IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 119, No. 2, April – June, 2015, pp. 277–306

Forecasting of wet- and blowing snow in Hungary

Katalin Somfalvi-Tóth[1], **János Tordai**[2], **André Simon**[1*], **Kornél Kolláth**[1], and **Zsuzsanna Dezső**[2]

[1]*Hungarian Meteorological Service,*
Kitaibel Pál u. 1., H-1024 Budapest, Hungary

[2] *Department of Meteorology, Eötvös Loránd University,*
Pázmány Péter sétány 1/a, 1117 Budapest, Hungary

**Corresponding author E-mail:simon.a@met.hu*

(Manuscript received in final form September 8, 2014)

Abstract—Deep cyclones, originating in the Mediterranean area, are frequently the cause of heavy precipitation and environments characterized by large temperature gradients and strong wind. In winter period, several types of precipitation can be observed in such situations, including freezing rain and wet snow, which can cause serious damage on the electricity power lines or other infrastructure. On March 14–15, 2013, deep snowdrifts resulted in blocking of thousands of vehicles on Hungarian highways. Similar cases motivated the research of these phenomena in Hungary, using and adapting empirical approaches to calculate wet snow loads on wires or to calculate the blowing snow index (BSI) to assess the intensity of the snowdrifts development. Forecasting of these parameters is possible by using inputs from global and limited numerical weather prediction models (ECMWF, WRF). The paper describes methods for wet- and blowing snow diagnostics and classification of their intensity. The results are demonstrated on case studies and supported by observations and available damage reports. The possibility of further refinement of the diagnostics and its operational application is also discussed.

Key-words: wet snow, blowing snow, forecasting, winter weather, numerical models, WRF, diagnostics

1. Introduction

Wet snow is defined as “deposited snow that contains a great deal of liquid water” (*Glickman et al.*, 2000). It typically occurs during snowfall within the temperature range between 0 and +3 °C (*ISO*, 2001), though, snow accretion on structures have sometimes been observed also by temperatures below zero

(*Sakamoto*, 2000). The liquid water content of the accreted wet snow is usually between 5 and 40% (*Admirat*, 2008). Heavy and long-lasting snowfall in such conditions can develop considerable snow loads on wires, sometimes in order of several tens of N/m (*Makkonen* and *Wichura*, 2010). Serious problems with electricity failures caused by wet snow are frequently reported in cold regions or in mountains (*Eliasson et al.*, 2013; *Bonelli et al.*, 2011).

The study of wet snow occurrence in Hungary started in 2009, and it was related to situation with heavy snowfall and large damage on electricity power lines in the southwest part of Hungary on January 27–28, 2009 (*Tóth et al.*, 2009). Methods of *Sundin* and *Makkonen* (1998), *Poots* (1996), and *Admirat* (2008) were tested with use of both observational data and analysis and forecasts of the WRF (Weather Research and Forecasting) model (*Skamarock et al.*, 2008). The method of Admirat has recently been refined and adapted with respect to long- term observations (*Nygaard et al.*, 2013). In Hungary, in some years, up to 35 wet snow events can occur (*Gulyás et al.*, 2012) a substantial portion of these events is related to intense cyclogenesis in the Mediterranean area and frequent passages of cyclones over or near Hungary. These are characterized by widespread and high amount of often mixed-phase precipitation, including wet snow. Adjusted diagnostics of wet snow accretion and estimation of the snow sleeve mass and diameter was tested in these types of situations and the analyses and forecasts obtained from the WRF model run at relatively high (2.7 km) resolution were investigated and compared with available observations and reports. Drifting or blowing snow occurrence in Hungary can be sometimes related to intense cyclogenesis over the Mediterranean as well (it usually develops on the northwestern flanks of propagating cyclones). Similarly to wet snow, combination of several meteorological parameters (snowfall, wind, snow density, snow depth, surface temperature) must be taken into account during forecasting of blowing snow. Over the past years, several methods were elaborated in order to study and forecast its development (*Baggaley* and *Hanesiak*, 2005). There were attempts to parameterize the blowing snow as function of wind, temperature, and state of the snow surface (*Li* and *Pomeroy*, 1997). These studies motivated the development of a comprehensive index (blowing snow index or BSI) for forecasting blowing snow in Hungary. The index was proposed with a purpose of easier evaluation of blowing snow conditions and more precise determination of areas eventually threaten by snow drifts. The method was developed upon several case studies and recently tested during severe wind- and snowstorms of January 18 and March 14–15, 2013, which hit the western part of Hungary. Above all, the usefulness of the short-range (mainly 24h) forecasts of the BSI distribution in the forecasting praxis was evaluated and compared with available observations.

This paper is divided in five sections. In the next one, we describe the methods of the wet- and blowing snow diagnostics, in Section 3 we explain the synoptic background of some major (or interesting) weather events, and we present the corresponding results (forecasts compared with observations) in Section 4. Conclusions are given in Section 5.

2. Methodology

2.1. Method of wet snow diagnostics

Admirat (2008) proposed a formula for calculation of the diameter Φ (m) of the snow sleeve accumulated on the wire. He expected that the snow sleeve has nearly cylindrical shape and started from the relationship between the variation of Φ and the mass M (kg/m), supposing that the density of the accreted snow ρ_s (kg/m^3) is constant:

$$\Phi \frac{d\,\Phi}{d\,t} = \frac{2}{\pi \rho_S} \frac{d\,M}{d\,t} . \tag{1}$$

The time variation of the mass is proportional to flow R of the snow, which passes a rectangle surface S (of unitary length and of width equal to Φ). It is expected that the airflow in front of the wire is perpendicular with respect to this surface. The basic formula for the flow (similar to the formula for accretion intensity in *Nygaard et al.*, 2013) yields:

$$R = c\,\sqrt{u^2 + w^2}\; S\,, \tag{2}$$

where u is the horizontal wind speed, w is the terminal velocity of snowflakes (both in m/s), and c is the mass concentration of wet snow in the air. Because c is usually not directly measured, it is often parameterized from water equivalent precipitation intensity at the ground P (mm/h):

$$c = \frac{P}{3600w} . \tag{3}$$

Thus, the time variation of the mass can be expressed as:

$$\frac{d\,M}{d\,t} = \beta R = \frac{\beta P}{3600} \sqrt{1 + \frac{u^2}{w^2}}\; \Phi . \tag{4}$$

In Eq. (4), the parameter β is the collection coefficient (sometimes named also as coefficient of sticking efficiency). It expresses that only a part of the snowflakes crossing the area of the wire is accreted (some snowflakes will not accrete due to curvature of the flow around the wire or some snowflakes break up).

The final formula of *Admirat* (2008) for the diameter variation can be obtained from the combination of Eqs. (1) and (4):

$$\frac{d\Phi}{dt} = \frac{2K}{\pi \rho_S}\ , \tag{5}$$

where $K = \frac{\beta P}{3600}\sqrt{1+\frac{u^2}{w^2}}$.

Neither β nor ρ_S are measured or calculated in the used numerical models and these variables had to be parameterized. It is often expected that β is indirectly proportional to wind speed (*Admirat*, 2008), however, it was shown that such approach significantly decreases the role of wind in the snow accretion model described by Eq. (5). *Nygaard et al.* (2013) proposed a computation of beta, denoted BETA_U, in which beta is indirectly proportional to the square root of the wind speed u ($\beta = 1/\sqrt{u}$), which has been used in this study. The density of the accreted snow can vary between 100 and 800 kg/m^3 (including extreme cases), and laboratory studies indicate that it is also dependent on the wind speed. One of the suggested empirical formulas (*Admirat*, 2008) used in the presented wet snow calculations yields:

$$\rho_S = 200 + 20u\,. \tag{6}$$

Because w is usually also not observed at synoptic stations, it is supposed to be constant in many wet snow studies. Here a value of 1.5 m/s was used, which is in the middle between $w = 1$ m/s proposed by *Admirat* (2008) and the average fall velocities of wet snow ($w = 2$ m/s) reported by *Yuter* (2006).

For diagnostics, based on data from synoptic stations with direct observation of the weather type, wet snow was considered if the 2 m temperature was between 0 and +3 °C and if snowfall, corresponding to 70–75 codes of the SYNOP report (*WMO*, 1995), was present at the same time. Because there were no reports of the liquid water content, we used the assumption that there must be a positive heat flux from the environment to the snowflakes, so that the snow surface can melt and accrete. It can be shown that this is equivalent to condition that the environmental wet-bulb temperature t_w is positive (*Makkonen*, 1989):

$$t_w > 0 \tag{7}$$

For NWP data, the same temperature conditions for wet snow were used as in case of observed data. It was supposed that the fraction of frozen precipitation (FR) had to be between 0.7 and 0.98 as used in the BETA_U model (denoted as FR method in this paper). We also tested a method, where snowfall was distinguished from liquid precipitation upon the 850/1000 hPa relative topography – $RT_{850/1000}$ (*Cantin* and *Bachand*, 1993). *Hirsch* (2006) showed that in the area of Hungary snowfall might be usually expected by $RT_{850/1000} \leq 1300\ gpm$. This method was chosen because it is often used in the operational forecasting, and it could be very simply applicable on basic model fields or sounding data. Because the $RT_{850/1000}$ method does not provide any information about the liquid water content of the precipitation, we used the condition Eq. (7) to distinguish between wet- and dry snow. The FR and the $RT_{850/1000}$ criterions calculated from model forecasts were also applied on wet snow diagnostics at synoptic stations, where no direct observation of the precipitation type was available.

Eq. (5) has been integrated for a 24-hour period with 1-hour timesteps, during which P and u were considered to be constant (u was equal to the average of the wind at the start and end of the step). As final output, we visualized the difference ($\Delta\Phi$) between the diameter of the snow sleeve and the diameter of the wire without snow d, which is taken equal to 0.031 m (typical diameter of transmission wires). The advantage of calculating $\Delta\Phi$ is that it can be relatively easily measured or even visually estimated (e.g., upon photographs).

The estimation of the snow mass on the wire was based on combination of Eqs. (4) and (5):

$$\frac{dM}{dt} = K\Phi. \tag{8}$$

If the wind is assumed to be constant for the whole wet snow period, the diameter can be converted to snow mass with use of a simple geometrical relationship (expecting nearly cylindrical shape of the snow accumulation):

$$M = \frac{\rho_S \pi}{4}\left(\Phi^2 - d^2\right). \tag{9}$$

Upon several cases and damage reports in Hungary, it was proposed to issue warning in cases where certain threshold of calculated snow mass or increase in the diameter would be exceeded (*Table 1*). However, alertness in some situations can be recommended already by lower values (2–3 cm diameters of snow accumulation), especially if higher snow density can be expected or if the wet snow event is combined with strong wind (so-called wind-on-ice load).

Melting of snow is not yet included in the presented wet snow diagnostics. This can eventually cause overestimation, especially when the wet snow parameters are integrated for a long period, during which the character of the weather significantly changes (but this was not typical for the evaluated cases).

