Scaling Snowdrift Development Rate

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ABSTRACT

For successful snowdrift modeling, measured drift shapes should be geometrically similar to full-scale ones and develop at rates that scale in a known manner. Consensus exists on most modeling methods and similitude requirements needed to meet these objectives. A notable exception is the manner to scale drift development rates. This paper presents our rationale for rate scaling based on independent model and prototype mass-transport measurements, as originally proposed by Anno in 1984. We validate this approach by comparing the rate of drift development for a model Wyoming snow fence with corresponding field data. Anno's method yields excellent agreement, while alternatives differ substantially.

Key words: Scaling laws, Snowdrift modeling, Time scaling

INTRODUCTION

The term snowdrifting usually refers to the wind-driven erosion, transport and deposition of fallen snow. Drifting snow can reduce visibility and impair movement on roads and railways, cause building roofs to fail, block air intakes, and render access-ways inoperable. Reviews by Mellor (1965), Kind (1981) and Tabler et al. (1990a) provide general descriptions of snowdrifting physics and drift-control techniques.

We may consider two snow-transport mechanisms to be relevant to snowdrifting around structures: saltation and turbulent diffusion. In saltation, the wind lifts loose particles and carries them a short distance downwind as gravity pulls them down to impact the snow surface. Impacting particles rebound or knock loose other particles, and the process continues provided the wind speed or friction velocity is above a threshold value. In diffusion, turbulent mixing holds particles aloft against the pull of gravity, resulting in long, irregular trajectories that generally do not contact the snow surface. The saltation layer near the snow surface acts as the source of particles for diffusion, which becomes an increasingly important transport mechanism as wind speed increases.

Physical modeling is one way to simulate snowdrifting around structures to improve their performance. The main objectives of such modeling are to predict snowdrift patterns and their rates of development. Papers by Strom et al. (1962), Odar (1965), Kind (1976, 1986), Wuebben (1978), Iversen (1979, 1980), Anno (1984), Isyumov et al. (1989), and Kwok et al. (1992), among others, show considerable consensus on appropriate modeling methods and similitude requirements. A notable exception is the manner to scale drift development rates. This problem persists for two main reasons: practical modeling necessitates distortion of some important similitude parameters, making the correct choice of time scale unclear, and good field data to validate model formulations are scarce.

We present here our formulation for snowdrift modeling in a wind tunnel. In particular, we discuss our rationale for time scaling based on independent model and prototype mass-transport measurements, as originally proposed by Anno (1984). We validate this approach by comparing the rate of drift development for a model Wyoming snow fence with corresponding field data. We also discuss other time-scaling methods and compare their predictions with our own.

SIMILITUDE REQUIREMENTS

In general, accurate snowdrift modeling requires preservation of geometric, kinematic and dynamic similitude between model and prototype. Geometric similitude is easily achieved by constructing a model with a uniform geometric scale factor,

$$L_p/L_m = \lambda \qquad (1)$$

where L represents any characteristic length and subscripts m and p refer to model and prototype, respectively.

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Kinematic similitude requires that we simulate the turbulent atmospheric flow that drives snowdrifting. Here, we may follow standard wind-engineering practice (Cermak 1975, Simiu and Scanlan 1978, Isyumov et al. 1989). The mean atmospheric wind-speed profile follows the logarithmic relationship for fully rough flow with neutral stability:

$$\frac{U}{u_*} = 2.5 \ln \frac{z}{z_o} \tag{2}$$

where U is the mean wind speed at height z, u_* is the friction velocity, and z_o is the aerodynamic roughness height. This expression also holds above a saltating snow layer provided we use z_o', the roughness measured during saltation (Budd et al. 1966, Oura et al. 1966, Tabler 1980a, Tabler and Schmidt 1986). Thus, similarity of the mean wind profile requires

$$\left(\frac{z_o'}{L}\right)_m = \left(\frac{z_o'}{L}\right)_p . \tag{3}$$

Isyumov et al. (1989) also recommend that we preserve the turbulence intensity of the atmospheric flow,

$$I_m = I_p \tag{4}$$

and the length scale of turbulence,

$$\left(\frac{L_{turb}}{L}\right)_m = \left(\frac{L_{turb}}{L}\right)_p . \tag{5}$$

Most researchers agree with the need to meet requirements 1–3 and the desirability of meeting requirements 4 and 5. These requirements can be met in wind tunnel modeling, and hence flow-field similitude can be attained.

