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GIS-Based Three-Dimensional Snowdrift Computer Model

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ABSTRACT

The snowdrift transport model SnowTran3D has been modified to work integrally with Geographic Information System (GIS) software to allow use of the model with standard GIS tools and layers, thus enabling direct display and analysis of drifts on roads and other features of interest. This is being developed as a planning tool for state and local DOTs (departments of transportation) and the U.S. Army for deployment of road maintenance equipment. It also is being developed as a forecasting tool for FHWA (Federal Highway Administration), in conjunction with real-time meteorological forecasting, to allow posting of 48-hour forecasts of drift formation on roads. Preliminary model validation data show that SnowTran3D is capable of correctly predicting drift location and volume for drifts deposited in the lee of a road or berm. Improvements in the embedded wind model are needed to accurately predict separation zones and their attendant drift formations.

Key words: Snowdrift forecasting, snow on roads, snowdrift control

INTRODUCTION

Though snowfall in its own right degrades mobility on roads and traveled ways, drifting snow further exacerbates the problem. Drifting often continues well beyond the conclusion of the storm and poses a continued maintenance issue for days after the initial snowfall has been cleared. Furthermore, when roads are built or modified or roadside vegetation changes because of fires, logging, or plantings, the effects of drifting are seldom considered in advance, though these effects on drifting can be profound. Military operations can be negatively affected by drifting snow when it accumulates on existing or planned routes, yet these missions are often carried out in areas where little is known about drifting history. Understanding the spatial and temporal variation in snow cover due to drifting enables effective route planning and design for new roads and allocation of maintenance equipment for existing roadways.

In many locales, long-time residents and seasoned highway crews know the key areas where drifting chronically degrades road conditions and requires continual maintenance. Though this information is invaluable, it is not useful for new construction, and may not be available when deploying armed forces into new theaters of operation. SnowTran3D is a computer model developed by Liston and Sturm (1998) to compute the transport and deposition of snow on a gridded topographic domain. This model has been modified to work within a Geographic Information System (GIS) framework so that its output can be used in standard GIS software as a tool for route planning and maintenance decision support for State DOTs and the U.S. Army. This report outlines the model approach and presents preliminary model results and validation for use

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on roadways and other man-made features. Recommendations for future model improvements are given.

TRANSPORT MODEL

Once snow falls it is often redistributed by wind; snow is scoured off highlands and windward slopes and deposited in low-velocity zones and wake regions. The dominant transport mechanisms are saltation and turbulent suspension. Their relative contribution to the overall transport is a function of the wind speed (Pomeroy and Male 1992). The wind applies a shear to the snow surface, and once the shear exceeds a threshold value the snow begins to move. Initially particles roll over each other or creep across the snow surface. With increased surface shear, the particles hop off the surface and are carried by the wind for a short distance before splashing back into the snow surface, knocking other particles loose, perpetuating the process. This latter mechanism, known as saltation, is confined to a few centimeters above the snow surface (Kobayashi 1972). As the wind speed increases, snow particles are carried aloft from the saltation layer via turbulent diffusion. These particles are lifted several meters into the air, and can travel many meters with the wind before they are lost due to sublimation or redeposited on the snow surface.

The change in snow depth, ζ, with respect to time depends on the water-equivalent snow precipitation, P, the sublimation flux, q_v, and changes in the horizontal saltation and suspension mass transport rates, Q_s and Q_t, respectively (Liston and Sturm 1998).

$$\frac{d\zeta}{dt}=\frac{1}{\rho_s}\left(\rho_w P-\frac{dQ_s}{dx^*}-\frac{dOQ_t}{dx^*}+q_v\right) \tag{1}$$

where t is time and x^* is the coordinate direction defined by the wind vector. Equation 1 is solved for each grid cell in the domain and is coupled to the adjacent cells through the spatial derivatives. Liston and Sturm (1998) give detailed discussion of the solution of equation 1.