Table 1. Proposal on wet snow warning thresholds upon calculated mass and diameter of snow accumulation on wires (*Somfalvi-Tóth*, 2014). The values of $\rho_S = 300$ kg/m^3 and d=0.031 m were chosen for this conversion, based on Eq. (9)

Wet snow mass *M* **[kg/m]**	**Increase of the snow-sleeve diameter** $\Delta\Phi$ **[cm]**	**Proposed level of warning**
1.5	5.5	1
3	8.6	2
5	11.8	3

2.2. Method of blowing snow diagnostics

In situations with blowing snow we evaluated the so-called blowing snow index (BSI) parameter (*Tordai*, 2012). The index evaluates six meteorological parameters, which can influence the development of snowdrifts. This influence is represented by weighting functions *f*. These can be negative – thus, one term itself can counteract positive contributions of other terms (e.g., snowdrifts are improbable by very low windspeed, even if other conditions would be optimal). The maximum values of the weighting functions are 1. The final formula for BSI sustains from the sum of the functions:

$$BSI = f(T)+f(T_s)+f(U)+f(G)+f(H)+f(\rho_H)\,, \qquad (10)$$

where $f(T)$ represents temperature at 2 m, T_s is the surface (skin) temperature, U is the wind speed at 10 m, G is the wind gust at 10 m, H is the snow depth, and ρ_H is the snow density. The criteria and formulas for determination of each weighting function (given in *Table 2*) were based on the work of *Tordai* (2012), and it was only slightly modified for mathematical reasons. The thresholds in the weighting function calculations were determined upon observations and several case studies of blowing snow. The BSI can acquire negative values (if impact of certain components would strongly inhibit the development of blowing snow). The maximum possible value is 6 (very high probability of snowdrift development). Although BSI is rather related to probability of blowing (or drifting) snow occurrence, higher values of BSI usually also indicate higher intensity of snowdrift production. It has been observed that blowing snow is probable by BSI exceeding 2, values exceeding 3.5 are already significant and are usually accompanied by light or moderate development of snowdrifts.

Table 2. Determination of respective weight functions (f) in the calculation of the BSI index

State determinating parameter	Interval	Weight function
T [°C] (2 m temperature)	$T \le -6.5$	$f(T)=1$
	$-6.5 < T \le 0.5$	$f(T)=-0.0087T^2 - 0.1727T + 0.2447$
	$T > 0.5$	$f(T)=-(0.0181T)^2 - 0.139T + 0.2257$
T_s [°C] (Surface temperature)	$T_S \le -3.0$	$f(T_S)=1$
	$-3.0 < T_S \le -0.5$	$f(T_S)=-0.0406T_S^2 - 0.2436T_S + 0.6342$
	$-0.5 < T_S \le 2.0$	$f(T_S)= 0.3397\exp(-1.5717\,T_S)$
	$T_S > 2.0$	$f(T_S)=-0.1264T_S^2 + 0.5056T_S - 0.4915$
U [m/s] (10m wind)	$U < 4.0$	$f(U)=1.014U - 4.014$
	$4.0 \le U < 15.0$	$f(U)=-0.0076U^2 + 0.2314U - 0.7616$
	$U \ge 15.0$	$f(U)=1$
G [m/s] (10m wind gust)	$G < 6.0$	$f(G)=-0.075G^2 + 1.1192G - 3.9657$
	$6.0 \le G \le 21.0$	$f(G)=-0.0029G^2 + 0.1416G - 0.6952$
	$G > 21.0$	$f(G)=1$
H [cm] (snow depth)	$H < 5.0$	$f(H)= 0.0732H^2 + 0.6711H - 4.9321$
	$5.0 \le H < 31.0$	$f(H)=-0.0007H^2 + 0.0538H + 0.0022$
	$H \ge 31.0$	$f(H)=1$
ρ_H [kg/m^3] (snow density)	$\rho_H < 100.0$	$f(\rho_H)=1$
	$100.0 \le \rho_H < 240.0$	$f(\rho_H)=-1.83\times10^{-5}\rho_H^2 + 0.0019\rho_H + 0.9912$
	$\rho_H \ge 240.0$	$f(\rho_H)=-0.0534\rho_H + 13.207$

At the Hungarian Meteorological Service, warnings on blowing snow have already been issued prior to development of BSI, although the criteria for it were arbitrary. Upon these criteria, we developed a simple warning decision index (WDI) in order to compare the original formulation (*Table 3*) with a warning system proposed upon BSI thresholds (*Tordai*, 2012). When using BSI, it was recommended to issue first level (yellow) warning on blowing snow for values higher than 3.5. Strong development and second level (orange) warnings can be expected by BSI exceeding 4, and very severe blowing snow and third level of warnings (red) can occur by BSI equal to 4.5 or higher.

Both BSI and WDI were estimated upon data from synoptic station observations (and compared with forecasts of these parameters from numerical models). We considered only stations, where measurements of snow depth and density were available, or where it was possible to assess them using spatial and temporal interpolations. Instead of the skin surface temperature (which can eventually be the temperature of the snow surface, and it is usually not measured at the stations), we used the near-surface temperature measured 5 cm above the terrain. We also checked the reports on drifting- and blowing snow, which are coded at certain synoptic stations (*WMO*, 1995). We assumed that the code on slight or moderate drifting snow (36) would nearly correspond to current yellow warning, the codes 37 (heavy drifting snow), 38 (slight or moderate blowing snow) to orange and the 39 code (heavy blowing snow) to red warning. Though, the original definitions of drifting and blowing snow are rather related to visibility conditions as to height or intensity of snowdrift production.

Table 3. Blowing snow warning criteria of the Hungarian Meteorological Service and corresponding WDI codes and algorithms. The meaning of parameters is the same as in Table 2, except for R_{24} (snow precipitation of past 24 hours, in mm) and R_{03} (snow precipitation of past 3 hours, in mm)

HMS warning criteria	Level of warning	WDI algorithm	WDI code
The wind produces snowdrifts of low depth occurring on territories covered by fresh snow	Yellow 1	$U \geq 4\,m/s \quad H \geq 5\,cm$	1
The wind accompanied by strong gusts (> 60 km/h) produces deep (depth locally > 0.5 m) snowdrifts on territories covered by fresh snow	Orange 2	$U \geq 4\,m/s \quad H \geq 5\,cm$ $G \geq 16.7\,m/s \quad R_{24} \geq 1\,mm$	2
The wind accompanied by strong gusts (> 60 km/h) produces deep (depth > 0.5 m at many places) snowdrifts on territories covered by fresh snow. Besides, snowfall can be still expected (several cm of fresh snow).	Red 3	$U \geq 4\,m/s \quad H \geq 5\,cm$ $G \geq 16.7\,m/s \quad R_{24} \geq 1\,mm$ $R_{03} \geq 0.1\,mm$	3

2.3. Description of numerical models and their setup used in the study

Blowing snow parameters were calculated from operational forecasts of the deterministic ECMWF global numerical model (*Persson*, 2011), which outputs were available in a regular latitude-longitude grid of 0.125 degree (nearly 16 km) horizontal resolution. The wet snow has been diagnosed upon outputs of non-hydrostatic limited area model WRF (*Skamarock et al.*, 2008). The WRF model, implemented and computed at the Hungarian Meteorological Service (HMS), provides data at nearly 2.7 km horizontal resolution and 37 vertical levels. In the HMS implementation, WRF is using the microphysics scheme of Thompson (*Thompson et al.*, 2004) and the YSU PBL scheme (*Hong et al.*, 2006) for the parameterization of planetary boundary layer processes. The higher horizontal resolution (compared to global models) and advanced physical parameterizations are important to obtain finer, mesoscale structures in the precipitation, temperature, and wind fields and the estimates of the precipitation type (fraction of frozen precipitation, *FR*). This seems to be currently more important by wet snow, which occurrence fits a relatively narrow temperature interval and which parameters (snow sleeve diameter and mass) are more sensitive on the precision and exact quantity of input parameters than in the BSI case.

3. Selected synoptic situations

3.1. Blowing snow on January 18, 2013

On January 18, 2013, the weather over Hungary was largely influenced by a deep cyclone, which centre was over the Adriatic Sea (*Fig. 1*). The cyclone had initially developed over the Bay of Genoa (on January 15) and became deeper as a result of interaction with an upper air potential vorticity (PV) anomaly, which centre was situated over the southwest flank of the surface low. The cyclone later moved toward east-northeast. The drop of the pressure over the Balkan Peninsula and increase of the pressure gradient in the north-south direction induced a low-level jet and cold-air advection over the western part of Hungary (*Fig. 2*). This was the primary reason for strong wind and gusts observed at several places in northwestern Hungary (the maximum wind gust, 21.4 m/s was reported at Sármellék at 09:40 UTC). The depth of the snow cover over western Hungary had already been high (20–50cm at many places) as a result of previous snowfalls. In the same region, moderate snowfall (up to 10 mm of precipitation) occurred on January 18 as well (*Fig. 3*). Although, at several stations, where blowing snow was observed, only light precipitation was measured (or estimated from radar measurements) during the event.

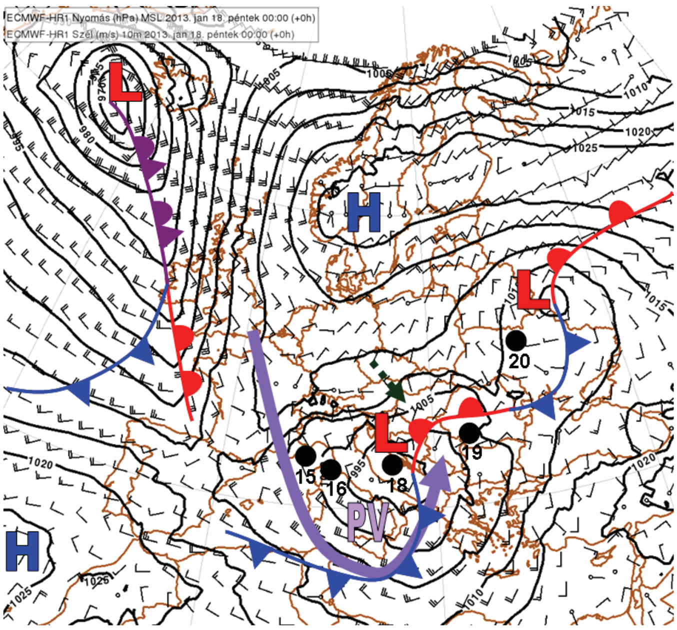

Fig. 1. ECMWF analysis of mean sea level pressure (lines, by 5 hPa), 10 m wind (barbs), and fronts valid for January 18, 2013, 00:00 UTC. The letters L and H represent lows and highs, respectively. The letter "PV" marks the position of the center of the upper-air PV anomaly; the arrow-headed line shows the segment of the upper-air jet surrounding the anomaly (at nearly 250 hPa height). The dots show the positions of the centre of the studied Mediterranean cyclone on January 15, 16 (and 17), 18, 19, and 20, 2013. The dashed line points toward northwestern Hungary, where the blowing snow event occurred.