Dynamic similitude requires that we preserve the relative importance of all forces governing snowdrifting. This is much more difficult to achieve. Several authors have compiled lists of similitude parameters based on force ratios (e.g., Strom et al. 1962, Odar 1965, Kind 1976, Iversen 1979). Kind (1986) carefully reviewed these similitude requirements and discussed their relative importance for practical modeling. Because snowdrifting is fundamentally an interplay between fluid forces, particle inertia and gravity, similitude parameters comprising these forces are probably most important:

$$C_d \frac{\rho L}{\rho_p D} \tag{6}$$

$$\frac{U^2}{gL} \tag{7}$$

$$\frac{U^2}{gL}\left(\frac{\rho}{\rho_p - \rho}\right) \tag{8}$$

where C_d = particle drag coefficient
D = particle diameter
g = gravitational acceleration
ρ and ρ_p = fluid and particle densities, respectively.

Parameter 6 represents the ratio of fluid drag to particle inertia. Strom et al. (1962) and Kind (1986) suggested that an alternative form is the ratio of particle fall velocity, w, to flow velocity:

$$\frac{w}{U} . \tag{9}$$

Model particles exist that preserve requirement 9. Parameter 7 is Froude number, the ratio of particle inertia to particle weight, and 8 is termed densimetric Froude number to account for fluid buoyancy. As we will discuss in the next section, Froude number is difficult to preserve in a wind tunnel, and its role is quite important.

In principle, we should also preserve snow material properties such as angle of repose, cohesion and coefficient of restitution. However, distortion in angle of repose should primarily affect small-scale features such as cornices and have little influence on overall drift size or shape. Particle cohesion and coefficient of restitution pertain to the dynamics of saltating particles as they splash into the snow surface. Work by Schmidt (1980, 1986) and Pomeroy and Gray (1990) suggests that these parameters are important if one attempts to relate snow transport to wind speed. However, they may not significantly affect the distribution of drifting snow around a structure, and we can directly measure mass transport in a wind tunnel rather than predict it using wind speed.

DISTORTIONS FOR PRACTICAL WIND TUNNEL MODELING

For model snowdrifts to be geometrically similar to prototype ones, areas of erosion and deposition should be similar throughout drift development. The model incident flow field will be similar to the prototype one by meeting requirements 1–5. Kind (1976), Anno (1984) and others have argued that to preserve the shape of erosional and depositional areas around a structure, we must preserve the ratio of friction velocity to the threshold friction velocity where saltation ceases:

$$\frac{u_*}{u_{*t}} . \tag{10}$$

Around bluff bodies (i.e., most buildings and structures), flow fields in turbulent flow are largely independent of Reynolds number. Furthermore, most velocity gradients are quite steep, so that distortion of u_* / u_{*t} should not appreciably alter the shape of the initial erosion and deposition areas. That is, both Reynolds number and u_* / u_{*t} can be distorted in the model, provided the flow remains fully rough. Kind (1976) proposed a minimum Reynolds number during snowdrifting to ensure fully rough flow:

$$\frac{u_*^3}{2g\nu} > 30 \qquad (11)$$

Requirement 11 essentially places a lower limit on the flow velocity for wind tunnel modeling of about 0.23 m/s. Kind (1976, 1986) has noted that it may be possible to relax this requirement, although model-particle threshold velocities are not far below it.

Most model studies are concerned with drifting over large areas, to include upstream features and long drift lengths. Thus, we generally use relatively small-scale models (1:50 to 1:200). Minimum flow-velocity requirements conflict with Froude number similitude at these scales, yielding model Froude numbers that are too large. This in turn results in particle trajectories that are proportionately longer in the model (relative to structural dimensions) compared to the prototype. This distortion can cause model particles to overshoot wake areas that field particles would fall into, distorting model collection efficiency. An example of this problem is snow drifting behind a leeward-facing step, such as a stepped roof. A lower model collection efficiency would lead to underprediction of the drift development rate. We must be aware of such problems, and should attempt to calibrate model drift development rates against field data for classes of structures such as leeward steps.

