical tools needed for calculation of deposition rates. In early investigations, deposition and erosion in the vicinity of an obstacle were associated with local eddy patterns, and it was assumed that deposition would occur in zones where wind speed was reduced below some critical value. Odar's studies (35, 36) laid emphasis on surface shear stress as a controlling factor, and Cermak (9) made explicit postulations that deposition would occur or cease according to whether surface forces were respectively less or greater than (a) values required for particle motion at the surface or, alternatively, (b) corresponding forces for an unperturbed flat surface away from the obstacle. Cermak's analysis indicated that conditions for initiation of particle movement are given by the dimensionless parameters (u_*/w) and (u_*d/ν), in which d is either particle diameter or equivalent surface roughness and ν is kinematic viscosity of the air. The first of these parameters is of obvious relevance to turbulent diffusion, as it is the inverse of the exponent in Eq. 9. The second parameter is more questionable, because most snow surfaces appear to be aerodynamically rough. A more plausible alternative for the parameter governing threshold shear is one used in essentially similar form by Bagnold (1), Odar (35, 36), Owen (37), and Radok (38): this is the parameter γ discussed and evaluated in the foregoing discussion of saltation. In any event, this topic ought to be reviewed in the light of realistic field data before any modeling is undertaken.

Once the relevant aerodynamic characteristics of the flow around an obstacle have been determined in the particle-free wind tunnel, there remains the problem of computing deposition rate as a function of position. Cermak's notes (9) give no indication how this might be done; they are concerned mainly with delineation of equilibrium drift profiles. Radok (38) argued convincingly that deposition rates ought to be deducible from mass flux divergence considerations; this seems eminently reasonable in the light of turbulent diffusion theory, but practical methods of calculation remain to be developed. In the present state of uncertainty it may be preferable for engineering purposes to approach the problem of deposition rates by considering the energetics, rather than invoking the detailed mechanics, of the process. One possibility would be to determine from wind tunnel tests the power expended by the air stream in drag resistance against an obstacle, and to compare this with the power required to suspend snow particles (given by turbulent diffusion theory) to obtain an estimate of rate of deposition in the vicinity of the obstacle. This would not, of course, give deposition rate as a function of position, but the general geometry of drift patterns could be determined independently from the local eddy structure.

Actually, although modeling without aerosols may have an important part to play in determining aerodynamic characteristics, it does not appear particularly attractive as a final engineering design procedure, as the practical simplification realized by eliminating the aerosol is probably outweighed by additional theoretical uncertainties and practical difficulties in simulating accumulating drift forms.

Water Flumes

Water flumes carrying solid particles in turbulent suspension have been used for modeling as an alternative to wind tunnels, notably by Theakston (43). The fundamental principles governing transport and deposition in a liquid are similar to those involved for wind transport (2, 3, 4, 5), but there are significant differences in magnitude for certain effects, because the densities of liquid and particle are of similar magnitude, whereas the densities of air and typical solids differ by about 3 orders of magnitude. In some respects this makes the problems of liquid transport more difficult than corresponding problems for air transport.

CONCLUSIONS

The basic processes of wind transport are now reasonably well understood, and there is a body of reliable field data for wind transport across flat unobstructed surfaces. The emphasis for fundamental field studies might now be switched to (a) natural deposition and erosion processes on flat unobstructed surfaces, (b) effects of flow perturbation on velocity, mass flux, and particle concentration, and (c) rates of deposition and erosion on surfaces in regions of perturbed flow.

Wind-tunneling modeling procedures in general are highly developed, but so far no fully satisfactory techniques for modeling windblown snow have appeared. This situation can probably be remedied by drawing on reliable field data for a review of modeling criteria and establishment of suitable scaling factors. Modeling with introduced aerosols is immediately feasible, and it ought to be possible to establish both deposition patterns and rates of deposition. Modeling without aerosols is more uncertain; it is immediately capable of giving potential deposition zones, but prediction of deposition rates depends on untested hypotheses. More field data and improved theory for perturbed flows seem to be a prerequisite for complete modeling without aerosols.

In the practical field of engineering control the immediate outlook is for "more of the same," but over the longer term there ought to be scope for more efficient application of control principles by exploiting better education and communication, and by routine application of modeling. Needed to achieve the goal of prompt and inexpensive model tests are a special wind tunnel and trained staff capable of serving engineers throughout the country on a reimbursable basis.

