12.11 CLIMATIC PROBABILITIES OF SNOW DRIFT LOADING ON GABLE ROOFS

Arthur T. DeGaetano*
Northeast Regional Climate Center, Cornell University, Ithaca, New York

Michael J. O'Rourke
Rensselaer Polytechnic Institute, Troy, New York

1. INTRODUCTION

Information from the insurance industry indicates that about three-quarters of all structural losses due to snow result from drifting on multi-level roofs. On such roofs, snow tends to form a drift at the change in roof elevation. This can occur at a roof step (Fig. 1a) or in response to the change in slope of a gable roof (Figure 1b). OÕRourke et al. (1986) describe an extreme case that occurred in the Boston area, where the maximum load due to the drift (1369 kg m^{-2}) was over 18 times greater than the ground load (73 kg m^{-2}). In terms of more conventional climatological units, the load reflects the weight of the water equivalent of snow on a unit area of roof.

There are several different methods to determine the design drift loads on multi-level roofs. In all cases, the drift load is related to snow water equivalent data measured at ground level. The methods also limit the height of the drift to the difference in elevation between the two roof levels.

Currently, in the American Society of Civil Engineers (ASCE 1999) approach, the balanced load (P_d) that exists below the drift on a flat roof is a function of the 50-year mean recurrence interval ground load (P_g), the exposure factor (C_e), a thermal factor (C_f) and an importance factor (I).

$$P_d = 0.7 C_e C_t I P_g \qquad (1)$$

The exposure factor ranges from 0.7 (windy site with roof exposed on all sides) to 1.3 for a calm, sheltered site. The roof thermal environment is described by C_t , which varies from 1.0 to 1.2. The importance factor ranges from 0.8 to 1.2, with the lower factor used for agricultural structures and temporary buildings and the higher number for more essential facilities like hospitals and fire stations. For sloped roofs an additional factor C_s is required.

* *Corresponding author address*: Dr. Arthur T. DeGaetano, Northeast Regional Climate Center, Cornell University, 1115 Bradfield Hall, Ithaca, NY 14853; e-mail: atd2@cornell.edu

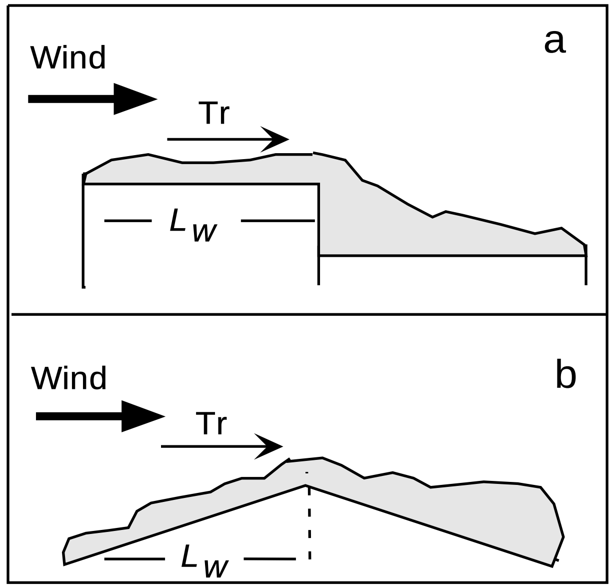

Figure 1. Schematic diagram of drift formation on a stepped (a) and gable (b) roof .

In this paper, a different approach to characterizing the potential and amount of snow drift loading is proposed. It is based on the climatological distribution of a drift metric, a value that incorporates information on both the availability of driftable snow and the occurrence of wind speeds (and directions) capable of producing a drift.

2. THE SNOW DRIFT METRIC

Unfortunately the climatological record does not provide information on the occurrence of drifting snow. Rather the term blowing snow is used to describe cases in which the wind lifts snow to a sufficient height (about 2 m) that it hinders horizontal visibility. Given this requirement, it can be assumed that reports of blowing snow underestimate the occurrence of drifting snow events. Nonetheless, the climatology of blowing snow events along with physical reasoning were used to define a set of conditions under which the occurrence of drifting snow was unlikely. Snow was assumed to be unable to drift:

1) after the occurrence rain, sleet or freezing rain;

2) following the occurrence of a temperature greater than 0¡C;
3) during any hour in which the wind speed was less than 19.3 m/s (12 kt); and
4) when 3 or more days had elapsed since the last occurrence of snowfall.