Some Froude distortion is acceptable for most classes of structures where the predominant snow transport is through or around the structure. Provided model trajectories are much shorter than drift lengths, particles will have many opportunities to interact with the near-field flow around the structure and deposit accordingly. We may estimate an acceptable minimum flow velocity based on the requirement that trajectories be much less than typical drift lengths, which are about 10 times structure heights, H (for two-dimensional or squat three-dimensional structures). Note that trajectory lengths are about 10 times trajectory heights h (Kobayashi 1972) and that saltation trajectory heights may be approximated by (Owen 1964):

$$h \approx \frac{u_*^2}{2g}. \qquad (12)$$

This leads to the requirement:

$$\frac{u_*^2}{2gH} << 1 \qquad (13)$$

to ensure that model particle trajectories remain small relative to drift lengths. It is fairly easy to meet requirement 13 provided we operate close to minimum velocities dictated by particle threshold speeds or minimum Reynolds number (eq 11).

TIME SCALING AND THE ROLE OF MASS TRANSPORT

Froude distortion makes the choice of time or rate scaling somewhat complicated, and researchers have tried many formulations (see Table 1). Iversen (1979,

Table 1. Dimensionless time scales applied to snowdrifting model studies.

Eq no.	*Parameter*	*Description*	*References*
(14)	$\frac{tU}{L}$	dimensionless velocity	Tobiasson & Reed (1966), Isyumov et al. (1989), Kwok et al. (1992)
(15)	$\frac{\rho}{\rho_p}\frac{tU}{L}$	modified dimensionless velocity	Kwok et al. (1992)
(16)	$\frac{\rho}{\rho_p}\frac{U^2}{gL}\left(1-\frac{U_t}{U}\right)\frac{tU}{L}$	transport rate parameter	Iversen (1980), Kwok et al. (1992)
(17)	$\frac{w}{u_{*t}}\frac{\rho}{\rho_p}\frac{U^2}{gL}\left(1-\frac{U_t}{U}\right)\frac{tU}{L}$	modified transport rate parameter	Iversen (1979)
(18)	$\frac{\rho}{\rho_b}\frac{U^2}{gL}\left(1-\frac{U_t}{U}\right)\frac{tU}{L}$	modified transport rate parameter	Iversen & Wang (1991)
(19)	$\frac{\rho}{\rho_p}\frac{U^2}{gL}\left(1-\frac{U_t}{U}\right)\frac{tU}{L}\Big/\left(\frac{z_0'}{H}\right)^{3/7}$	transport-rate/roughness parameter	Iversen (1980)
(20)	$\frac{qt}{\rho_b H^2}$	dimensionless mass transport	Anno (1984)

1980) and Anno (1984) have both argued in favor of using dimensionless mass transport to scale time. This has intuitive appeal: the greater the rate of mass transport in proportion to structure volume or area, the faster the drifts will develop. Implicit in both approaches is the assumption that model and prototype collection efficiencies are identical (i.e., model distortions are small) or that model collection efficiency can be calibrated against field data for the class of structure of interest. The essential difference between these two methods is that Iversen explicitly includes various functional forms of mass flux q based on saltation
mechanics, whereas Anno leaves the form of q unspecified. Iversen's time or rate parameters thus depend explicitly on flow velocity and particle characteristics such as threshold speed and density. Model and field mass transport do not need to be measured using this approach. However, Iversen's method contains a fundamental, implicit assumption: *the functional form of q used in time scaling must accurately describe both model and field mass transport.* Anno's approach allows for independent determination of model and field mass transport: we may measure it directly in the wind tunnel and estimate it in the field based on the best available transport formulation.

