Relation between atmospheric icing and some meteorological characteristics at high-mountain sites in Slovakia and Bulgaria

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***Abstract* – To study the relationships between the atmospheric icing and some meteorological elements the icing measurements at four meteorological stations – Chopok (2004 m) and Lomnický štít (2634 m) in Slovakia and Murgash (1687 m) and Botev vrah (2376 m) in Bulgaria for the period 1998-2007 were used. Apart from the standard meteorological observations the data set include records for the ice mass (in kg m^{-2}) measured 3 times a day for the Slovak stations and information about the duration and the dimensions of the ice depositions (the last is for one older period) for the Bulgarian stations. Additionally, data from three Czech icing sensors (Icemeter) for the last two years were used.**

The radiuses of the rime depositions, the wind loads and the combined ice- and wind loads on vertical and horizontal metal poles with diameter 5 and 30 mm for all registered icing events (in the Bulgarian stations) were recalculated with a simple icing model and compared with the measured values from the visual observations and the icing sensors (not presented here). Information on the icing frequency, the type of icing and the icing intensity in these regions was achieved.

Keywords: atmospheric icing, occurrence and mass of atmospheric icing, annual course, statistical characteristics

I. Introduction

In addition to the dynamic-climatic effects, the atmospheric icing accretion and its shape are affected above all by the meteorological factors (air temperature, relative humidity, wind direction, wind speed, and others), by the microstructure of clouds (water content, spectrum of droplets), as well as by the properties of the objects (shape, quality of surface and material, its temperature) on which ice is created. Therefore, the further analysis is focused to the study of the relationships between atmospheric icing and principal meteorological characteristics which have crucial importance for the origin and creation of ice but not to the study of the influence of the cloud microstructure parameters and of the properties of objects because it requires wider study and experimentation.

II. Material and Methods

Solution of the investigated problem is based on experiment. The necessary experimental data of icing were obtained at the meteorological observatories Chopok (φ = 48°56′ N, λ = 19°35′ E, h = 2004 m a.s.l.) and Lomnický štít (φ = 49°12′ N, λ = 20°13′ E, h = 2634 m a.s.l.) during the 1998–2007 period. Measurements are curried out on a horizontal pair of orthogonal (N – S and E – W) wooden rods at the standard height of 2 m above ground [1, 5, 6]. Diameter of the rods is 0.032 m with a length of 1 m. After the melting of icing and its measuring we get the value of atmospheric icing in kg m^{-2}. The calculated mean value of both rods is put down into the records. The measurements are performed 3 times a day at 7, 14, and 21 h of the local time.

In additional to the hourly values of meteorological elements: air temperature, relative humidity, wind direction, and wind speed were applied at the investigation of meteorological conditions favourable for icing growth. To each time interval with ice the mean values of these parameters were calculated and added.

The observations in Bulgaria were carried out visual and with two icing sensors.

III. Results and Discussion

A. *Relation between icing and air temperature*

From the physical reasons of icing accretion such as condensation and sublimation of water vapour, deposition of supercooled water droplets in clouds on the subjects and their freezing or the rainfall on strongly undercooled objects it follows, the atmospheric icing is associated with the oversaturation of air mass by water vapour at the negative air temperature.

By processing of 10 year measurements of ice it was shown, that not only at Chopok but also at Lomnický štít the mean air temperature in the time interval with ice accretion was always negative. It is a truth there were also the values above 0 °C in some hours of these intervals (mainly in summer), but it is apparently connected with the manner of determining of the length of icing creation. On the other side, it was found, although at Chopok much rarer, the ice creation occurred at the air temperature around -20 °C during the time internal. Also from that reason follows that at Chopok the mean air temperature under icing is substantially higher than at Lomnický štít.

This value calculated for Chopok is -6.5 °C, while at Lomnický štít -7.9 °C in the investigated period.