Because of variation in topography, the wind direction and magnitude typically vary over a domain. Since measured wind information is typically reported on a spatial resolution of hundreds of kilometers, there needs to be a way to interpolate the available wind data to each grid cell in the domain. Though this can be done using regional atmospheric models, the computational overhead associated with the solution of the relevant momentum and continuity equations would yield model runs that are slower than real time. To simplify the interpolation of the observed wind speed to the model grid, it is modified locally by multiplying it by a weighting factor, W:

$$W=1+\gamma_s\Omega_s+\gamma_c\Omega_c \tag{2}$$

where Ω_s and Ω_c are the topographic slope and curvature, respectively, and γ_s and γ_c are constants that weight the relative influence of slope and curvature on modifying the wind speed (Liston and Sturm 1998). The convention used is that lee and concave slopes produce negative values of Ω_s and Ω_c, thereby reducing the wind speed, and windward and convex slopes increase the wind speed. The wind-shear velocity, u_*, at the surface is then computed from the local wind velocity, u_r, at elevation, z_r, assuming a logarithmic variation of wind speed with height:

$$\frac{u_r}{u_*}=\frac{1}{k}\ln\left(\frac{z_r}{z_o}\right) \tag{3}$$

where z_o is the aerodynamic roughness height of the surface, and k is von Kármán's constant.

Vegetation plays an important role in this transport process. It not only acts as a roughness element (thereby affecting surface shear) but can provide sheltering from the wind. To account for this latter effect Liston and Sturm (1998) define a vegetation snow-holding capacity, C_v, which is the depth of snow the vegetation holds or can shelter from the wind. Once the accumulated snow depth exceeds the snow-holding capacity for a particular vegetation type, any additional snow is available to be transported by the wind. Since the vegetation roughness height decreases as the snow depth increases, the aerodynamic roughness height is approximated by

$$z_o = z_{o,\mathrm{veg}} \frac{\zeta}{C_v}\left[1+\left(\frac{z_{o,\mathrm{snow}}}{z_{o,\mathrm{veg}}}-1\right)\right] \qquad \text{for } \zeta \le C_v \tag{4}$$

$$z_o = z_{o,\mathrm{snow}} \qquad \text{for } \zeta > C_v$$

where *veg* and *snow* refer to initial values for the vegetation and snow cover, respectively. When the snow depth exceeds the holding capacity of the vegetation, and the wind speed is greater than the threshold velocity for the snow, saltation begins. The saltation layer's effect on wind shear is accounted for considering

$$z_o = 0.12\frac{u_*^2}{2g} \tag{5}$$

where g is the gravitational constant (Liston and Sturm 1998).

Standard raster GIS data layers for topography and vegetation are used as model input (Fig. 1). Also, information about the vegetation aerodynamic roughness height and snow capture depth needs to be provided. The required meteorological data is wind speed, wind direction, average air temperature, humidity, and precipitation (snow water equivalent or SWE). This may be climatological or forecasted data specified at hourly to daily time intervals.