Iversen et al. (1979, 1980, 1991) have modeled snowdrifting in a wind tunnel using a variety of particles, and have used saltation-based formulations of transport rate to derive time-scaling parameters 16–19. Iversen (1980) obtained good collapse of model mass-transport and drift-development rates using saltation-based expressions 16 and 19. Iversen (in press) also showed that Owen's (1964) saltation expression collapses well the measured transport rates of sand in a wind tunnel:

$$q = \frac{\rho u_*^3}{g}\left(1 - \frac{u_{*t}^2}{u_*^2}\right)\left(0.25 + \frac{w}{3u_*}\right). \qquad (21)$$

It is reasonable that saltation is the predominant transport mechanism for wind tunnel models because we generally operate near particle threshold speeds to minimize Froude-number distortion. However, field measurements indicate a more important role for diffusion in seasonal snow transport.

Budd et al. (1966) made extensive measurements of drifting snow mass flux in Antarctica over a broad range of wind speeds and 8 measurement heights from 0.03 m to 4.0 m. Tabler (1991) integrated these results (via Mellor and Fellers 1986) and obtained the following best-fit expression:

$$q_{0-5} = U_{10}^{3.80} / 233,846 \qquad (22)$$

where the subscript 0–5 indicates the integration is from the snow surface to 5 m.

Pomeroy et al. (1988, 1990, 1992) have developed a comprehensive, process-based model of snowdrift transport, termed the Prairie Blowing Snow Model (PBSM). They calibrated this model using their own mass-flux measurements, and found that diffusion predominates over saltation for wind speeds above about 8 m/s (Pomeroy and Male 1992, Tabler, Pomeroy and Santana 1990a). Pomeroy et al. (1993) also applied the PBSM to predict the seasonal snow transport for two sites in Saskatchewan. They found that diffusion accounted for roughly two-thirds of the predicted seasonal transport.

Tabler et al. (1990b) developed a simple approximation to the transport rate predicted by the PBSM for the case of unlimited snow supply:

$$q_{0-5} = \frac{U_{10}^{4.04}}{458,800}. \qquad (23)$$

They found good agreement between this expression and seasonal snow transport at Prudhoe Bay, Alaska, measured using snow fences. Equation 23 also approximates eq 22, the fit to the Antarctic snow transport data. These results provide a degree of independent confirmation of the PBSM.

Collectively, these field mass-transport results indicate that a) diffusion predominates over saltation for seasonal snow transport, and b) field mass-transport rate does not have the functional dependence on flow velocity given by saltation-based expressions. Thus, the use of saltation-based time-scaling parameters 16–19 can lead to inaccurate predictions for drift development rates simply because saltation expressions do not accurately predict mass transport in the field. Anno's approach to rate scaling (eq 20) avoids this problem by providing for independent specification of model and field transport rates.

VALIDATION OF ANNO'S TIME SCALING FOR A WYOMING SNOW FENCE

Field data suitable for validating time-scaling approaches are rare (Haehnel and Lever, in press). For this purpose, we require concurrent measurements of drift geometry and snow transport during drift development. The best field data exist for snow fences. In this section, we compare drift development on a Wyoming snow fence with corresponding model data obtained in the CRREL snowdrifting wind tunnel.

Drift development based on field measurements of capture efficiency

Tabler and Jairell (1993) measured the capture efficiency, η, defined as the change in drift mass, m_{drift}, with respect to the incident snow transport, $Q \equiv qt$, for 2.4–3.8-m-high Wyoming snow fences. The three independent methods used yielded comparable results: initial capture efficiency, η_0, when the fences were empty averaged about 95%; η then dropped as the fence filled. They fitted a functional form to these data that gave a reasonable fit:

$$\eta = \eta_o \sqrt{1 - \left(\frac{A}{A_e}\right)^2} \tag{24}$$

where $\eta_0 = 0.95$ and $A_e = 25H^2$ (the selected fence capacity). If we approximate drift bulk density, ρ_b, as a constant, we may write capture efficiency as the change in dimensionless drift area, A/H^2, with respect to dimensionless mass transport, $qt/\rho_b H^2$:

$$\eta \equiv \frac{dm_{\text{drift}}}{dQ} \approx \frac{d(A/H^2)}{d(qt/\rho_b H^2)}. \tag{25}$$

