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Blowing Snow Forecast Using Numerical Atmospheric Model Output Data

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Abstract—The object under study is the blowing snow, i.e., the transport of snow lifted from the snow surface. The method is described for predicting the blowing snow initiation using the output data of the WRF-ARW numerical atmospheric model. The skill scores are presented for the forecasts for January 2013 calculated from data of 10 stations of the Canadian weather observation network.

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INTRODUCTION

The problem of investigation and physical modeling of snow drifting is especially urgent for northern regions where the cold period is long. If wind speed is high, the blizzard is a severe weather event which can cause great damage. The average blizzard duration in the European part of Russia is about 30 days per year. Intense blizzards can form snowdrifts which block transport routes. Blizzards sweep snow away from fields and lead to their dehydration. On the contrary, excessive snowdrifts slow down the snow melting. The blizzard-induced redistribution of snow cover in mountain and piedmont regions leads to the accumulation of the great additional volume of snow in the near-ridge zones of mountain ranges. In many cases, this results in the activation of snow avalanches and mudflows. Blizzards make essential contribution to the redistribution of pollutants in the atmosphere and on the underlying surface and, perhaps, to the radionuclide transport.

There is no modern numerical method for the snow drifting prediction in Russian practice. The latest computational method for the blizzard forecast was developed in 1989 [7]. In recent 25 years, the characteristics of forecasting models and computers have changed considerably.

The numerical weather prediction methods used in Russia do not consider the blowing snow as a separate forecasted object. The present paper proposes a method for the snow drifting prediction based on the mesoscale model outputs.

The blizzard is a complex natural phenomenon. The wind flow including snow behaves in a way differing from that for the pure airflow, because snowflakes affect wind speed and reduce turbulence in the lower atmospheric layers. When wind reaches a certain speed in the surface layer, ground snow starts moving that leads to the blowing snow formation. Snowflakes hit the snow surface, destruct it, and make new particle masses move.

When predicting blizzards, great attention is traditionally paid to regular blizzards, i.e., to the blizzards accompanied by snowfall. The forecast of regular blizzards particularly depends on the forecast of solid precipitation. The object of the present study is the blowing snow, i.e., the snow drifting from the surface.

The objective of the present paper is to forecast the blowing snow occurrence (with the subsequent verification of the forecast) using the output data of the numerical atmospheric model. To predict the snow drifting, it is extremely important to determine a threshold wind speed whose exceeding initiates the blowing snow. The scientific literature suggests several approaches to its determination [5, 11, 13]. All existing methods for the prediction of critical wind speed come to the determination of the value of velocity (friction velocity or wind speed at a certain height) at the specified snow surface conditions.

A CRITERION FOR THE BLOWING SNOW INITIATION

To diagnose and to forecast the blizzard initiation, it is important to determine favorable meteorological conditions for the beginning of the snowflake lift. The snow cover presence is required for the blowing snow development. In our case, the criterion is the presence of snow cover with the depth of >0.1 m. If snow depth is smaller, the snow cover is mosaic (with high probability) and the amount of snow may be insufficient to saturate the lower atmospheric layer with suspended snow particles. The value of 2-m temperature equal to –1 C was taken as the critical one. The blowing snow at the temperature above –1 C is a rather rare event.

The authors of [1] compared three formulae for computing critical wind speed whose exceeding initiates the blowing snow. As a result, the most successful method for this characteristic was identified. The selected method presupposes that air temperature is a predictor of snow cover parameters. The observations conducted by Canadian specialists [11, 12] revealed that the wind speed needed to start the blowing snow depends on air temperature.

The lower air temperature is, the lower wind speed is sufficient to lift snow particles to the air. Indeed, on average, the lower temperature is, the smaller snow density and snow water equivalent are. Solid precipitation at the temperature below –20 C almost guarantees dry fluffy snow. However, at lower temperature the metamorphism processes leading to snow firnification are activated within the snow cover. According to [11], the active metamorphism starts at temperature below –27.27 C. Hence, at the further temperature drop, wind speed required for the blizzard initiation increases. The wind speed of about 7 m/s is taken as the minimal speed for the snow drifting initiation. At this wind speed, the blizzard will start only in the most favorable conditions, at the minimum snow density. It is assumed that such conditions correspond to the temperature of –27.27 C.

The derived dependences of a threshold wind speed on air temperature may be numerically expressed through the following relationship [11]:

$$U_{\mathrm{th}} = a + b(T + c)^2 \tag{1}$$

where a, b, and c are the constants equal to 6.975 m/s, 0.0033 m/s C, and 27.27 C, respectively.