Furthermore the drifting process depletes the supply of snow from the windward roof section. This reduction in available snow was tracked and drifting terminated when the roof was cleared of snow. These rules generally match those given by Li and Pomeroy (1997).

The process of snow drift formation depends on two factors, the transport rate and trapping efficiency. Tabler (1994) describes the transport rate for fully developed flow as

$$Tr = \frac{u_{10}^{3.8}}{8445} \qquad (2)$$

where u_{10} is the wind speed (ms^{-1}) at a height of 10 m. Based on this equation the transport rate has units of kg $m^{-1}sec^{-1}$. In TablerÕs equation, fully developed flow describes transport that is unaffected by boundary conditions or other discontinuities. According to Takeuchi (1980), fetches of 150-300 m are required for transport rates to reach equilibrium. As such distances are not representative of wind fetches across roofs, an adjustment based on the square root of roof fetch (aligned with the wind) was used to account for nonequilibrium transport rates. It was assumed that a 225 m fetch produced fully developed flow. Thus, the transport rate associated with smaller fetches is given by:

$$Tr' = Tr\left(\frac{L_w}{225}\right)^{0.5} \qquad (3)$$

where Lw is the length (along the axis of the wind) of the windward roof (Fig. 1).

While the transport rate gives the amount of snow that is removed from the windward roof, all of this snow is not deposited on the leeward side of the roof discontinuity. Rather, some of this snow may be carried away from the roof and not contribute to the drift. The percentage of transported snow that is deposited in the drift is given by the trapping efficiency. Water flume simulations on scale models representing different roof geometries place the trapping efficiency for roof level snow transport at roughly 0.5. Therefore only half of the snow that is transported from the windward roof contributes to the drift on the lower roof section.

Annual maximum snow drift loads (kg m^{-1}) were calculated for 53 geographically diverse U.S. first order weather stations based on the above equations and hourly weather observations. At most stations drift loads could be computed for the period 1951-1995. Hourly wind speeds were the only required input to Eq (2). However, hourly weather occurrence and temperature variables were also required to determine whether the snow cover was driftable.

Daily observations of snow depth, snow fall and liquid equivalent precipitation were also necessary, as Eq (2) expresses the amount of transported snow in terms of weight (kg). By our definition, driftable snow is less than 3 days old and is unadulterated by precipitation in a form other than snow. Therefore the density of the driftable snow can be reasonably estimated as the ratio of the 3-day liquid equivalent precipitation accumulation to the 3-day snowfall total. This density allows the weight of driftable snow on the source roof to be computed assuming the ground and roof snow depths are equal.

Transport of driftable snow was allowed during each hour that the wind exceeded the 19.3 m s^{-1} drifting threshold, but ceased when the total amount of transported snow exceeded the available weight on the source roof. The source roof could also have been depleted of driftable snow via melting or sublimation. To avoid estimating snow removal due to these processes directly, the daily depth of snow on the ground observation was used as a surrogate for the presence of snow on either roof. It was assumed that both the source and drift roofs were free of snow during periods when the snow depth observation was zero. Thus, separate snow drift loads were computed for each period of uninterrupted snow cover during the winter season, and the largest load was retained as the annual maximum. Occasionally, the annual maximum snow drift load occurred during a different time period than highest annual snow water equivalent observation.

Separate annual maximum snow drift load series were computed for 8 equal wind direction bins bracketing the major compass points. This allowed an assessment of the effects of roof orientation on drift loading. For instance, a stepped roof, such as that illustrated in Figure 1a, would only be prone to drifting when the wind was aligned along the axis of the roof in a direction upwind of the step. Typically, in such cases the fetch along the upper roof that supplies the snow for drifting is much larger than the length of the lower roof. In the case of the gable roof (Fig. 1b), drifting can occur on either side of the ridgeline and thus two separate annual maximum series need to be considered, each representing the larger of the drifts produced by two wind directions 180¡ out of phase. For instance, a gable roof with its ridgeline oriented east-west, would be subject to drifting under northerly or southerly winds. The maximum drift for a given year therefore must represent the larger of the drifts produced by these opposing wind directions.

Each annual maximum drift series was fit to a Gumbel distribution which allowed the 50-year mean recurrence interval drift load (kg m^{-1}) to be computed. This value was then expressed as a ratio of the product of the 50-year ground snow load (kg m^{-2}) given in ASCE (1999) and the roof fetch (m). Computed in this way, the ratio provides an upper limit on the drift loading associated with a given 50-year ground snow load, since the 50-year drift and 50-year ground loads do not necessarily occur simultaneously. Furthermore the drift load (total surcharge load per unit width perpendicular to the step) can not exceed the product of the ground load and snow source fetch length as this later figure defines the total amount of snow that is available for drifting.