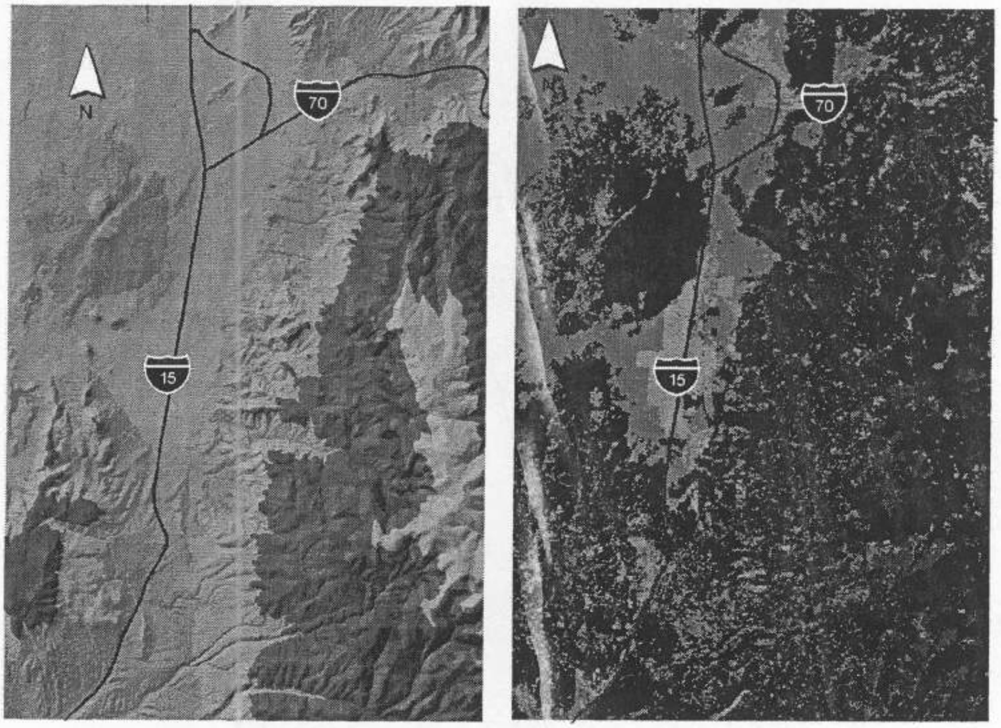

Figure 1. Topographic (left) and vegetation (right) data layers for the region surrounding Cove Fort, Utah (10-m grid resolution).

MODEL VALIDATION

SnowTran3D was originally developed to model the redistribution of snow due to drifting on the Arctic Tundra (Liston and Sturm 1998). The principle application there is estimation of seasonal snowpack water content for water resource management. In this work we have adapted the model to predict snowdrift accumulation on roads. Furthermore, the model has been updated to facilitate interfacing it with ESRI's ArcINFO, ArcView GIS software. This allowed the model input to be prepared and the model output to be analyzed using off-the-shelf (OTS) GIS data layers and standard GIS tools already in widespread use by the military and DOTs. Figure 1 shows topography and vegetation data obtained from the USGS for Cove Fort, Utah. The interstate data layer was furnished by the Utah State DOT. Though OTS information such as this is preferred, it is not always available.

Figure 2 shows synthesized topographic data of a firing range located at Fort Drum, New York, where we are validating the SnowTran3D model for use on a road network. In this case the available topographic data predated the addition of the road network. Using the original topography and the electronic road design drawings, we generated an "as-built" topography of the domain in the GIS environment. The elevated roadbeds are readily identified in contrast to the surrounding topography in Figure 2.

Figure 2. Synthesized topography of a firing range at Fort Drum Military Reservation, New York (2-m grid resolution). Dots indicate the snow depth survey locations taken on 4 January 2001.

The Fort Drum site was chosen for validating the model because high-resolution digital elevation data were readily available and the site contained a road network that was not used during winter months, facilitating measurement of snow accumulation without having to deal with traffic. Meteorological equipment was installed at the site to measure wind speed and direction, snow depth, air temperature, and humidity. A networked video camera also was set up at the site to monitor the snow conditions throughout the winter months.

After a substantial snowfall (at least 20–30 cm) and a subsequent drifting event, measurements of snow depth were taken throughout the study area. During the two winters spanning 1999 and 2001, we made three field measurements documenting the drift accumulation at the site. For two of these documented events (2 February 2000 and 31 December 2000) the antecedent condition was bare ground. In this work we will present some of the data for the December 2000 event. In this event the snow ended on 25 December but snow continued to drift until the 31st. The measurements were made on 4 January 2001. The black circles in Figure 2 indicate where snow depth measurements were taken on 4 January. The location of the snow depth measurements was surveyed using a Wild T200 EDM survey station (1-second theodolite). The snow depths were made using a MagnaProbe snow depth probe (Holmgren and Sturm 1998). The X pattern was chosen to capture the spatial variation in snow depth throughout the domain. The closely spaced measurements in the upper right of Figure 2 were cross sections taken through predominantly 2-D topographic features.

Figure 3 shows the results of a model run simulating the documented event ending on 31 December 2000. In this figure the black indicates places where snow was scoured, and white indicates deposition. The remainder of the domain has a snow depth unchanged from the average precipitation depth (28–32 cm). The wind direction during this event was predominantly out of the WSW.