Inserting eq 24 into 25 and integrating yields a expression for drift development on a Wyoming snow fence based on capture-efficiency field data:

$$\frac{qt}{\rho_b H^2} = 26 \text{ arc sin}\left(\frac{A}{25H^2}\right). \tag{26}$$

Equation 26 predicts the dimensionless transport required to fill a Wyoming snow fence to a given proportion of its capacity. This is exactly the form that we require to validate model drift development rate. However, it does contain some uncertainty. Tabler and Jairell's (1993) measured capture efficiencies show a scatter of about ±20% around eq 24. Numerical simulations by Tabler and Jairell (1993) suggest that capture efficiency should be largely independent of fence height but could decrease slightly with increasing wind speed. Also, Tabler (1980b, 1985) has shown that drift bulk density increases slightly with drift size due to compression by the overlaying snow. Incorporating these effects, we expect eq 26 to approximate the true drift development curves for 2–4-m-high Wyoming snow fences within an overall uncertainty of about ±30%.

A drift development field study

Tabler (1989) conducted a field study to document drift development on a 1.8-m high Wyoming snow fence. He measured five sets of drift profiles over a 32-day period. He also recorded hourly wind speed, air temperature, the output of a blowing snow detector (essentially a visibility meter), and observer notes pertaining to snow conditions and the intensity of drifting, if any. Tabler also provided hourly estimates of "potential" mass transport using the measured wind speed and eq 23, and estimates of drift bulk density based on earlier work (Tabler 1985).

Note that eq 23 applies to conditions of unlimited snow supply; it therefore over estimates Q during supply-limited conditions (conditions commonly encountered during the 32-day test period). We applied a first-order correction to account for this: we assumed that the hourly mass transport equaled the calculated potential transport, eq 23, except when no drifting was specifically noted; in this latter case, we assumed that the transport was zero. This method probably still overestimates mass transport for those hours just prior to exhaustion of the snow supply, but it provides a reasonable upper bound. Table 2 presents our compilation of Tabler's (1989) drift development data. The dimensionless drift areas in Table 2 are slightly larger than those reported by Haehnel and Lever (in prep.) because that earlier work mistakenly omitted the measured windward drift areas.

Table 2. Dimensionless drift area versus dimensionless mass transport for a 1.8-m-high Wyoming snow fence based on field measurements by Tabler (1989).

Date (1984)	*27 Nov*	*28 Nov*	*3 Dec*	*17 Dec*	*22 Dec*
A/H^2	6.4400	9.0900	9.9000	14.290	18.530
$Q/\rho_b H^2$	5.8505	14.256	16.548	26.087	52.226

Comparison with model drift development

We may compare drift development based on these two sets of field data with corresponding model results obtained in CRREL's snowdrifting wind tunnel (Haehnel et al. 1993). This facility consists of a 0.5-m × 0.5-m closed-loop wind tunnel with fine glass beads as the model snow material. The model Wyoming snow fence is at 1:116 scale compared with the 1.8-m fence tested by Tabler (1989). Table 3 compares the model and prototype values of several similitude parameters. In particular, note that model Froude number is about an order of magnitude too high, but that the model satisfies requirement 13 that particle trajectories be much smaller than drift lengths. Model densimetric Froude number falls just within the range of field values.

Figure 1 compares the model drift development data with eq 26, derived from Tabler and Jairell's (1993) measured capture efficiencies, and Tabler's (1989) drift development field study. The model data

Table 3. Values of model and field similitude parameters for 1.8-m, 1:116-scale Wyoming snow fence.

Parameter	*Model*	*Field*
ρ_p / ρ	2,000	600
w / u_{*_t}	1.4–2.3	1.4–2.6
angle of repose (°)	19–32	40–45
u_* / u_{*_t}	1.15	0.4–4.0
z_0' / H	2.2×10^{-3}	10^{-4}–10^{-3}
$u_*^2 / 2gH$	0.11	0.001–0.02
U^2/gH	90	2–30
$\frac{\rho}{\rho_p}\frac{U^2}{gH}$	5×10^{-2}	0.3–5×10^{-2}
$\frac{\rho}{\rho_p}\frac{U^2}{gH}\left(1-\frac{U_t}{U}\right)$	6×10^{-3}	0–4×10^{-2}

agree well with the capture-efficiency based curve. The discrete measurements by Tabler (1989) fall to the right of this curve, consistent with the expected overprediction of mass transport using eq 23 when snow supply was nearly exhausted.