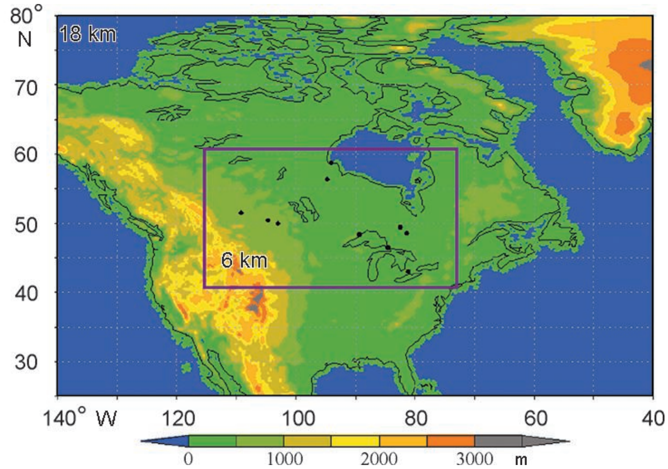
The physical sense of the constants a and c is described above. The constant b is the similarity criterion for the wind speed increase depending on temperature.

WRF-ARW MODEL CONFIGURATION

The present study utilizes WRF-ARW model forecasts as inputs for the blizzard forecast algorithm. This model is one of the best and most widely used in the world. It proved to be good for solving scientific and applied problems and is convenient in use [4].

To solve the formulated problem, observational data on the blowing snow are needed. Unfortunately, the quality of blizzard observations at the Russian weather station network is quite low that hampers their use. In situ measurement data contain great number of gaps and errors. For example, the analysis of data for winter 2012/13 revealed that about 10 cases of blowing snow were registered in the whole European part of Russia that is obviously not true. Therefore, it was decided to use data from the Canadian weather network. The territory of Canada was chosen as an area for testing the proposed method of blowing snow prediction. The data from 10 stations (located in Saskatchewan, Ontario, and Manitoba provinces) for January 2013 were used for verification (see the figure). Hourly observational data were utilized, the weather type was determined for each observation time. The total duration of blowing snow during the mentioned period for all stations is 246 hours.

The series of experiments with the WRF-ARW model using the nested grids with the spacing of 18 and 6 km were conducted to get input data for the implementation of the numerical algorithm for the blowing snow forecast (see the figure). The model was run for 36 hours, the results of simulation for the first 12 hours were not taken into account (calculations were conducted for the initial time of 12:00 for every day of January starting from 12:00 on December 31). Thus, 31 forecasts were obtained for January 2013. The results of the experiments based on the 6-km grid were used for the further research.



Computational domain of the WRF-ARW model. The location of Canadian weather stations is shown with black dots. The color scale describes elevation above the sea level.

The accuracy of the diagnosis and prediction of blowing snow directly depends on the quality of WRF-ARW forecasts. Therefore, it is important to determine the most suitable configuration of the WRF-ARW model taking into account the specific features of forecasting snow cover characteristics and simulating atmospheric conditions for the cold season. According to the results of WRF-ARW model forecast quality improvement [3, 15], the polar version of the model was used. Convection, cloud microphysics, planetary boundary layer processes, and processes on the underlying surface were parameterized according to [8], [14], [9], and [10], respectively. The MODIS database with the resolution of 0.5 was used to describe the underlying surface characteristics for the analyzed territory. The fields of the GFS global model (USA) with the spatial resolution of 0.5 and temporal resolution of 6 hours were used as initial and boundary conditions for WRF-ARW in all experiments.

Table 1 presents average skill scores for the forecasts of 10-m wind speed (*U*, m/s), 2-m air temperature (*T*, C), and 2-m relative air humidity (*H*, %) based on WRF-ARW. The forecasts with the spatial resolution of 6 km were verified for January 1–31, 2013. The mean absolute error MID, error time dispersion DISP, and correlation between the series of observations and forecasts CORR for the lead times of 12 and 36 hours were computed. The value of dispersion was found from the formula

$$\mathrm{DISP} = \frac{(x \quad x_{\mathrm{m}})^2}{n \quad 1} \tag{2}$$

where n is the sample size, $(x - x_{\mathrm{m}})$ is the deviation of each value from the mean. The unit of dispersion corresponds to the squared unit of the variable it is calculated for.

The results of verification for the forecasts of major meteorological parameters are quite satisfactory. The practice of using mesoscale models [1, 2] demonstrated that the obtained forecast errors are among the least ones. Thus, the WRF-ARW forecast quality allows using WRF-ARW outputs (temperature, humidity, and wind) as inputs for the blowing snow prediction.