3. EXTREME DRIFT LOAD CLIMATOLOGY

Figure 2 shows the 50-year drift load ratios for the 53 stations analyzed. Each value represents the drift load ratio associated with the wind direction that produced the largest drift. Across the country the range of 50-year drift load ratios is fairly narrow, with values ranging from 0.03 at Pendleton, Oregon and Little Rock, Arkansas to 0.24 at Rapid City, South Dakota. Pockets of high drift load ratios exist to the east of Lake Erie and across a broad area of the Great Plains region. The lowest drift ratios are generally in the Southeast and Northwest.

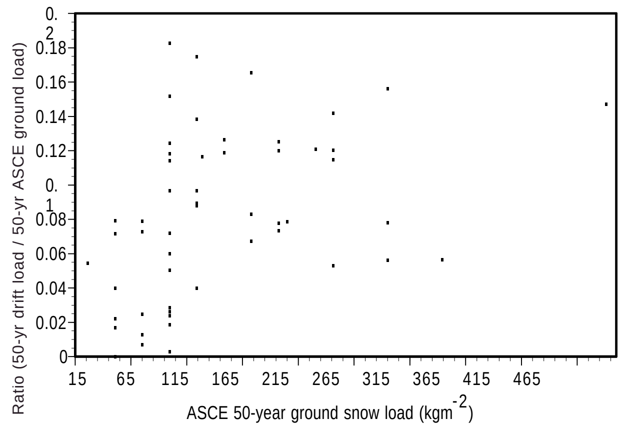

Figure 3. Scatterplot of 50-year drift ratios and corresponding 50-year recurrence interval ground snow loads at 53 U.S. stations.

Although this pattern of maxima and minima suggests a relationship between the drift load ratio and ground snow load, Figure 3 suggests that this is not the case. Rather, the largest drift load ratios for a single wind direction (in this case northwest) typically occur in association with mod-

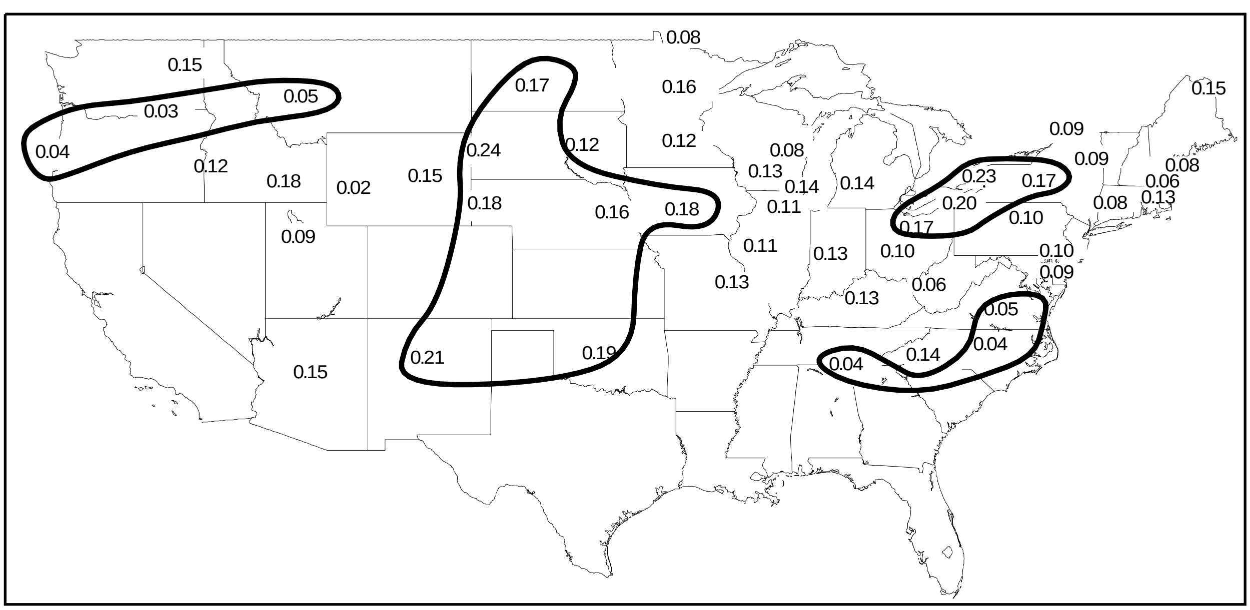

Figure 2. Maximum 50-yr drift load ratios. Regions with the highest and lowest drift ratios are outlined.