COMPARISON OF DEVELOPMENT TIME PREDICTIONS FOR A WYOMING SNOW FENCE

The main purpose of a time-scaling method is to predict the time expected for drifts to develop on a structure to a certain size having measured the model drift-development rate. Figure 1 shows this as a dimensionless plot, with the form of the prototype q unspecified. If we knew the average snow flux at our field site, we could use these results to predict, for example, the average time to saturate the drift. Rather than provide a single result, however, we may assume a form for $q(U)$ to predict drift-development time versus flow velocity. This turns out to be an effective way to compare the predictions from different time-scaling methods.

As noted earlier, Anno's (1984) method allows independent selection of $q(U)$, and we may select the validated expression 23. The methods of Iversen (1979, 1980, 1991) require that $q(U)$ be the saltation-based expressions used to derive the rate-scaling parameters 16–19. We may also produce a time-velocity curve using straight Froude scaling.

Figure 2 compares these four methods of scaling model drift development against a curve derived from Tabler and Jairell's (1993) capture-efficiency field data. Shown is the time required to develop a drift on a 1.8-m Wyoming snow fence to a size of $A/H^2 = 18.5$ (slightly below the expected saturation size) as a function of wind speed. The following details pertain to the application of the methods compared in Figure 2:

1) *Field data.* Equation 26, based on Tabler and Jairell's (1993) capture-efficiency field data, predicts $qt/\rho_b H^2 = 22$ for $A/H^2 = 18.5$. We may then insert eq 23 to produce a time-velocity curve based on field data.
2) *Anno's (1984) method.* Our model results suggest $qt/\rho_b H^2 \sim 25$ for $A/H^2 = 18.5$. This small difference from the field data could reflect random error or model distortion. We apply Anno's method exactly as for the field data, by inserting eq 23 for $q(U)$.
3) *Froude scaling.* To obtain a drift size of $A/H^2 = 18.5$, the model would run at 3.8 m/s for 2.39 hr. Froude scaling normally dictates fixed time and

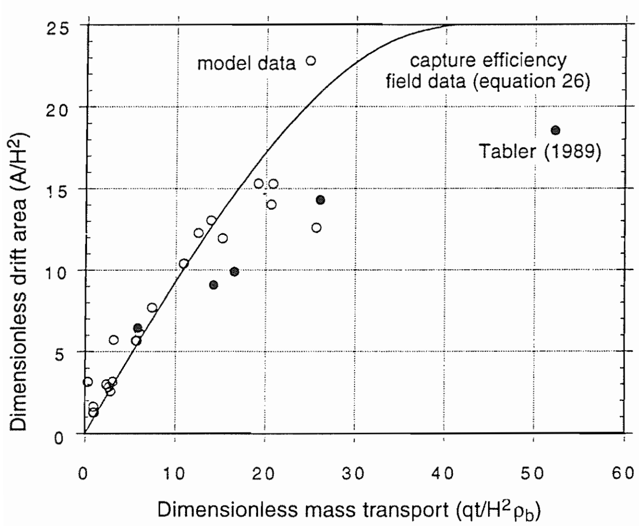

Figure 1. Comparison of model and prototype drift development on a Wyoming snow fence.