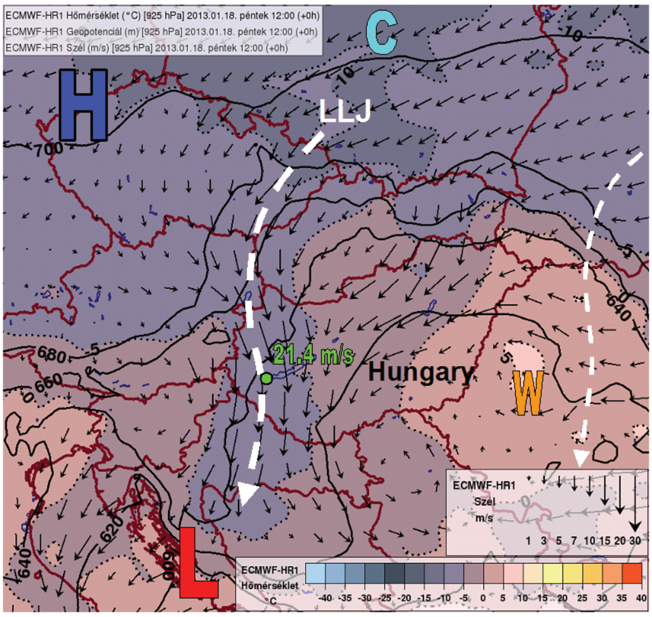

Fig. 2. ECMWF analysis of 925 hPa geopotential (lines, by 20 gpm), temperature (°C, shaded), and 925 hPa wind (arrows, m/s) valid for January 18, 2013, 12:00 UTC. The letters L, H represent low and high pressure, respectively; C, W the cold (warm) airmasses. The dashed line approximately shows the axis of the low level jet (LLJ). A point is placed on the area of the station Sármellék, where the maximum wind gust (21.4 m/s) was recorded on January 18, 2013, 09:40 UTC.

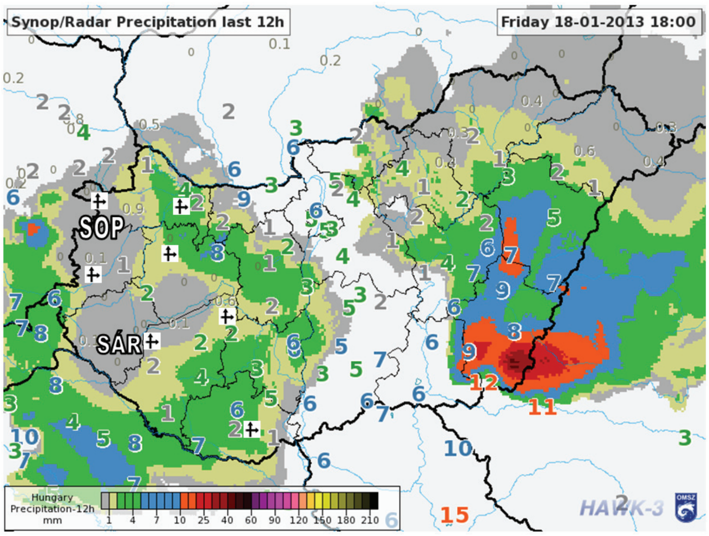

Fig. 3. 12 h precipitation amounts valid for January 18, 2013, 18:00 UTC from stationary measurements (numbers) and radar estimates (shaded). Stations, where drifting or blowing snow was coded in the past weather (–01 h) section are emphasized by square and symbol of blowing snow. Meteorological stations Sopron Kuruc-domb and Sármellék are denoted by abbreviations SOP and SÁR.

3.2. Wet snow on February 6–7, 2013

The weather in central Europe was governed by large area of low pressure (exhibiting several centres) and by a frontal system, which evolved in the Mediterranean region. On February 6–7, 2013, one of the centers of the low pressure was situated over Hungary and east Slovakia (*Fig. 4*). The eastern part of the countries was located in the warm zone of the system, while the colder air propagated around the low-pressure center and forced the mild air toward the mountainous region in northeast Hungary and east Slovakia (*Fig. 5. a–b*). There was an intensive positive temperature advection and high (almost 100%) mean relative humidity between 925–600 hPa (not shown), especially in east Slovakia, where heavy snowfall occurred. Vertical cross-sections of temperature show that across Hungary and Slovakia, over the localities, where wet snow was reported/diagnosed, there was a 200–300 meters deep layer of 0–2 °C temperature (*Fig. 6. a–b*). This layer was well expressed over the northern part of Hungary and the central-eastern part of Slovakia, where 10–20 mm precipitation occurred (*Fig. 7*). Upon precipitation estimates from radars and temperature profiles, favorable wet snow conditions could have developed on the southern slopes of the mountains in the central part of Slovakia, but surface observations were sparse in this region. Damage reports and photographs (*Railpage.net,* 2013) indicate that wet snow occurred also in the valley of the river Hornád (on the railway between Krompachy and Margecany). There was no positive temperature layer on the vertical cross-sections in this region, probably because the valley is not yet resolved by the ECMWF model orography by current resolution (nearly 16 km). The cross-sections also show that the area of the positive temperature layer reduced in time as the cold-air advection was progressing (marked by the decrease of the near-surface equivalent potential temperature).

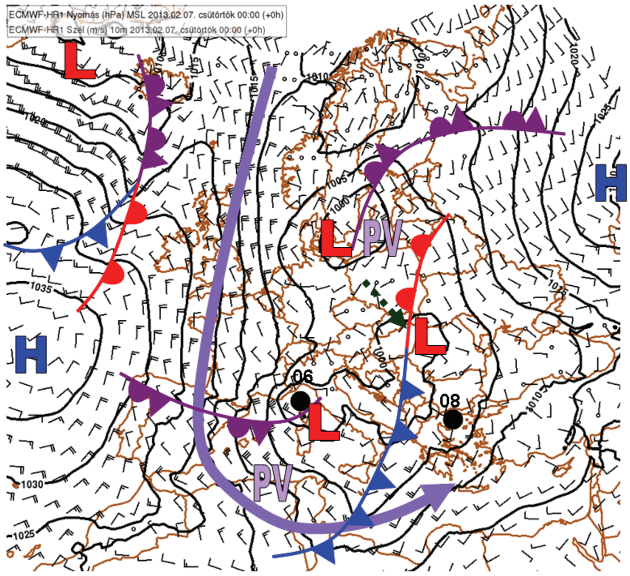

Fig. 4. As in *Fig. 1* but for February 7, 2013, 00:00 UTC. The dots show the positions of the (deepest) centre of the Mediterranean cyclone on 6, 7, and 8 February, 2013. The dashed line points toward the border region of northeastern Hungary and southeastern Slovakia, where the wet snow event occurred.

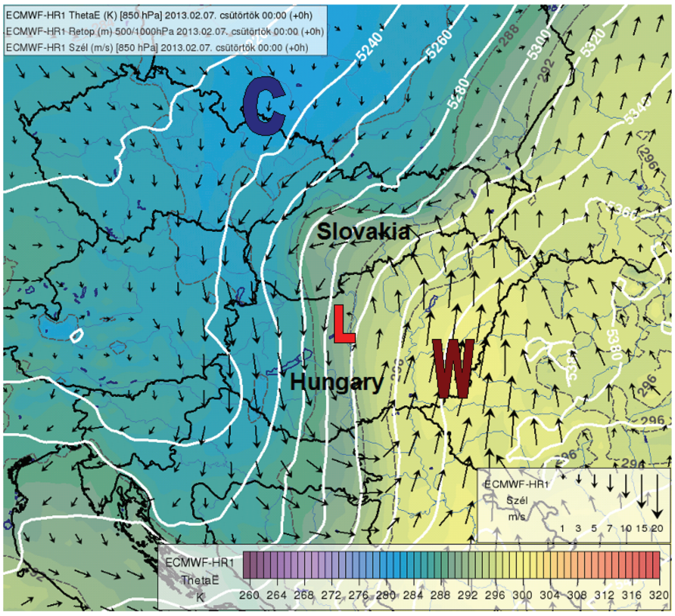

Fig. 5a. ECMWF analysis of the 850 hPa equivalent potential temperature (color shades and dashed lines, K), wind field (arrows, m/s), and the 500/1000 hPa relative topography (white lines, m) valid for February 7, 2013, 00:00 UTC. The letter L denotes the center of the cyclonic circulation over Hungary, letters W, C show the warm and cold air-masses.

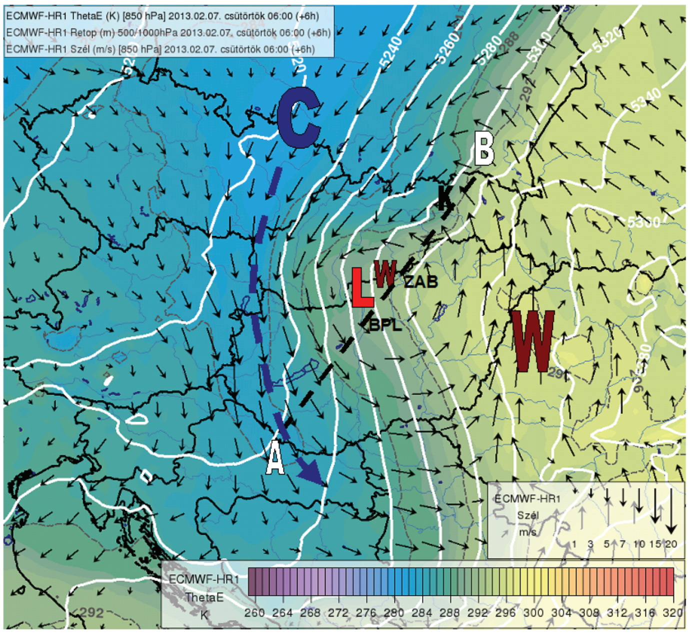

Fig. 5b. As in *Fig. 5a* except for the 6h ECMWF forecast valid for February 7, 2013, 06:00 UTC. The dashed, arrow-headed line schematically shows the flow of the colder airmass, which started to surround and force the warmer air away. The AB line shows the direction of the cross-section in *Fig. 6a-b*. The abbreviations BPL, ZAB emphasize the positions of the weather stations at Budapest Lőrinc and Zabar, respectively (mentioned also later in the text). The letter K denotes the town Krompachy in Slovakia (wet snow caused damages were reported in its neighborhood).

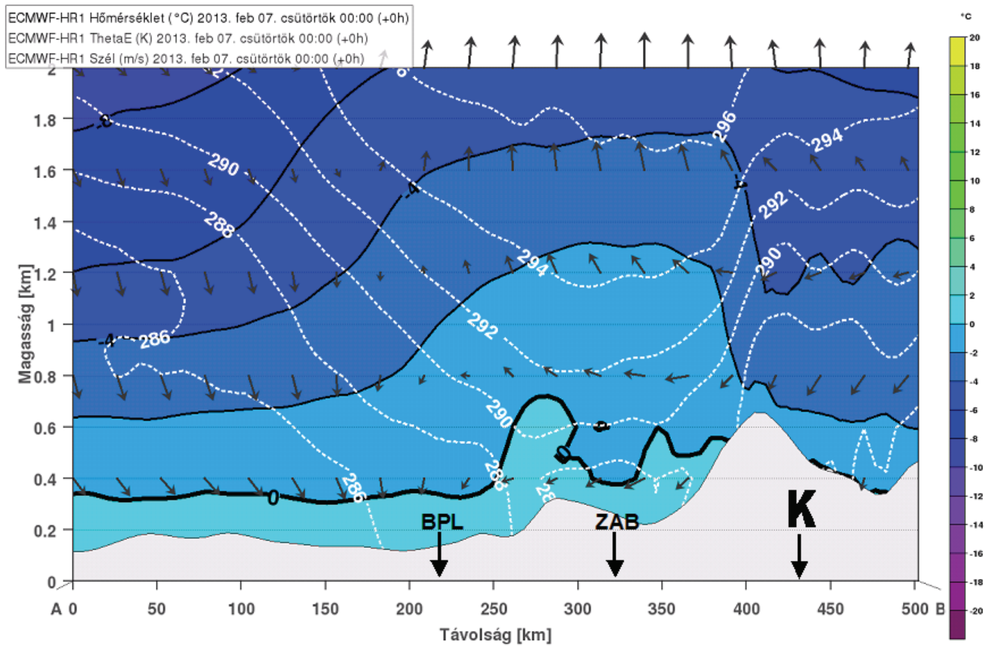

Fig. 6a. ECMWF analysis of temperature (shades and solid lines by 2 °C), equivalent potential temperature (dashed lines, by 2 K) and wind (arrows, m/s) valid for February 7, 2013, 00:00 UTC in a vertical cross-section, which direction is shown in *Fig. 5b*. The abbreviations and arrows mark places, where wet snow was diagnosed/reported (see also *Figs. 5b* and *14a-b*).