REFERENCES

1. Bagnold, R. A. The Physics of Blown Sand and Desert Dunes. Methuen, London, 1941.
2. Bagnold, R. A. Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid Under Shear. Proc. Royal Soc., London, A225, 1954, pp. 49-63.
3. Bagnold, R. A. Some Flume Experiments on Large Grains but Little Denser Than the Transporting Fluid, and Their Implications. Proc. Institute of Civil Engineers, Part 3, 1955, pp. 174-205.
4. Bagnold, R. A. The Flow of Cohesionless Grains in Fluids. Philosophical Trans., Vol. 249, 1956, pp. 235-297.
5. Bagnold, R. A. Auto-Suspension of Transported Sediment: Turbidity Currents. Proc. Royal Soc., London, A265, 1961, pp. 315-319.
6. Becker, A. Natural Snow Fences Along Roads. Bautechnik, Vol. 22, 1944, pp. 37-42.
7. Budd, W. F. The Drifting of Non-Uniform Snow Particles. In Studies in Antarctic Meteorology, American Geophysical Union, Antarctic Research Series, Vol. 9, 1966.
8. Budd, W. F. Dingle, R., and Radok, U. Byrd Snow Drift Project. In Studies in Antarctic Meteorology, American Geophysical Union, Antarctic Research Series, Vol. 9, 1966.
9. Cermak, J. E. Note on the Determination of Snow-Drift Location and Stability. U. S. Army Cold Regions Research and Eng. Laboratory, Tech. Note, 1966.
10. Dingle, R., and Radok, U. Antarctic Snow Drift and Mass Transport. Internat. Assn. of Scientific Hydrology, Publ. 55, 1961, pp. 77-87.
11. Finney, E. A. Snow Control on the Highways. Eng. Exp. Station, Michigan State College, Bull. 57, 1934.
12. Finney, E. A. Snow Control by Tree Planting. Eng. Exp. Station, Michigan State College, Bull. 75, 1937.
13. Finney, E. A. Snow Drift Control by Highway Design. Eng. Exp. Station, Michigan State College, Bull. 86, 1939.
14. Hollung, O., Rogers, W. E., and Businger, J. A. Development of a System to Measure the Density of Drifting Snow. Joint Dept. Electrical Eng., Dept. Atmospheric Science, Washington Univ., Tech. Rept., 1966, 54 pp.
15. Imai, I. On the Principle of Similitude in the Model Test of Snowstorm. Seppyo, Vol. 11, 1949, pp. 14-16.
16. Jenssen, D. Univ. of Melbourne, PhD thesis, 1963.
17. Keitz, E. L. Prevention of Snowdrifting at the Dye Sites. College of Eng., New York Univ., Rept. 799.01, 1960.
18. Keitz, E. L. Dye Site Snow Drift Tests, Series 1. College of Eng., New York Univ., Progress Rept. 741.02, 1960.
19. Keitz, E. L. Snow Drifting Tests on the Marie Byrd Replacement Facility. College of Eng., New York Univ., Manuscript, 1960.