VERIFICATION OF INITIATION AND DURATION OF BLOWING SNOW

In January 2013, 48 cases of blowing snow of various duration values were observed at 10 Canadian weather stations; their total duration was 246 hours. The following assumption was used to evaluate the quality of blizzard initiation diagnosis. The blizzard occurrence was considered accurately predicted if the time difference t between the blowing snow initiation identified from experimental and observational data was 3 hours. As a result, 42 of 48 blowing snow events were predicted correctly, six events were not predicted, 12 events were falsely predicted.

To assess the quality of blowing snow duration simulation, three gradations were utilized: the simulated blowing snow duration differs from the observed one by not more than 30% (the first gradation), by not

Table 1. The skill scores for the WRF-ARW forecasts of wind speed, air temperature, and relative humidity averaged over 10 weather stations

Parameter	MID	DISP	CORR
Lead time is 12 hours			
U, m/s	1.5	1.3	0.7
T, °C	2.3	3.4	0.8
H, %	10	40	0.6
Lead time is 36 hours			
U, m/s	1.8	1.8	0.7
T, °C	2.1	3.2	0.8
H, %	12	48	0.6

Table 2. The contingency table for the blowing snow forecasts for January 2013 at 10 Canadian weather stations

Forecast	Observation		
	Blowing snow	No blowing snow	Total
Blowing snow	$n_{11} = 174$	$n_{12} = 72$	$n_{10} = 246$
No blowing snow	$n_{21} = 83$	$n_{22} = 7111$	$n_{20} = 7194$
Total	$n_{01} = 257$	$n_{02} = 7183$	$n_{00} = 7440$

more than 60% (the second gradation); the third gradation includes all other cases. The skill scores for the forecasts of blowing snow duration are the following:

t_{pr}, %	30	(31–60)	60
Number of forecasts	28	8	6

The duration of 28 of 42 correctly predicted blizzards differed from the observed duration by not more than 30%. Only for six forecasts the duration of snow drifting considerably differs from that registered at the station. The analysis of model data reveals a slight trend towards the underestimation of blowing snow duration. In 64% of cases, the simulated blizzard duration is shorter than the actual one.

Table 2 presents the contingency table which indicates the degree of efficiency of the method for the blowing snow occurrence forecast. In this case, the forecasts of blizzard initiation were verified every hour. If the blowing snow was predicted and observed during a specific hour, the forecast was considered accurate. In total, 7440 observations were conducted at 10 stations in January 2013.

To verify the blowing snow occurrence forecasts, the following scores were calculated in accordance to the methodological instructions [6]:

—the accuracy of the blowing snow occurrence forecast:

$$\mathrm{AOF} = \frac{n_{11}}{n_{10}} \quad 100, \tag{3}$$

—the hit rate of the blowing snow occurrence forecast:

$$\mathrm{HR} = \frac{n_{11}}{n_{01}} \quad 100, \tag{4}$$

—the Pierce–Obukhov score:

$$\mathrm{POS} = \frac{n_{11}}{n_{01}} \quad \frac{n_{12}}{n_{02}}, \tag{5}$$

— the Bagrov score:

$$\mathrm{BS} = \frac{\mathrm{TA} \quad \mathrm{ARF}}{1 \quad \mathrm{ARF}}, \tag{6}$$

—the accuracy of random forecasts:

$$\mathrm{ARF} = \frac{m_1 \quad m_2}{n_{00}}, \quad m_1 \quad \frac{n_{10}n_{01}}{n_{00}}, \quad m_2 \quad \frac{n_{20}n_{02}}{n_{00}}, \tag{7}$$

—the total accuracy:

$$\mathrm{TA} = \frac{n_{11} \quad n_{22}}{n_{00}} \quad 100. \tag{8}$$

Here, n_{11} is the number of accurate forecasts of the blowing snow; n_{22} is the number of accurate forecasts of the blowing snow absence; n_{01} is the number of cases with the blowing snow; n_{02} is the number of cases without the blowing snow; n_{10} is the number of the blowing snow occurrence forecasts; n_{20} is the number of the blowing snow absence forecasts; n_{12} is the number of inaccurate forecasts of the blowing snow occurrence; n_{00} is the total number of forecasts of occurrence and absence of the blowing snow for the analyzed sample (see Table 2).

The resulting skill scores for the forecasts of the blowing snow occurrence are rather high: the Pierce–Obukhov score is 0.61, the Bagrov score is 0.67. As given in the methodological instructions [6], the forecasts where BS > 0.33 are reliable. To assess the forecast efficiency, it is recommended [6] to use the total score of accuracy and hit rate of the event occurrence. It is calculated as a sum of the accuracy and hit rate of the event occurrence and, hence, its maximal value is equal to 200%. According to [6], if the value of the total score is above 130% the forecast quality is satisfactory. This score for the blowing snow occurrence forecast is 142%. Thus, according to all forecast skill scores, the blowing snow occurrence forecast based on the proposed algorithm can be considered successful.

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