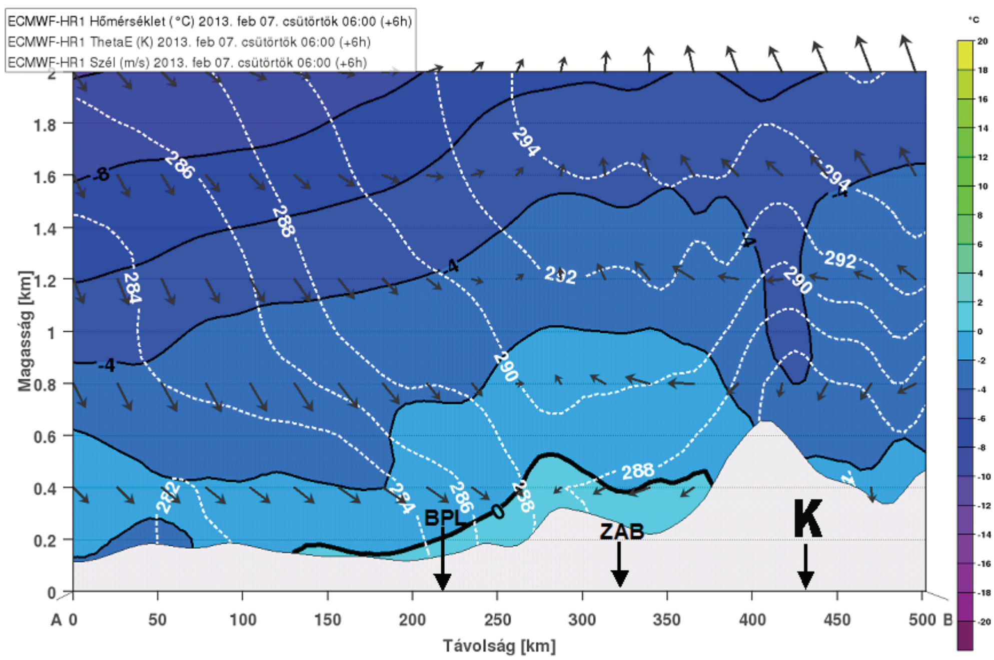

Fig. 6b. As in *Fig. 6a* but for the ECMWF forecast of temperature valid for February 7, 2013, 06:00 UTC.

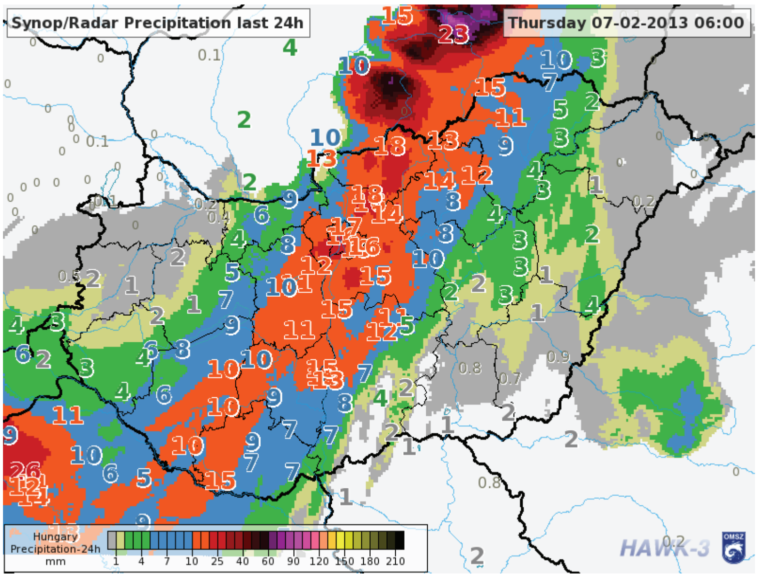

Fig. 7. As in *Fig. 3* but for 24 h precipitation amounts valid for February 7, 2013, 06:00 UTC.

3.3. Wet- and blowing snow on January 24–25, 2014

On January 25, 2014, a cyclone with centre over southern Italy and the Adriatic Sea was moving eastwards (*Fig. 8.*). Its frontal system affected several countries of southern and central Europe causing extraordinary heavy snowfall (Slovenia, Croatia, Serbia, Bulgaria). The northern flank of the warm frontal precipitation band also reached the southern part of Hungary (already on January 24, 2014). At 850 hPa level ECMWF analyses (*Fig. 9*), it was possible to observe that while the cold-air advection already started over large part of western Hungary, there was still a “tongue” of warmer and moist air overturning toward the southwest part of Hungary, where the intense snowfall occurred. This is likely a signature of an occlusion process (in rather mesosynoptic scale), similar to the one observed in the February 6–7, 2013 wet snow situation. The maximum of 20 mm precipitation in Hungary was also reported close to this area (*Fig. 10*).

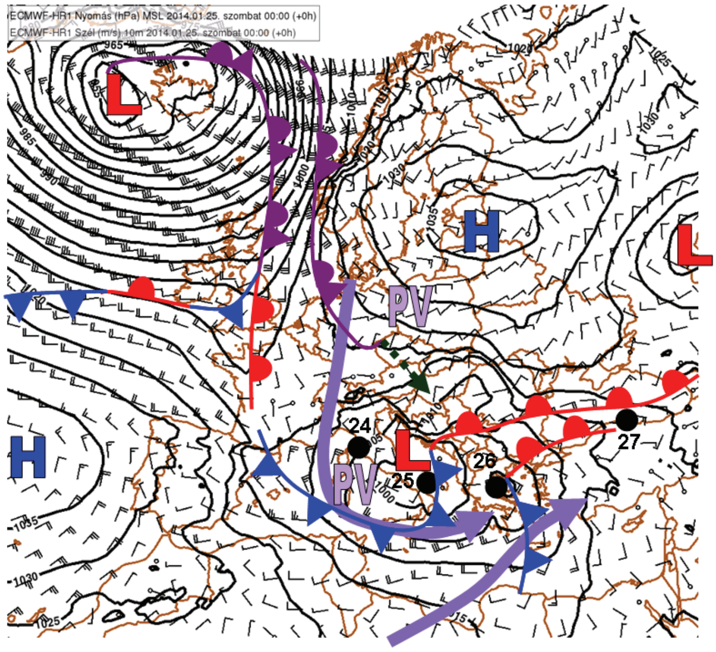

Fig. 8. As in Fig. 1 but for January 25, 2014, 00:00 UTC. The dots show the positions of the (deepest) centre of the Mediterranean cyclone on January 24–27, 2014. The dashed line points toward southwestern Hungary, where both wet snow and blowing snow were observed.

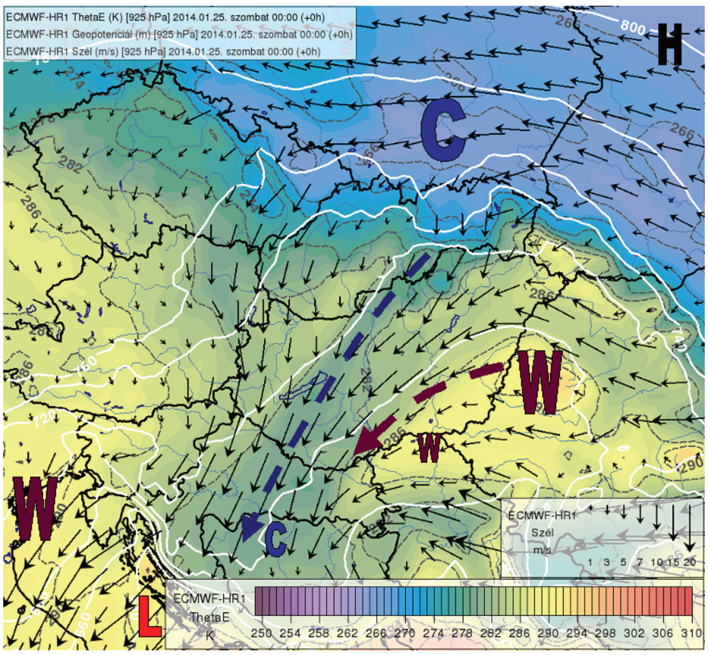

Fig. 9. ECMWF analysis of the 925 hPa equivalent potential temperature (color shades and dashed lines, K), wind field (arrows, m/s), and geopotential (solid lines, m) valid for January 25, 2014, 00:00 UTC. The letters L, H represent low and high geopotential, respectively; C and W represent the cold (warm) regions. The dashed lines schematically show the flow of colder/warmer air over Hungary.

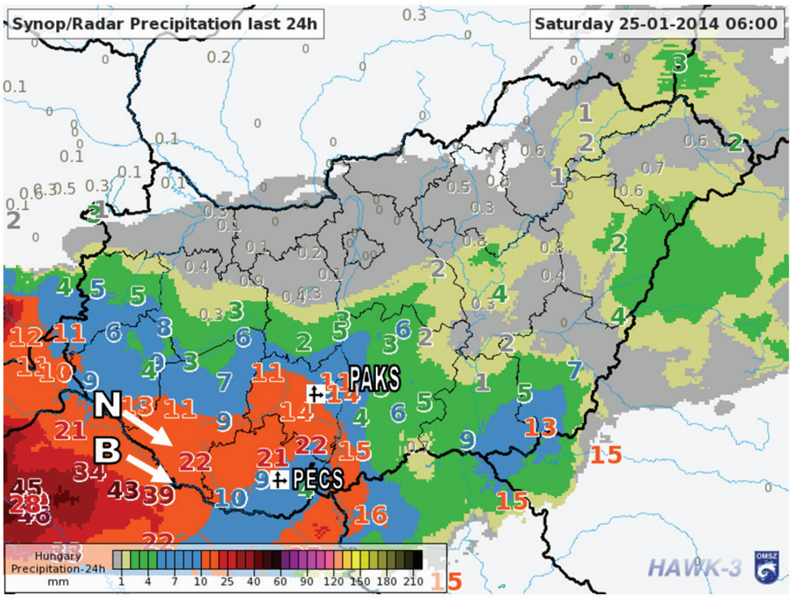

Fig. 10. As in *Fig. 3* but for 24 h precipitation amounts valid for January 25, 2014 06:00 UTC. Meteorological stations Pécs-Pogány and Paks, which reported blowing snow on January 24, 2014, are displayed. Arrows denoted by letters B and N point toward the position of settlements Barcs and Nagyatád, respectively. Damage due to wet snow was reported in their surroundings on January 24–25, 2014.