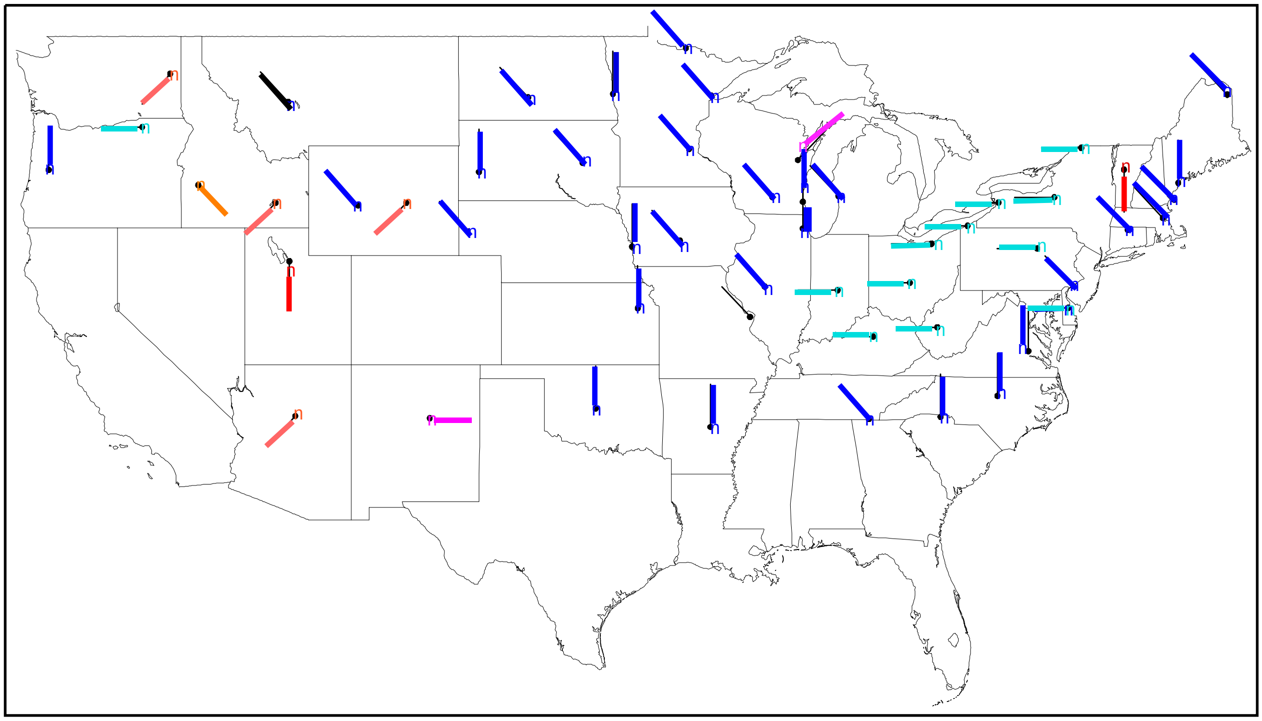

Figure 4. Map of wind direction producing the highest 50-year recurrence interval drift load.

erate ground snow loads. There is also considerable variability in the drift load ratios associated with 100-150 kg m^{-2} ground snow loads.

An analysis of the wind direction that produces the maximum drift load ratio, shows an interesting geographic pattern (Fig. 4). Maximum drifts are primarily associated with northwesterly and northerly winds, particularly in the Upper Mississippi Valley and along the Middle-Atlantic and New England Coast. Over a broad area of the Ohio Valley into interior New York and Pennsylvania the largest drifts are associated with westerly winds. There is not a preferred wind direction associated with maximum drifting at stations in the Intermountain West.

4. SUMMARY

The development of a drift load metric shows that an additional snow load (total surcharge load per unit width perpendicular to the step) equal to 10-20% of the ground snow load × snow source fetch length must be considered in the design of roofs prone to drift formation. Although there is relatively little spatial variation in this drift surcharge, the amount of drifting is influenced by wind direction. For instance, under easterly winds, the drift load ratio averages only 0.03. This finding suggests that roof orientation (with respect to the predominate drift producing winds) along with structural design that includes the appropriate drift surcharge provide complementary methods for mitigating snow-induced roof failures.

5. REFERENCES

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