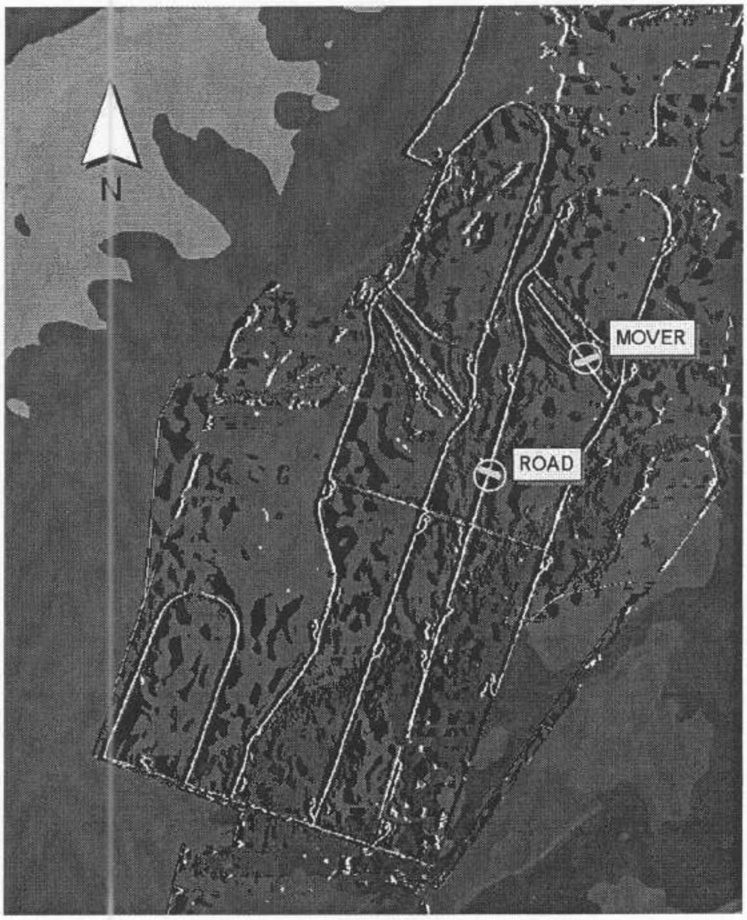

Figure 3. Simulated drifting on the firing range at Fort Drum Military Reservation, New York. Average accumulated snow depth was 30 cm. White areas indicate deposition of the snow due to drifting, while black areas indicate wind-driven scour.

The drifting predicted by the model clearly outlines the roadbeds in the domain (Fig. 3) with scour evident on the upwind side of the road and deposition on the lee. Figures 4 and 5 give a comparison of the measured and predicted snow depth over two of the 2-D cross sections taken in the field. The location of both of these features is indicated in Figure 3. The first is an elevated roadbed (road, Fig. 3) and the second is a berm for a moving target (mover, Fig. 3). In both Figures 4 and 5 we compare the actual topography and the representation of the topography given by the digital elevation model (DEM).

In Figure 4 the measured and DEM representation of the topography for the roadbed are very close. Differences at the road surface indicate that the surveyed points should have been closer together to properly capture the topography in that region. In general the predicted drift location agrees well with the field, though the shape of the drift differs. In the field and model the windward slope is scoured to the vegetation capture depth. On the leeward slope the field drift gradually tapers away from the crest of the road at first, and then there is a steep slip face and the snow surface falls away quickly. At the base of the slip face the snow depth is roughly equal to the precipitation depth. The predicted lee drift puts essentially all of the snow in the first grid cell beyond the edge of the road, even leaving the drift somewhat above the adjacent road topography. This "overshooting" of the drift depth is a result of the simplification in the surface wind model. Equation 2 adjusts the wind based on the slope and curvature of the local topography. Since the wind field is computed using the snow surface topography, and the leeward intersection of the road and the drift is concave, equation 2 treats this as an area of reduced velocity, and the snow is not transported out of the grid cell as expected. A large overshoot in drift depth would increase the windward slope significantly and tip the scale in the other direction so that the grid cell would be given a higher velocity, and the snow would be scoured off that cell and deposited in the adjacent cell.