4. Results for wet- and blowing snow diagnostics

4.1. Blowing snow on January 18, 2013

The January 18, 2013 weather situation was one of the most serious blowing-snow events of the past ten years in Hungary. The blowing snow developed at a large area (almost entire western Hungary), causing serious problems in transport and requiring numerous actions of the disaster management (*Fig. 11*). Such cases are relatively rare – for example, between 2007 and 2012 there was only one case that the highest, third-level warning was issued on blowing snow (18 second- and 60 first-level warnings were issued during the same period). Only light-to-moderate snowfall (few mm of precipitation) had been expected upon available NWP forecasts a day before this event, hence, the intensity of the snowdrift developments had been debated in the HMS forecasters team. The 24h forecast of BSI from the January 17, 2013, 12:00 UTC ECMWF run indicated a possibility of very intense blowing snow for the area northwest of the Lake Balaton (*Fig. 12a*). This area was also emphasized in the WDI outputs (*Fig. 12b*). Though, there would hardly be any transition between the yellow and red warning in WDI (the red warning is distinguished from the orange one only upon the presence of precipitation, which had been forecast by the ECMWF model for the entire area with strong wind). The analysis of respective weighting functions present in Eq. (10) reveals that all of them positively contributed to BSI in the model forecast for the localities (meteorological stations Sopron Kuruc-domb and Sármellék), where snowdrifts were expected (*Table 4*).

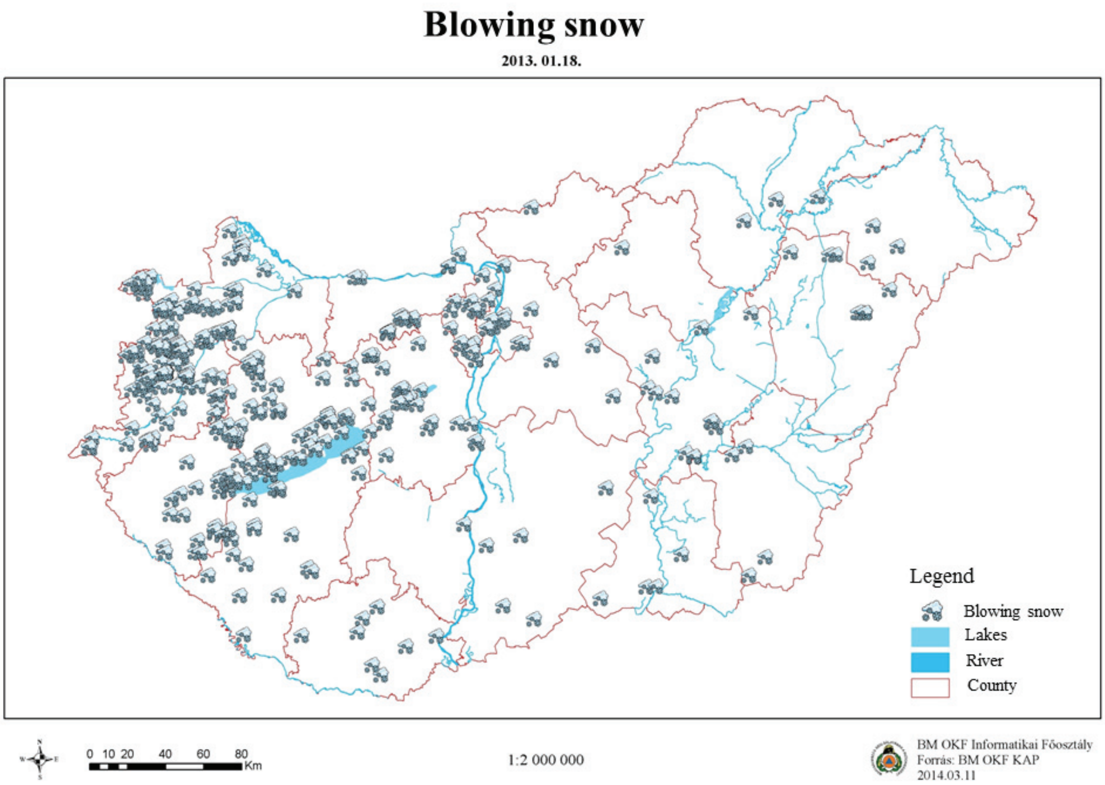

Fig. 11. Actions of the disaster management on January 18, 2013. (source: National Disaster Management Directorate General, with permission)

Table 4. Weighting functions, BSI, and WDI for Sopron Kuruc-domb and Sármellék, derived from the ECMWF 24h forecast valid for January 18, 2013, 12:00 UTC.

Station	$f(T)$	$f(T_S)$	$f(U)$	$f(G)$	$f(H)$	$f(\rho_H)$	***BSI***	***WDI***
Sopron	0.77	1	0.83	0.97	1	0.81	5.4	3
Sármellék	0.84	1	0.71	0.91	1	0.78	5.2	3

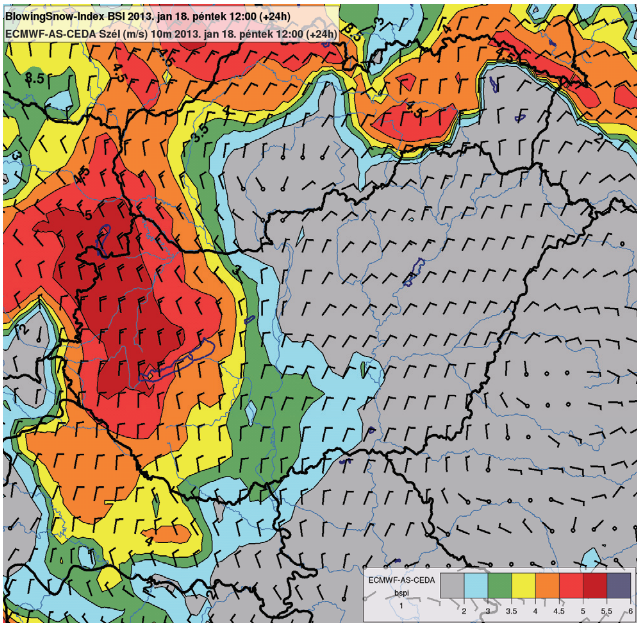

Fig. 12a. ECMWF 24 h forecasts of BSI (shades and solid lines) and 10 m wind (barbs, m/s) valid for January 18, 2013, 12:00 UTC.

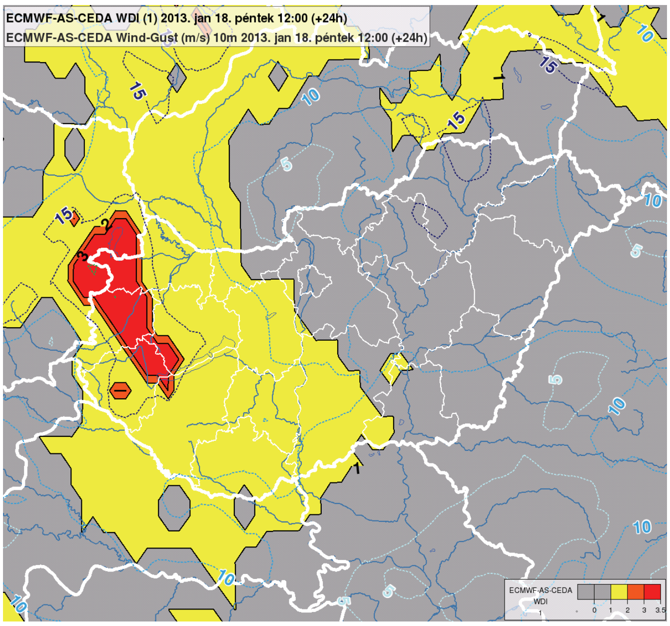

Fig. 12b. ECMWF 24 h forecasts of WDI (shades and solid lines, by 1) and of wind gusts (dotted lines, by 5 m/s) valid for January 18, 2013, 12:00 UTC.

Available observations, close to the time of the forecast validity (January 18, 11:40 UTC), show that drifting or moderately blowing snow was really coded at several stations in western Hungary (*Fig. 13*). Though, heavy blowing snow (code 39) was not observed and BSI estimated from the measurements did not exceed 5. This could have been caused by the use of temperature measured close to terrain surface, instead of the skin surface temperature (of the snow cover), because the weights of surface temperature are significantly lower in the observations (*Table 5*) than in the forecasts. Interestingly, WDI would suggest only 1st level of warning for the evaluated stations. The main reason for it is that only low precipitation amounts were reported at stations concerned (although light or moderate snowfall had been coded at some observation dates). One possible explanation is that the strong wind blew the snow off the measuring devices. The radar-estimated precipitation indicates that the real snow precipitation could have been somewhat bigger compared to surface observations, though this was not typical in the area of highest gust and snowdrift occurrences (refer to *Fig. 3*).

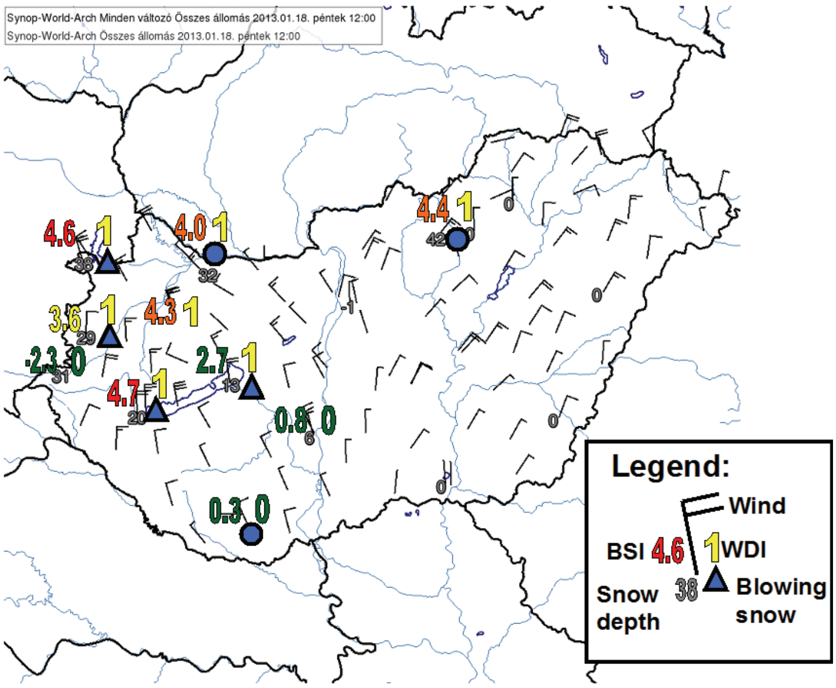

Fig. 13. Observations of 10m wind (barbs, m/s) and snow depth (numbers, cm) from Hungarian meteorological stations on January 18, 2013, 12:00 UTC. Further numbers (see the description in the legend) denote the estimated value of BSI and WDI valid for 11:40 UTC. The circles are drawn at stations, where drifting snow (code 36) was reported on January 18, 2013, triangles are for blowing snow (code 38).

Table 5. As in *Table 4* but derived from observations at Sopron Kuruc-domb and Sármellék, on January 18, 2013, 11:40 UTC.