20. Kelly, G. R., Keitz, E. L., and Strom, G. H. Scale Model Studies on Snow Drifting. College of Eng., New York Univ., Progress Rept. 549.01, 1960, 56 pp.
21. Kimura, K., and Yoshisaka, T. Scale Model Experiments on Snowdrifts Around Buildings. Seppyo, Vol. 4, 1942, pp. 96-99.
22. Landon-Smith, I., Woodberry, B., and Wishart, E.R. The Photoelectric Metering of Wind-Blown Snow. Austral. Nat. Antarctic Res. Expeds., Interim Report, Publ. 79, 1965.
23. Langleben, M. P. The Terminal Velocity of Snowflakes. Quart. Jour. Royal Met. Soc., Vol. 80, 1954, p. 174.
24. Liljequist, G. H. Energy Exchange of an Antarctic Snowfield. Norwegian-British-Sweden Antarctic Expedition 1949-52, Scientific Results, Vol. 2, Part 1C, 1957.
25. Lister, H. Solid Precipitation and Drift Snow. Trans-Antarctic Expedition 1955-58, Scientific Rept. 5, 1960.
26. Litvinov, L. V. Determination of the Steady-State Velocity of Falling Snow Particles. Izv. Akad. Nauk SSSR, Geophys. Series, Vol. 7, No. 853, 1956; English translation by Def. Res. Board of Canada, T238R.
27. Magono, C. Fall Velocity of Snowflakes. Researches on Snow and Ice, No. 1, 1953, pp. 19-28; also Yokohama Univ., Sci. Rept. Series 1, No. 2, p. 18.
28. Mellor, M. Gauging Antarctic Drift Snow. In Antarctic Meteorology, Pergamon, 1960, pp. 347-354.
29. Mellor, M. Fall Velocity of Snow Particles. U.S. Army Cold Regions Research and Eng. Laboratory, Tech. Note, 1964.
30. Mellor, M. Blowing Snow. U.S. Army Cold Regions Research and Eng. Laboratory, USACRREL Monographs, Part 3, Section A3c, 1965.
31. Mellor, M. Light Scattering and Particle Aggregation in Snowstorms. Jour. Glaciology, Vol. 6, No. 44, 1966, pp. 237-248; also USACRREL Research Rept. 193.
32. Mellor, M., and Radok, U. Some Properties of Drifting Snow. In Antarctic Meteorology, Pergamon, 1960, pp. 333-346.
33. Nakaya, U., and Terada, T. Simultaneous Observations of the Mass, Falling Velocity and Form of Individual Snow Crystals, Investigations on Snow. No. 4, Jour. Faculty Sci., Hokkaido Imp. Univ., Series 2, Vol. 1, 1935, pp. 191-200.
34. Nøkkentved, C. Drift Formation at Snow Fences. Stads-og Haveingenøren, Vol. 31, No. 9, 1940.
35. Odar, F. Scale Factors for Simulation of Drifting Snow. Jour. Engineering Mechanics Div., ASCE, Vol. 88, No. EM2, 1962.
36. Odar, F. Simulation of Drifting Snow. U.S. Army Cold Regions Research and Eng. Laboratory, Research Rept 174, 1965.
37. Owen, P. R. Saltation of Uniform Grains in Air. Jour. Fluid Mechanics, Vol. 20, 1964, pp. 225-242.
38. Radok, U. Deposition and Erosion of Snow by the Wind. U.S. Army Cold Regions Research and Eng. Laboratory, Research Rept. 230, 1968.
39. Silberman, E. Modeling Blowing Snow. U.S. Army Snow Ice and Permafrost Research Establishment, unpublished manuscript, 1960.
40. Stehle, N. S. Studies of Snow Movement in a Wind Duct. U.S. Nav. Civil Engineering Lab., Tech. Rept. R-420, 1965.
41. Strom, G. H., Kelly, G. R., Keitz, E. L., and Weiss, R. F. Scale Model Studies on Snow Drifting. U.S. Army Snow Ice and Permafrost Research Establishment, Research Rept. 73, 1962.
42. Tanifuji, S. and Ogawa, T. An Experimental Study on Snow Drift Control—Highway Maintenance in Snowy Districts. Dept. of Public Works, Research Institute, Ministry of Construction, Japan, Vol. 100, 1956, pp. 17-32.
43. Theakston, F. H. Snow Accumulation About Farm Structures. Agricultural Engineering, March 1962, pp. 139-161.
44. Tobiasson, W., and Reed, S. Use of Field Models to Study Snow Drifting. U.S. Army Cold Regions Research and Eng. Laboratory, Tech. Note, 1966.

45. Wishart, E. R. A New Photoelectric Drift Snow Gauge. Austral. Nat. Antarctic Res. Expeds., Interim Repts., Ser. A, Vol. 4, Publ. 79, 1965, pp. 19-26.

Informal Discussion

A. R. Jumikis

There are arguments pro and con. There are no cookbook recipes available for all road and snowdrifting conditions.

L. Gary Byrd

Perhaps there is a warrant for research in the economic area relative to this whole question of the investment in achieving drift control.

M. E. Volz

I was recently subjected to a practical application of the nonpermeable snow fence that is made out of snow, and it worked very successfully. It was at the airport at Madison, Wisconsin. On the upwind side of the runway, which is the prevailing cause of their snowdrifting, they had plowed back about 20 or 30 ft and made a small ridge so that they did not have a problem close to the runway. They then proceeded out onto the field approximately 200 ft and very slowly raised a huge windrow. It was the most successful thing that I have seen and did not cost anything beyond the mechanics of actually building this nonpermeable snow fence.

Jumikis

That is true. If one has the manpower, one can make a good dense snow fence or a snow wall by means of blocks of snow or simply by shoveling up a snow wall. This method has been used in Russia. However, this method cannot be used with the first drifting snow in winter because not enough snow is yet available for building a snow fence.

L. H. Watkins

I should like to make an observation about a rather contradictory sort of problem that arises with us because we are pressed very often to put fences alongside highways for a number of different reasons, not only as snow fences but also as noise barriers and windbreaks. For the last 2 purposes, we erect the fence as close to the carriageway as we can get it and then it is in the optimum position for depositing snow on the carriageway when the snow falls. I do not really know the answer to this one. If you can design a barrier that will do all these things, I would be very much obliged.