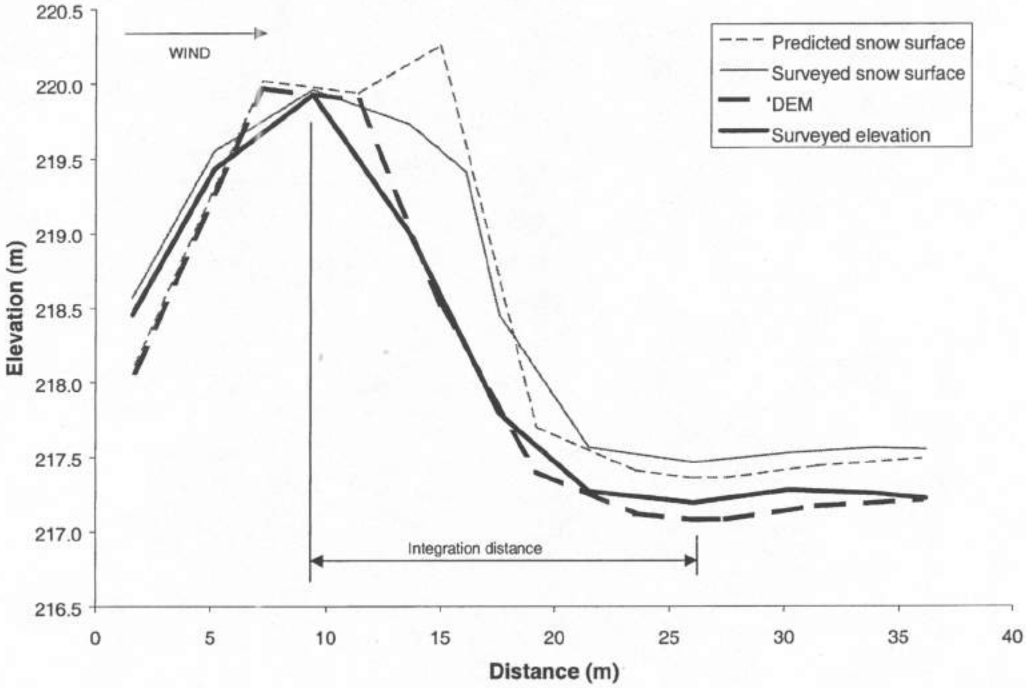

Figure 4. Comparison of field measurements and model results for an elevated road cross section.

This is not the only limitation of the current wind model. Since equation 2 merely adjusts the wind speed based on a contraction or divergence of the topography, separation zones are not identified at all in the current model. Though equation 2 will do a reasonable job of depositing snow behind a leeward-facing stepped feature, such as the lee of the elevated road bed in Figure 4, it cannot predict a windward separation zone on a bluff face, for example, and the associated triangular drift that is deposited there. This is a deficiency that will be addressed in future work. Regardless, at present the model does a fair job predicting drift location with a very simple wind model.

Furthermore, a comparison of the drift area between the field and model reveals that the model does a good job of getting the right amount of snow deposited on the lee of the road. We computed the drift area between x = 9.4 m and x = 26 m (where x is the distance plotted in Figure 4). This integration distance is shown in Figure 4. Table 1 compares the drift area for the field and model. Despite the slight mismatch in the drift geometry we are encouraged by how well the model predicted the drift area.

Table 1. Comparison of drift area between the measured field data and the model results.