Station	$f(T)$	$f(T_S)$	$f(U)$	$f(G)$	$f(H)$	$f(\rho_H)$	***BSI***	***WDI***
Sopron	0.68	0.18	0.85	0.91	1	0.96	4.6	1
Sármellék	0.73	0.84	0.78	0.86	0.8	0.74	4.7	1

4.2. Wet snow on February 6–7, 2013

Wet snow calculations were provided upon WRF model run based on February 6, 2013, 12:00 UTC. In the first calculation, the FR criterion was chosen for wet snow diagnostics (*Fig. 14a*).

Wet snow was detected at several places in Hungary and Slovakia (mostly in the southern part of central Slovakia and in the valley between the towns Košice and Prešov), though, the values of $\Delta\Phi$ were mostly below the proposed warning thresholds (maximum detected values were 5–6 cm). When using the $RT_{850/1000}$ criterion, the area of potential wet snow occurrence became considerably bigger (*Fig. 14b*), and the condition for first-level warning according to *Table 1* would be fulfilled on several places. The maximum detected $\Delta\Phi$ was about 8 cm. If we assume, that the density of the wet snow on wires was between 250 and 300 kg/m^3 (according to mean wind speed in this area), this diameter would be equivalent to 2.2–2.7 kg/m snow-mass, which can potentially cause damage on the overhead lines, particularly if the wind speed is strong. The comparison of the diagnostics on observations (*Table 6a*) and on the corresponding model outputs (*Table 6b*) showed that the FR-criterion largely reduced the precipitation, which potentially occurred in wet snow form. This is the main cause of the differences between the forecast diameters (wet snow loads) and the ones diagnosed upon observations, because forecasts of other parameters (wind-speed, temperature) were relatively close to the observed ones. Examination of the course of FR (e.g., for station Košice, *Fig. 15*) showed that this parameter was rather low when the temperature was higher than 1 °C, although, in the reality, snowfall was reported in such conditions. The low *FR* could have been partially also influenced by somewhat higher (by 0.5–1 °C) temperature in the model compared to observations. The $RT_{850/1000}$ criterion seemed to be more successful in detection of wet snow occurrence, but it is possible that the diagnosed values of the snow sleeve diameter were too high when using this method (especially in the area of Budapest, where wet snow accretion on wires corresponding to $\Delta\Phi$ of 5 cm or bigger probably did not occur).

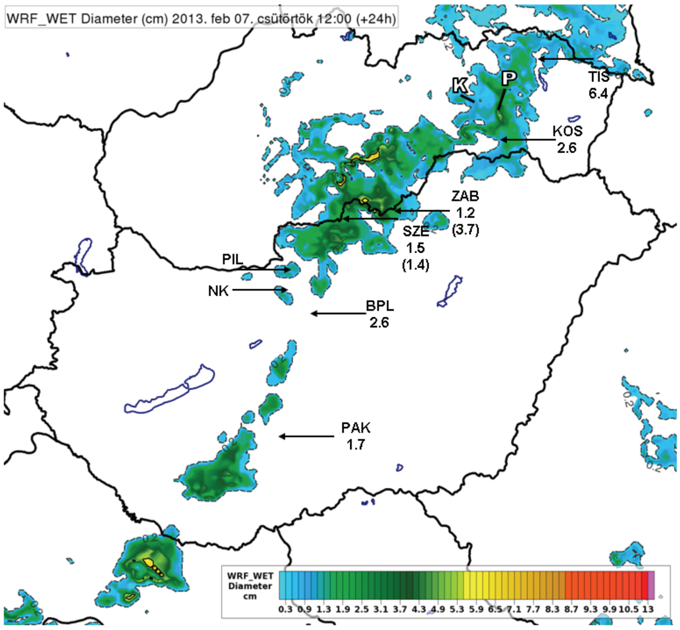

Fig. 14a. WRF 24 h forecast of the snow sleeve diameter increase (shades, in cm) valid for February 7, 2013, 12:00 UTC calculated using the FR method. The solid lines denote the diameters of 5.5 and 8.6 cm corresponding to warning thresholds. The arrows and abbreviations denote the positions of weather stations and localities, where wet snow was reported/diagnosed (PAK-Paks, BPL-Budapest Lőrinc, SZE-Szécsény, ZAB-Zabar, KOS-Košice, TIS-Tisinec, NK- Nagy-Kevély, PIL-Pilis). The numbers show the increase of the snow sleeve diameter (cm) assessed from the observations (as in *Table 6a*). The thick line denoted K (P) shows the direction of the railway between Krompachy and Margecany (Prešov and Kysak), where damage due to wet snow was reported.

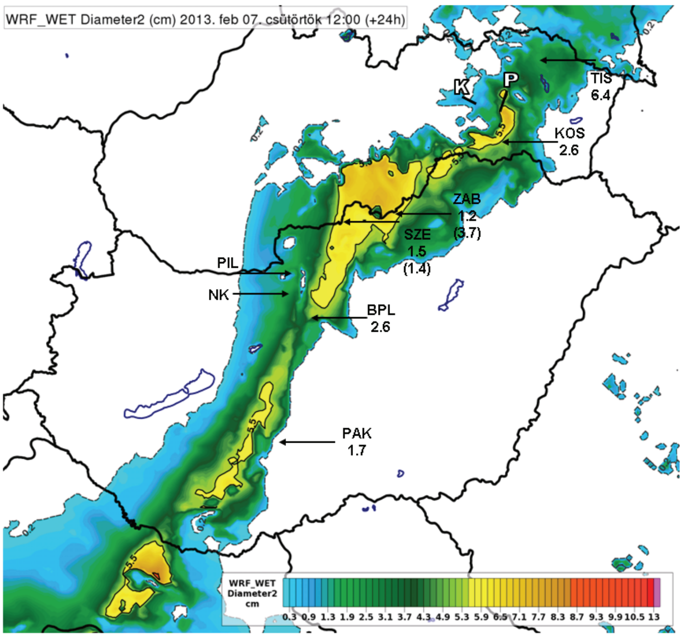

Fig. 14b. As in *Fig. 14a* but for the $RT_{850/1000}$ method.

Table 6a. Parameters of wet snow precipitation observed or derived from observations of several synoptic stations in Hungary and Slovakia during the period of February 6, 2013, 12:00 UTC – February 7, 2013, 12:00 UTC. There were no weather-type observations on the star-marked stations (Szécsény and Zabar), the wet snow period was assessed from the WRF model data (upper record using the FR, lower record in parenthesis the $RT_{850/1000}$ method). At the station Tisinec (marked by two stars), weather-type observations were not available between 20:00 and 05:00 UTC, but from the amounts and course of other parameters (snow-depth, temperature, wet-bulb temperature) it is probable that all the precipitation in this period was in wet snow form.

Synoptic station: **Parameter:**	**Paks (PAK)**	**Budapest Lőrinc (BPL)**	**Szécsény (SZE)***	**Zabar (ZAB)***	**Košice Letisko (KOS)**	**Tisinec (TIS)****
Station height (*ASL*) [m]	97	139	153	226	230	216
P [mm] Total precipitation	7.9	12.1	15.8	11.6	19.0	26.0
Pw [mm] Wet snow precipit.	5.15	8.3	4.35 (4.3)	3.7 (11.6)	8.08	20.5
U [m/s] Average wind	1.66	1.93	0.97 (0.73)	1.18 (0.99)	5.34	1.98
Δϕ [cm] Snow-sleeve diameter increase	1.68	2.60	1.50 (1.43)	1.18 (3.72)	2.64	6.41
M [kg/m] Wet snow mass	0.236	0.436	0.199 (0.185)	0.157 (0.639)	0.528	1.526

Table 6b. Parameters of wet snow precipitation derived from the WRF model forecasts valid for the period of February 06, 2013 12:00 UTC – February 07, 2013 12:00 UTC and for the grid-points nearest to observations listed in the *Table 6a*. The upper (lower) values are for the *FR* ($RT_{850/100}$) method of snowfall determination. The abbreviation NR (Not Relevant) means that wet snow was not detected.

Synoptic station: **Parameter:**	**Paks (PKS)**	**Budapest Lőrinc (BPL)**	**Szécsény (SZE)**	**Zabar (ZAB)**	**Košice Letisko (KOS)**	**Tisinec (TIS)**
Grid-point height (*ASL*) [m]	87.7	124.1	161.2	301.2	250.2	258.7
P [mm] Total Precipitation	10.86	17.63	19.37	18.49	17.83	8.06
Pw [mm] Wet snow precipitation	0 (0)	0 (16.81)	5.22 (19.37)	5.77 (18.49)	3.03 (17.24)	0 (6.7314)
U [m/s] Wet snow period average wind	NR (NR)	NR (2.19)	2.83 (2.26)	2.74 (2.12)	4.15 (3.33)	NR (2.64)
Δϕ [cm] Snow sleeve diameter increase	NR (NR)	NR (5.26)	1.64 (6.09)	1.83 (5.85)	0.98 (5.56)	NR (2.11)
M [kg/m] Wet snow mass	NR (NR)	NR (1.153)	0.26 (1.475)	0.297 (1.368)	0.157 (1.420)	NR (0.342)