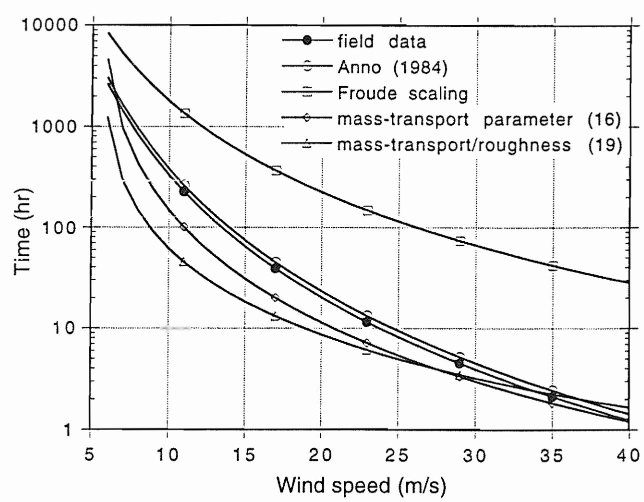

Figure 2. Comparison of predictions for drive-development time vs. wind speed for a 1.8-m-high Wyoming snow fence ($A/H^2 = 18.5$).

velocity ratios, $t_p/t_m = U_p/U_m, = (L_p/L_m)^{1/2} = 10.8$. This would yield a single prediction of 26 hrs at 41 m/s for drift development. We may produce a time-velocity curve by assuming that drift-development rate scales with Froude number. This leads to a rate-scaling parameter:

$$\frac{U^2}{gH} \cdot \frac{tU}{H}. \tag{27}$$

We obtain the Froude-scaling curve on Figure 2 by equating model and prototype values of this parameter.

4) *Transport-rate parameter.* Iversen (1980) showed a good collapse of model drift-development data using a saltation-based transport-rate parameter (16). We obtain the corresponding curve on Figure 2 by equating model and prototype values of this parameter.
5) *Transport-rate/roughness parameter.* Iversen (1980) improved the collapse of model drift-development data by incorporating aerodynamic roughness in parameter 16 to yield parameter 19. We obtain the corresponding curve on Figure 2 by equating model and prototype values of this parameter. We used the measured value of z_0' for the model and Tabler and Schmidt's (1986) empirical expression for the prototype as recommended by Tabler (1989):

$$z_0'(\mathrm{m}) = \frac{u_*^2(\mathrm{m/s})}{312}. \tag{28}$$

DISCUSSION

Figure 2 shows very good agreement between model data scaled using Anno's (1984) method and a time-velocity curve derived from field data. Because we used eq 23 for $q(U)$ for both the field-based eq 26 and the model data, the difference between these two curves reflects only the difference between measured model and prototype drift-development data, Figure 1. As noted, this difference could be due to model distortion, random experimental error, or the overall uncertainty associated with eq 26. Nevertheless, this comparison highlights the key advantage of Anno's method: we may specify prototype mass transport independently of model transport using the best means available (e.g., direct mass flux measurements, a sophisticated process-based model such as the PBSM, or a simple empirical expression such as eq 23).

Iversen's (1979, 1980, 1991) rate-parameter methods do not contain this advantage. Although also based on dimensionless mass transport, these methods specify $q(U)$ explicitly in a transport-rate parameter that applies to both model and prototype. Thus, we introduce error associated with any differences in the functions that best describe model and prototype transport. Figure 2 illustrates that these differences can overwhelm effects of model distortions and experimental uncertainty, leading to incorrect prediction of drift-development time by as much as a factor of 5.

Use of simple Froude scaling provides the poorest agreement with field results. This is not surprising given that wind tunnel modeling significantly distorts Froude number.

Work by Kwok et al. (1992) and Smedley et al. (1993) supports these findings. They applied several time-scaling methods to models studies of elevated buildings and compared the results to field data by Mitsuhashi (1982) obtained on these buildings in Antarctica. Kwok et al. used the transport expression of Budd et al. (1966) to estimate field mass transport based on reported wind-speed ranges between sets of drift profiles. Anno's (1984) method yielded good agreement between field data and model data at two scales (Smedley et al. 1993); application of eq 16 yielded poorer agreement (Kwok et al. 1992). Similarly, Anno's method produced the closest prediction to the actual drift-development time (Kwok et al. 1992).

Use of Anno's dimensionless mass-transport parameter 20 also provides a convenient, intuitive way to present model and prototype drift-development data. For example, if we divide both axes of Figure 1 by 25, we find that the total mass transport required to fill the fence is roughly 1.6 times the fence capacity. The format of Figure 1 also allow easy comparison of drift-development rates for different structures or structural variations to assess their relative performance.