	Drift area (m^2)	
	Road	Mover
Field	8.5	5.7
Model	9.5	4.6

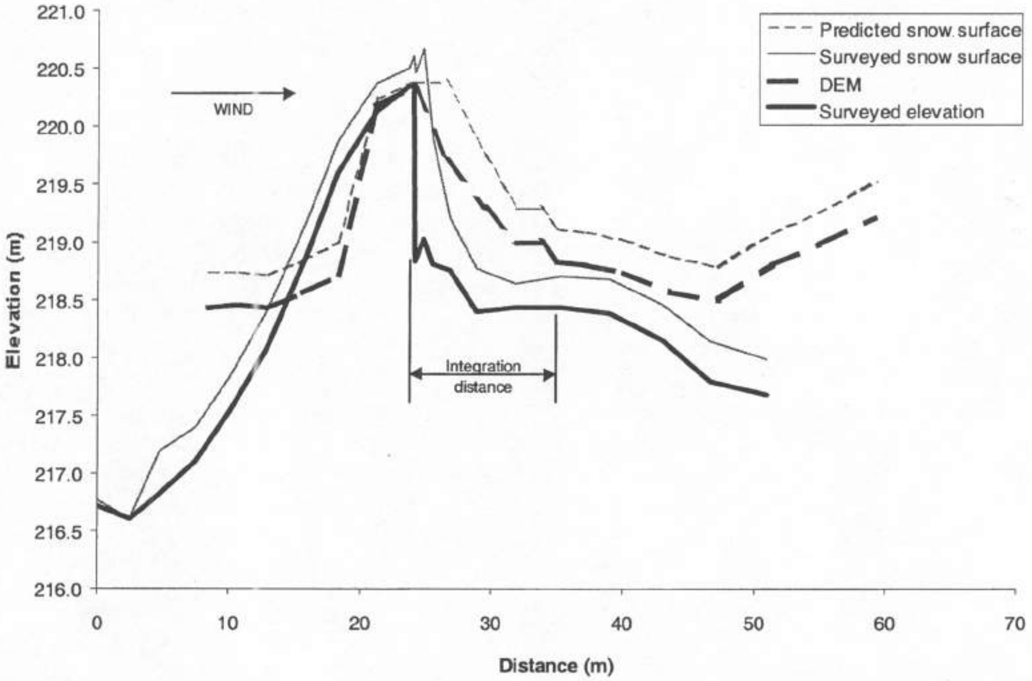

Figure 5. Comparison of field measurements and model results for a berm in front of a moving artillery target.

In Figure 5, we compare the results for the mover. What is readily apparent is that the DEM does not accurately reproduce the actual topography we measured in the field. Though the overall shape is preserved, the DEM shows the height of the berm as being too small, and the leeward side of the berm is depicted as sloped, when in actuality it is a vertical face. This points out an important fact when working with DEM data: the ability to accurately predict the drift location and extent depends on the accuracy of the digital topography available. Despite the effort to integrate the design information into the existing DEM to produce an "as-built" DEM, there are clearly areas where our synthesized DEM doesn't match the actual topography. For the road cross section in Figure 4, our effort produced a very good match; not so with this mover. Nevertheless, the drift location and depth seem reasonable for the actual geometry used by the model. Furthermore, the drift is very similar to that measured in the field. Since the modeled mover is about two-thirds the height of the actual mover we would expect the model to underpredict the leeward drift area. A comparison of the drift area given in Table 1 shows this is indeed the case; regardless, the agreement is much better than expected. We also note that the actual snow capture depth on the upwind slope of the mover appears to be about four times that used in the model (Fig. 5). Again, this illustrates the need for accurate input data to the model.

In the foregoing we have discussed the need for accurate DEM and vegetation data to generate accurate model predictions. Another important consideration is the spacial resolution of the grid and its impact on model accuracy. The model is capable of handling a wide range of grid increments (e.g., 10 cm to 5 km), and there is nothing in the physics of the model that is limited by spacial resolution per se. However, the grid resolution has to be carefully chosen to match the drift features of interest. For example, if the application is to predict snow distribution for snowmelt runoff predictions in a river basin, a 100-m or 1-km grid resolution may be appropriate for capturing the general location and extent of the large-scale drifts of interest. However, such a coarse grid would not be appropriate for predicting drift formation on a road network where the topography for the features of interest (e.g., a road cut) varies rapidly over short distances. In this latter case we have found that a grid resolution on the order of 10–20 m or less is needed to sufficiently resolve the road network topography, thereby giving a reasonable prediction of drift location and extent.

FIELD APPLICATIONS

In cooperation with the Federal Highway Administration (FHWA), we are adapting this model for forecasting snowdrift accumulation on roads. For this we use 48-hour forecast data generated by the DICAST* forecast model for meteorology input to the snow transport model. This gives forecast points every three hours out to 48 hours. The Cove Fort region shown in Figure 1 is one of the sites at which this model is being demonstrated. For this simulation, the forecast is for a regional snowstorm that starts 18 hours into the forecast and ends at hour 30. The wind persists to hour 33. Figure 6 shows the forecasted drift affected snow depth on the road for hours 20 and 24. The black double lines indicate the major roads through this region. The snow depth is coded in three bands to indicate a level of service for the road. White indicates snow depths greater than 15 cm, black is for snow depth between 7 and 15 cm, and clear is for snow depths less than 7 cm.

From Figure 6a we see that at hour 20 (two hours after the snow starts accumulating) the forecasted snow depth throughout the domain is less than 7 cm, yet the black patches indicate that drifting along the road has increased the snow depth locally to greater than 7 cm. By hour 24 the prevailing snow depth throughout the domain is over 15 cm (as indicated by the domain being almost completely white, Figure 6b). However, on some road sections drifting has actually reduced the forecasted snow depth by scouring the snow off the road, which is evident by the black patches on the roadway in Figure 6b.

Road maintenance personnel can use this information to plan when roads need to be plowed and where road conditions are going to be the worst. Figure 6a shows that because of drifting, the snow is deeper on sections of the road than the forecasted precipitation would suggest, warranting increased maintenance in those areas. This model will be used, in conjunction with algorithms to predict road surface friction and applying standard rules of practice for road maintenance, to provide a forecast tool to support winter road maintenance decisions.