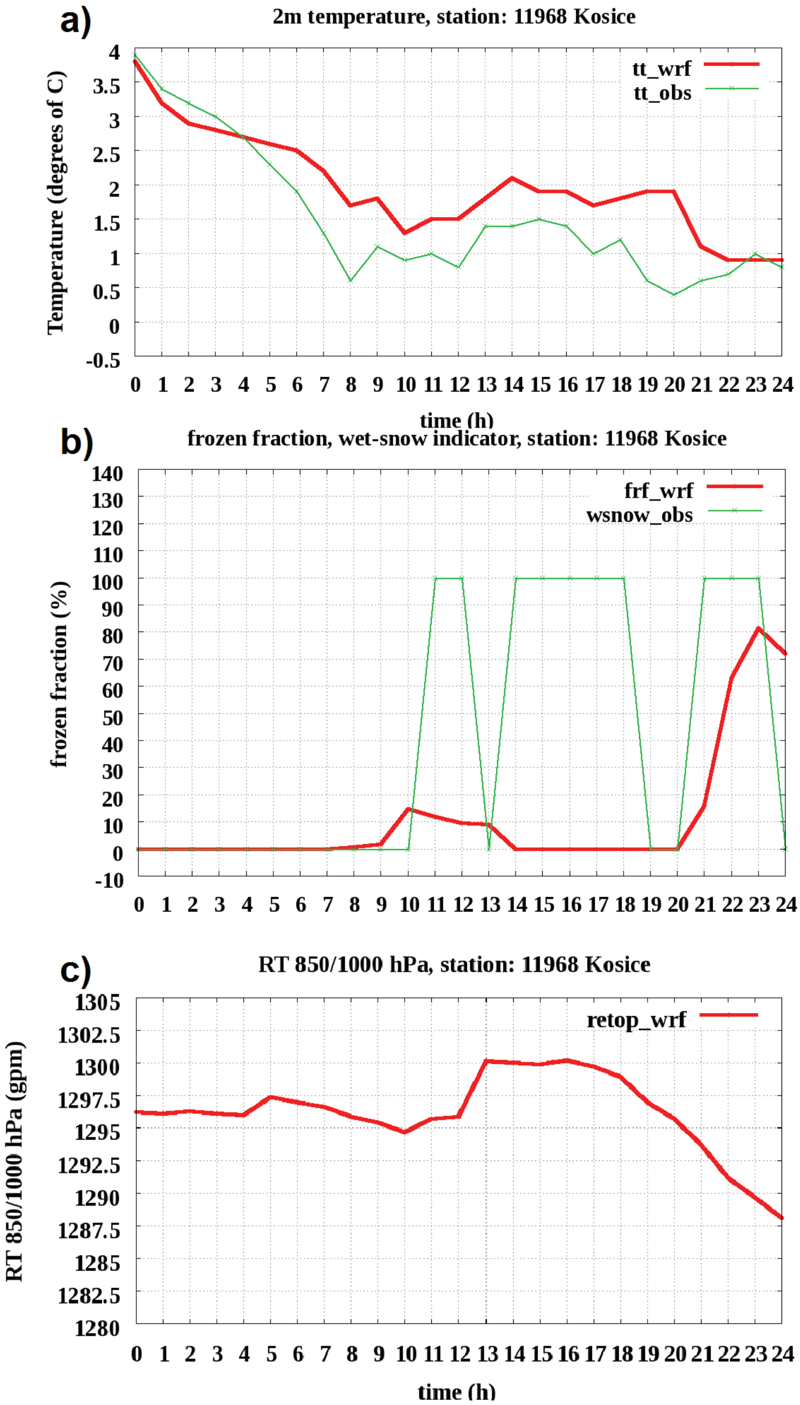

Fig. 15. Course of observed/diagnosed (thinner lines) and forecasted (thicker lines) meteorological parameters valid for the station Košice and for the period of February 6, 2013, 12:00 UTC –February 7, 2013, 12:00 UTC. The February 6, 2013, 12:00 UTC WRF run outputs were used for this visualization. The horizontal axis shows the time (h) from the start of this run. Evolution of the 2 m temperature is shown in a), figure b) shows the change of the model-computed fraction of frozen precipitation (FR). This is depicted together with an index showing detection of wet snow upon observed precipitation type, temperature, and wet-bulb temperature (0 – no wet snow, 100-wet snow). Figure c) shows the evolution of the $RT_{850/1000}$ parameter forecast by WRF.

Available reports (*Pilis parkerdő,* 2013) mentioned damage in the forest due to high snow loads in Pilis mountains, and there is also photographic evidence (*Kolláth*, 2013) of wet snow accumulated on wires in this region (e.g., in the area of the Nagy-Kevély mountain). Although, this region seemed to be only marginally affected by wet snow in the WRF forecasts (see *Figs. 14a–b*). In Slovakia, wet snow was reported on the railway electric power lines between the railway stations Margecany and Krompachy and also between stations Kysak and Prešov. Though, the damage on the power lines was probably not only direct, due to high loads on the wires, but it was also caused by trees, which broke under the weight of heavy, accumulated wet snow (*Railpage.net*, 2013). Wet snow was forecast for the surrounding of both above-mentioned railways. A local maximum of $\Delta\Phi$, close to the Kysak-Prešov railway, appeared in the diagnostic outputs, using both FR and $RT_{850/1000}$ methods.

4.3. Wet- and blowing snow on January 24–25, 2014

Most reports of the wet snow occurrence in Hungary and associated damage (electric power failures) were concentrated to the southwestern border of Hungary (region of Barcs and Nagyatád), yet, several thousands of inhabitants were concerned (*E.O.N. Hungária Zrt.*, 2014, data on power failures, photographs, and personal communication). The wet snow was diagnosed using both FR and $RT_{850/1000}$ criterions in this territory.

In case of *FR*, the forecast diameters of snow-sleeve mostly did not reach the proposed warning thresholds (5.5 cm, not shown). In the second diagnostics, significant, up to 8–9 cm diameters were predicted during the 24-hour accretion period, until January 25, 06:00 UTC (*Fig. 16*). Very high accumulation of wet snow was also forecast for the region close to the synoptic station Paks. However, here the development of wet snow was questionable: though the forecast 2 m temperature fitted the wet snow criterions (between 0 and 3 °C), in the reality, it was probably well below 0 °C during most of the investigated period, as indicated by observations of the Pécs and Paks stations.

During this situation, blowing snow was reported at synoptic stations Pécs and Paks. Its intensity was probably highest in the evening of January 24, 2014 (at around 21:00 UTC), when wind gusts of 12–15 m/s were observed. Upon available observations, the BSI was estimated to be 3.54 for Pécs and 3.49 for Paks. There were no snow density measurements in this case, thus, a mid-value of 170 kg/m^3 between the two thresholds mentioned in *Table 2* was used in this calculation. But, because of the uncertainty in both skin-surface temperature and snow density, it is probable that the true BSI values were bigger (e.g., in case of fresh snow, these parameters could have been lower and their weight functions higher). The more simple WDI index also indicated the possibility of blowing snow, corresponding to the first level warning at the two evaluated locations (*Fig. 17*).

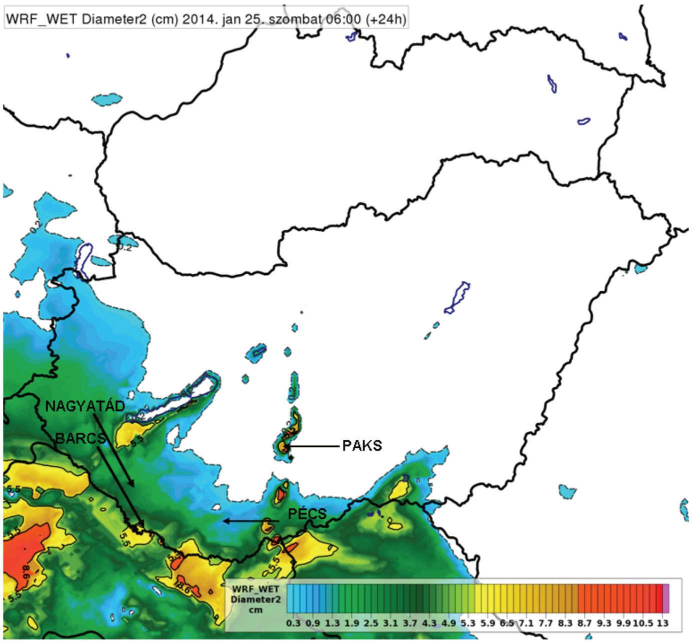

Fig. 16. As in *Fig. 14b* but for the 24 h forecast valid for January 25, 2014, 06:00 UTC. The arrows point toward Nagyatád and Barcs, where wet snow damages were reported and toward meteorological stations Pécs and Paks (mentioned in the text).

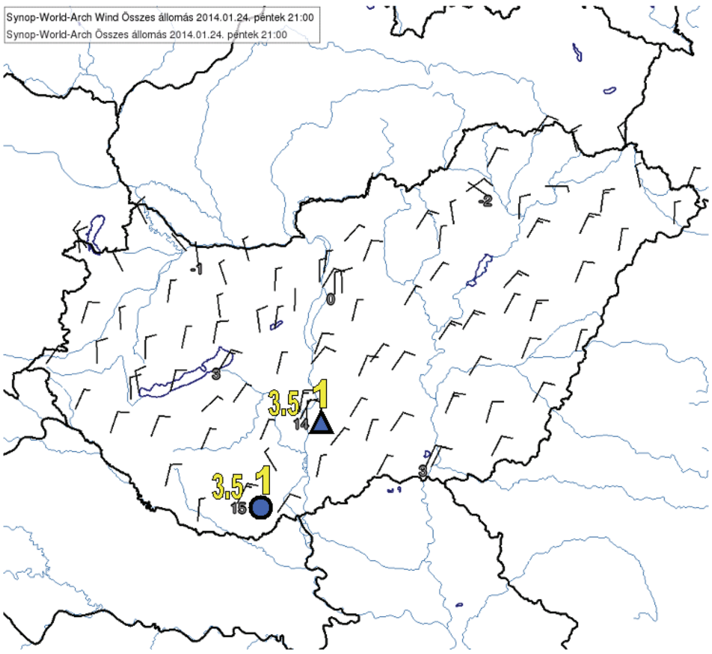

Fig. 17. As in *Fig. 13* except for January 24, 2014, 21:00 UTC. The BSI/WDI indices are valid for 20:40 UTC, the observations of drifting/blowing snow for 21:00 UTC (note that the station Pécs-Pogány reported blowing snow as well but only until 20:20 UTC).

The short-range ECMWF-based BSI forecasts showed maximum values exceeding 4 between Pécs and Paks but 3 hours later, on January 25, 2014, 00:00 UTC (*Fig. 18*). Evaluation of the BSI contributions showed that the temperature and snow-surface state were of at least same importance for snow-drift generation than wind, because the wind- and windgust speed were not as high as in the January 18, 2013 case (*Table 7*).

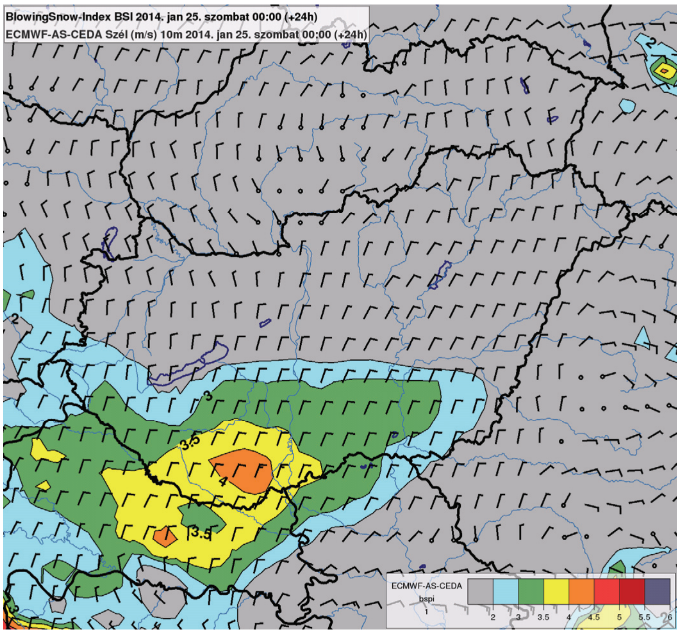

Fig. 18. As in *Fig. 12a* except for the 24-hour ECMWF forecast valid for January 25, 2014, 00:00 UTC.

Table 7. As in Table 4 but for the stations Pécs-Pogány and Paks, derived from the ECMWF 24 h forecast valid for January 25, 2014, 00:00 UTC.

Station	$f(T)$	$f(T_S)$	$f(U)$	$f(G)$	$f(H)$	$f(\rho_H)$	***BSI***	***WDI***
Pécs	0.63	1.0	0.44	0.70	0.5	0.83	4.1	1
Paks	0.56	0.97	0.17	0.38	0.3	0.83	3.2	1

5. Conclusion

The previous examples showed that the wet- and blowing snow occurrence is influenced by several factors (precipitation, wind, temperature) at once. Thus, foreseeing of such events only upon basic model outputs is not easy, and it requires a lot of forecasting experience and continuous study of typical synoptic and mesosynoptic situations favorable for wet- or blowing snow. There could be, for example, cases with one dominant factor (e.g., very strong wind), when significant snowdrifts can develop even in areas, where there is currently no or only very weak snowfall. Or, there are limit cases, where existence of blowing snow is determined by reaching of some sufficient (but not extreme) intensity for all contributing parameters, including skin-surface temperature and snow density (which are generally rarely studied in forecasting practice). Thus, indices like BSI or snow sleeve diameter can help the forecaster to immediately turn attention to areas, where such conditions could appear providing guidance for further analysis of the potential causes of the event. Another advantage of these methods is that they are relatively simple from computational point of view (extraordinary computational time and power are not required) and can be easily applied on outputs of various NWP models.