Note that the format of Figure 1 provides a clear assessment whether model or prototype snowdrifts have reached equilibrium. The model data on Figure 1 derive from several repeated tests. We stopped these tests when the drifts visually appeared to saturate (i.e., reach equilibrium). However, Figure 1 suggests that the drifts had not saturated, and in the future we plan to plot dimensionless drift area versus dimensionless mass transport during the tests themselves. Interestingly, model data presented in this same format by Smedley et al. (1993) also don't appear to saturate, again suggesting that visual assessment of equilibrium can be misleading.

Anno's (1984) time-scaling method is not without its drawbacks. Implicit is the assumption that mass transport correctly scales drift development independent of flow velocity (i.e., Reynolds and Froude numbers). While distortion of Reynolds and Froude numbers appears to be acceptable within the limits discussed earlier (fully rough flow, trajectory lengths much smaller than drift lengths), we must continue to seek high-quality field data to verify this assumption (Haehnel and Lever, in press).

CONCLUSIONS

Wind tunnel modeling of snowdrifting can fairly easily meet wind-field similitude requirements. However, it cannot achieve dynamic similitude for practical scale factors. In particular, Froude number is substantially too large. This Froude distortion results in model particle trajectories longer in proportion to structural dimensions than prototype ones, but we may minimize its effects by operating near minimum velocities established by roughness requirements or threshold speeds.

Froude distortion also directs the choice of a time-scaling method towards one based on dimensionless mass transport. Iversen's (1979, 1980, 1991) approaches explicitly include saltation-based transport expressions that therefore must apply to both model and prototype. Alternatively, Anno's (1984) method allows independent selection of the best approach to determine model and prototype transport. Because field measurements and process-based modeling indicate that diffusion predominates over saltation for seasonal snow transport, this advantage of Anno's method appears decisive. Nevertheless, to validate either method we must compare model predictions of drift development with corresponding field data. The capture-efficiency-based field data by Tabler and Jairell (1993) for Wyoming snow fences are the best available for this purpose.

Model results for a Wyoming snow fence obtained in the CRREL snowdrifting wind tunnel show quite good agreement with capture-efficiency-based field data. The model appears to underpredict slightly the rate of drift development, but we require more data to verify this given the scatter in the results. Drift–development field data by Tabler (1989) are reasonably consistent with these results if we accept that mass transport based on wind speed probably over estimates actual transport during the periods just prior to exhaustion of the snow supply.

Using our model data, we applied several time-scaling methods to predict the time-velocity curves to develop a nearly saturated drift on a Wyoming snow fence. Anno's approach yielded very good agreement with the curve derived from Tabler and Jairell's field data. Conversely, saltation-based time scales can lead to quite large discrepancies with these field results. These large discrepancies are due to differences in the functional forms that best describe model and prototype mass transport, and they confirm the advantage of Anno's method.

ACKNOWLEDGMENTS

The authors wish to thank Jeff Wilkinson for his help developing and operating our snowdrifting wind tunnel. We also would like to thank Dr. R. D. Tabler for providing us access to the snow fence drift-development data described herein. The authors gratefully acknowledge the support provided by the U.S. Army research program, *Design, Construction and Operations Technology for Cold Regions*, work unit AT42-CO-M08.

NOMENCLATURE

A	snowdrift cross-sectional area
A_e	equilibrium snowdrift cross-sectional area
C_d	particle drag coefficient
D	particle diameter
g	gravitational acceleration
H	structure height
I	turbulence intensity
L	characteristic length
L_{turb}	turbulence length scale
m_{drift}	mass of snowdrift
q	snow mass flux (kg/s/m-width)
Q	snow mass transport (kg/m-width)
t	time
U	free-stream flow velocity
U_{10}	wind speed at 10-m height
u_*	friction velocity
u_{*t}	saltation threshold friction velocity
w	particle fall velocity
z_0'	snowdrifting aerodynamic roughness
η	capture efficiency
η_o	initial capture efficiency
ν	kinemetic viscosity
ρ	air density
ρ_b	snowdrift bulk density
ρ_p	particle density

subscripts

m	model values
p	prototype (field) values

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