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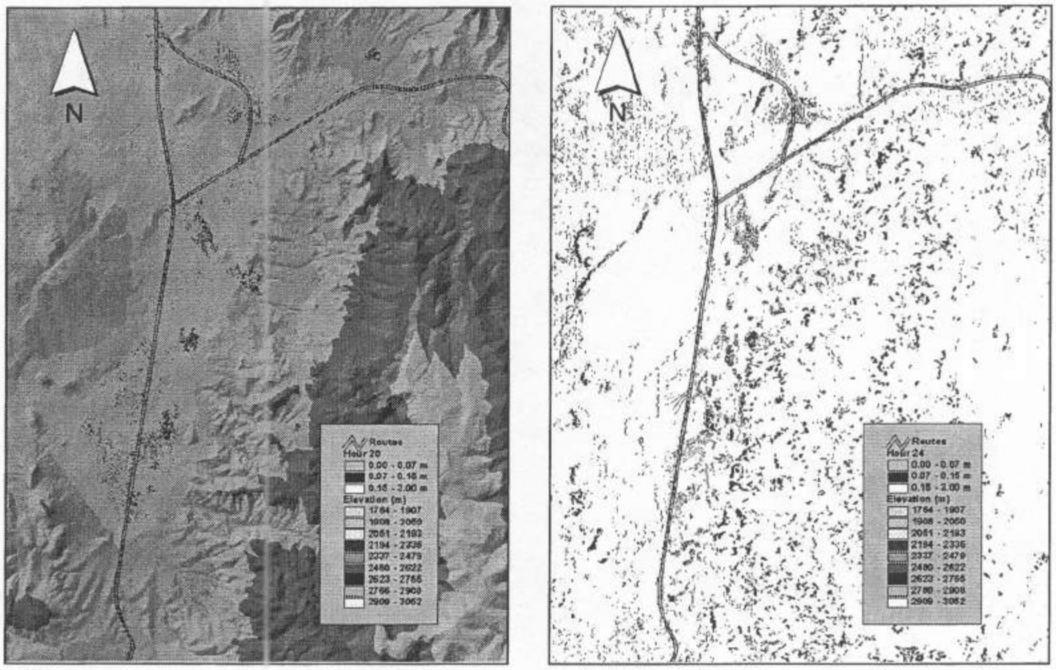
*Personal communication, Bill Myers, National Center of Atmospheric Research, Boulder, Colorado, January 2001.



(a) (b)

Figure 6. Predicted drift-affected snow depth, Cove Fort, Utah, for forecasted hours 20 (a) and 24 (b).

CONCLUSIONS AND RECOMMENDATIONS

Comparison of field measurements with model results of snowdrifts on a road network at Fort Drum, New York, suggests that SnowTran3D shows promise as a tool for predicting drifting on roads and other similar man-made features. Preliminary validation results suggest it is capable of capturing the approximate drift location and volume, but may not accurately predict drift shape. This latter deficiency can be important when there is some question as to whether or not the spatial extent of the drift will overlap a road. In this case a difference of 10 m in location of the drift can mean the difference between having to plow or not. Nevertheless, the current model shows promise in its capability to predict drift severity along road sections and identify areas where increased maintenance may be warranted.

Future revisions to the model will address the deficiencies in the current wind model. In particular, focus will be placed on developing an efficient model for predicting separation zones and refining velocity variation due to topography. As part of this work more detailed model validation will be carried out over the entire modeled domain to confirm that the model can adequately predict drift formation over a varied topography. Future model enhancements include the capability to predict drift formation around snow fences to aid in correct placement of fences to protect road sections from drifting.

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REFERENCES

Holmgren, J.A., and M. Sturm (1998) "Snow temperature and depth probe." U.S. Patent No. 5,815,064.

Kobayashi, D. (1972) "Studies of snow transport in low-level drifting snow." *Contributions from the Institute of Low Temperature Science*, Series A, No. 24, pp. 1–58.

Liston, G.E, and M. Sturm (1998) "A snow transport model for complex terrain." *Journal of Glaciology*, **44**(148): 489–516.

Pomeroy, J.W., and D.H. Male (1992) "Steady-state suspension of snow." *Journal of Hydrology*, **136**: 275–301.