The deficiency of the above-described diagnostic methods is that they can be interpreted or verified rather in qualitative sense. At Hungarian Meteorological Service, there is no parameter for blowing snow, which would forecast a directly measurable quantity (e.g., the height of the snowdrift), and such parameters are also not measured. Though, the statistically based BSI seems to be somewhat better in specifying the intensity of the event than indices based on arbitrary criterions (WDI). The BSI forecasts were also more consistent with the observed values than the simple WDI index in the evaluated cases. For future, it could be recommended to develop and test a "cumulative" form of BSI as well (e.g., a simple time-integral of this index), which could help to distinguish between short- and long-period blowing snow events, which can eventually cause especially high snowdrifts.

In contrary to blowing snow parameters, the algorithms for calculation of the wet snow mass on wires and diameter of snow accumulation give measurable quantities on outputs (although at the cost of several assumptions and simplifications). However, there are rarely precise reports based on such measurements in Hungary – generally no wet snow accumulation measurements are provided at the meteorological stations, estimates of the significance of wet snow loads can be currently done rather upon damage reports (e.g., from electricity companies) or upon photographs. The verification of the forecasts of wet snow or blowing snow parameters is further complicated by the fact that even observations of some "basic" input parameters (like precipitation type, snow depth, or snow density) are relatively sparse. These could be partially replaced by using interpolations or calculated from outputs of numerical models or nowcasting systems analyses – which is not an optimal solution, but even partial use of observations would still give better estimates of the real intensity of such events as if we would use only NWP model forecasts.

The determination of the type of precipitation and of the fraction of solid precipitation is very important for both blowing- and wet snow forecasting (essential for the latter one). It seems that numerical forecast of snowfall by positive temperature is still difficult, even in LAM models which use parameterization of microphysical processes. Although, we tested only the scheme of Thompson, which is currently operationally used, and which was suggested in other winter precipitation studies (e.g., *Nygaard et al.*, 2011, *Podolskiy et al.*, 2012, *Liu et al.*, 2011). The inaccuracy of some forecast parameters (e.g. temperature) and of the model parameterizations can be one of the reasons, why relatively simple, empirical approaches (e.g., the $RT_{850/1000hPa}$ method) can be still more successful than criterions, based on the direct outputs of the model microphysics or precipitation schemes. Improved parameterization of the type of precipitation and of other characteristics (terminal velocity of snowflakes, collection coefficient, accreted snow density, etc.) is necessary to get quantitatively useful results. The accretion models (e.g., of the one described by Eq. 5) are often tested under laboratory conditions with nearly constant wind or density of the accreted snow. But even in such cases, it is difficult to directly measure some input characteristics, e.g., the collection coefficient. Although it was shown that the evaporation/condensation processes do not have substantial effect on the accreted snow diameter or snow mass (*Admirat*, 2008), it can be expected that (especially for long accretion periods) the changes of the snow density or fall speed of snowflakes can have a non-negligible impact on the forecast wet snow characteristics.

The analyses of the pressure, geopotential, and temperature fields in Section 3 indicate that there are some similarities in the macro- or mesosynoptic situations, in which the wet- or blowing snow appears in Hungary. The most typical feature is a deep cyclone with center over Italy or the Adriatic Sea moving (extending) toward east-northeast; a deep upper-air trough (eventually a cut-off low) surrounded by a jet and situated on the west-southwest flank of the surface cyclone (indicating a strongly meridional type of circulation). The blowing snow can develop in presence of a mesoscale, low-level jet, which was observed in other cases as well, e.g., during the March 14–15, 2013 blowing snow event in western Hungary (*Simon et al.,* 2013). Wet snow often appears at or behind the warm frontal boundaries characterized by large temperature gradients but sometimes also in the neighborhood of stationary occlusions at the rear side of the cyclone. Although the BSI and wet snow parameters were developed in order to make the recognition of wet- and blowing snow conditions easier, we are convinced that the knowledge of typical types of synoptic situations, favorable for such events, is also important for their successful forecasting and should be further studied.

Acknowledgements: The authors are indebted to *Attila Nagy* and *Kornél Locher* (HMS) for their support and for providing the NWP data. We are also grateful to *Jozef Csaplár* (SHMÚ) for additional information and for sending us useful materials. The study has been prepared in the frame of the COST Action ES1002 WIRE and INCA-CE (2CE120P3) CENTRAL EUROPE projects, with the support of the European Regional Development Fund.

References

Admirat, P., 2008: Wet Snow Accretion on Overhead lines. In: Atmospheric Icing of Power Networks. Springer Netherlands, 119-169.

Baggaley, D.G. and *Hanesiak, J.M.*, 2005: An Empirical Blowing Snow Forecast Technique for the Canadian Arctic and the Prairie Provinces. *Weather Forecast. 20*, 51–62.

Bonelli, P., Lacavalla, M., Marcacci, P., Mariani G., and *Stella, G.*, 2011: Wet snow hazard for power lines: a forecast and alert system applied in Italy. *Nat. Hazard. Earth Sys. 11*, 2419–2431.

Cantin, A. and *Bachand, D.*, 1993: Synoptic pattern recognition and partial thickness techniques as a tool for precipitation types forecasting associated with a winter storm. Centre Meteorologique du Quebec Tech. Note 93N-002.

Elíasson, Á.J., Ágústsson, H., and *Hannesson, G.M.*, 2013: Wet-Snow accumulation - A study of two severe events in complex terrain in Iceland. 15th IWAIS conference. St. John's, Newfoundland and Labrador, Canada.

E.O.N. Hungária Zrt., 2014: Összesített üzemzavari adatok 2014.01.24. 15:00 - 2014.01.26. 15:00 (in Hungarian)

Glickman, T.S. (ed.), 2000: Glossary of Meteorology, 2d. ed., American Meteorological Society, Boston.

Gulyás, K., Somfalvi-Tóth, K., and *Kolláth, K.*, 2012: A tapadó hó statisztikus-klimatológiai viszonyai hazánkban. *Légkör 57*, 49–54. (in Hungarian)

Hirsch, T., 2006: Téli magyarországi nagy csapadékos helyzetek vizsgálata és előrejelzése. PhD thesis. ELTE, Budapest. (in Hungarian)

Hong, S.Y., Noh Y., and *Dudhia J.*, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Month. Weather Rev. 134*, 2318–2341.

ISO, 2001: Atmospheric icing of structures. International Standardization Organisation (ISO) International Standard 12494, Geneva, Switzerland.

Kolláth, K., 2013: 2013.02.07. Tapadó hó. Website http://mrstratus.blogspot.hu/2013/02/20130207-tapado-ho.html (in Hungarian).

Li, L. and *Pomeroy, J.W.*, 1997: Probability of occurrence of blowing snow. *J. Geophys. Res. 102*, 21955–21964.

Liu, C., Ikeda, K., Thompson, G., Rasmussen, R., and *Dudhia, J.*, 2011: High-Resolution Simulations of Wintertime Precipitation in the Colorado Headwaters Region: Sensitivity to Physics Parameterizations. *Month. Weather Rev. 139*, 3533–3553.

Makkonen, L., 1989: Estimation of wet snow accretion on structures. *Cold Reg. Sci. Technol. 17*, 83–88.

Makkonen, L. and *Wichura, B.* 2010: Simulating wet snow loads on power line cables by a simple model. *Cold Reg. Sci. Technol. 61*, 73–81.

Nygaard, K., Egil, B., Kristjánsson, J.E., and *Makkonen, L.*, 2011: Prediction of In-Cloud Icing Conditions at Ground Level Using the WRF Model. *J. Appl. Meteorol. Climatol. 50*, 2445–2459.

Nygaard, K., Egil, B., Ágústsson H., and *Somfalvi-Tóth K.,* 2013: Modeling Wet Snow Accretion on Power Lines: Improvements to Previous Methods Using 50 Years of Observations. *J. Appl. Meteorol. Climatol. 52*, 2189–2203.

Persson, A., 2011: User guide to ECMWF forecast products. Meteorological Bulletin M3.2, ECMWF.

Pilis parkerdő, 2013: Hótörés a Pilisben – balesetveszélyes az erdő Website, http://www.parkerdo.hu/index.php?pg=news_1_667. (in Hugarian)

Podolskiy, E.A., Nygaard, B.E.K., Nishimura, K., Makkonen, L., and *Lozowski, E.P.*, 2012: Study of unusual atmospheric icing at Mount Zao, Japan, using the Weather Research and Forecasting model, *J. Geophys. Res.: Atmospheres, 117(D12),* 1984–2012.

Poots, G., 1996: Ice and snow accretion on structures. Research Studies Press Ltd. – Wiley, Taunton, England.

Railpage.net, 2013: Sneh opäť ochromil železničnú dopravu. Website http://www.railpage.-net/modules/news/article.php?storyid=2560. (in Slovak)

Sakamoto, Y., 2000: Snow accretion on overhead wires. *Philos. T. R. Soc. Lon. A 358(1776)*, 2941–2970.

Simon, A., Kolláth, K., Somfalvi-Tóth, K., Dezső, Zs., and *Tordai, J.*, 2013: A 2013-as év veszélyes időjárási jelenségei. Presentation. *39. Meteorológiai Tudományos Napok*, 2013. November 21–22. http://www.met.hu/doc/rendezvenyek/metnapok-2013/21_Simon.pdf. (in Hungarian)

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.-Y., Wang, W., and *Powers, J.G.,* 2008: A description of the Advanced Research WRF version 3. *NCAR Technical Note NCAR/TN-475+STR*.

Somfalvi-Tóth, K., 2014: *Tapadó hó számolása HAWK3-ban.* Technical report, OMSZ. (in Hungarian),

Sundin, E. and *Makkonen, L.*, 1998: Ice Loads on a Lattice Tower Estimated by Weather Station Data. *J. Appl. Meteorol. 37*, 523–529.

Thompson, G., Rasmussen, R.M., and *Manning, K.*, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part-I: Description and sensitivity analysis. *Mont.Weather Rev. 132*, 519–542.

Tordai, J., 2012: A hófúvás előrejelzése Magyarország térségére. MSc thesis, ELTE, Budapest. (In Hungarian)

Tóth, K., Lakatos M., Kolláth K., Fülöp R., and *Simon A.*, 2009: Climatology and forecasting of severe wet-snow icing in Hungary. In: Proceedings of the 13th International Workshop on Atmospheric Icing of Structures, IWAIS 2009 and the Final Workshop of the COST Action 727 "Measuring and Forecasting Atmospheric Icing on Structures". Andermatt, Switzerland, 8–11 September 2009.

WMO, 1995: *WMO* Manual on codes. International Codes VOLUME I. 1 Part A — Alphanumeric Codes. WMO–No. 306.

Yuter, S.E., Kingsmill, D.E., Nance, L.B., and *Löffler-Mang, M.*, 2006: Observations of precipitation size and fall speed characteristics within coexisting rain and wet snow. *J. Appl. Meteorol. Climatol. 45*, 1450–1464.