Older data from european mountains showed for example, the mean air temperature under atmospheric icing was: at Kasprový vrch -7.0 °C in 1947-1953 period [4], at Milešovka -3.7 °C in winter (XII-II) 1955-1959 [9], at Snežka -6.6 °C in 1920-1932 period [8], at Brocken -4.1°C, at Zugspitze -8.0 °C and at Sonnblick -8.2 °C in 1920-1937 [2]. Based on these results it can be deduced that thermal conditions under icing creation are changed with altitude. The mean air temperature under ice decreases from the lower localities to the higher ones in annual sense.

The thermal conditions under icing change also during the year. It is certainly connected with the annual run of air temperature in generally. The annual pattern in Fig. 1 also confirms this fact. According to expectation, and as it can be seen from the course of the curves in Fig. 1, the annual

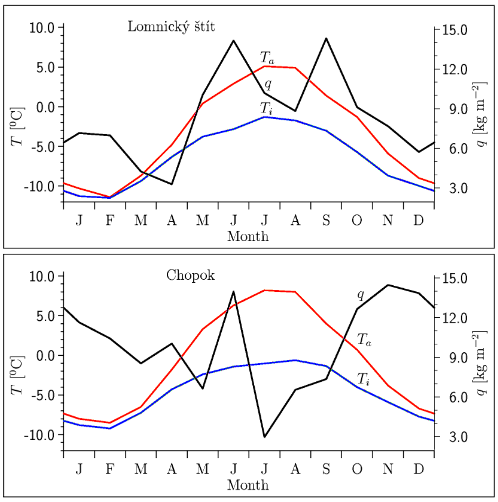

Figure 1. Annual course of the air temperature in generally (T_a) and under atmospheric icing (T_i), as well as mean icing masses (q) at Lomnický štít and Chopok during the 1998-2007 period.

course of air temperature under the ice (T_i) has similar tendency as the general annual course of air temperature (T_a), regardless of icing. At the same time the annual amplitude under icing is considerably smaller than the corresponding amplitude of air temperature in generally. The annual air temperature amplitude at Lomnický štít is higher than at Chopok. This fact documents in our mountainous regions the annual amplitudes of air temperature under icing increases with altitude. It follows it has an opposite tendency with height as the change of annual amplitude of the air temperature regardless of ice.

Monthly differences between total air temperature and air temperature under icing are the smallest in winter months and the highest in summer moths in both localities. Similar as in annual average, also in individual months of year the mean air temperature under icing at Lomnický štít is lower than at Chopok. The smallest differences between both localities are in warm part of the year from May to October and the highest in winter months.

Regarding the annual course of daily icing masses it can be seen in Fig. 1, the 10 year measurements are not suitable for the general conclusions. However, on the basis of previous results of 51 year measurements it was showed [6, 7] that these courses are opposite to each other in both sites. At Chopok, the mean daily ice masses are the highest in winter months when there are the lower values of air temperature under ice in the annual course, while at Lomnický štít the highest daily ice masses are in summer months with the higher negative values of air temperature.

Mean air temperature under various icing masses shows (Table 1) with increasing air temperature the atmospheric icing yield increases.

Table 1. Mean values of meteorological parameters under various atmospheric icing yields at Lomnický štít and Chopok during the 1998-2007 period various

	Lomnický štít					
Ice mass [kg m^{-2}]	≥0	≥10	≥20	≥30	≥50	≥100
Number of cases	1195	252	111	64	20	3
Air temperature [°C]	-7.9	-7.3	-5.8	-5.8	-5.9	-5.6
Air humidity [%]	93.1	93.4	94.5	93.8	94.3	93.3
Wind speed [m s^{-1}]	9.2	11.4	12.6	13.3	14.7	16.0
	Chopok					
Number of cases	1591	559	281	155	50	5
Air temperature [°C]	-6.5	-5.8	-4.9	-4.4	-3.6	-1.6
Air humidity [%]	93.4	94.5	95.5	96.0	96.1	99.0
Wind speed [m s^{-1}]	9.2	10.7	11.7	11.8	13.0	19.1

Table 2. Number of cases of rime-icing for two periods – 1 – 2006-2009; 2 – 1981-1990

Peak Botev vrah											
	VIII	IX	X	XI	XII	I	II	III	IV	V	VI
1	0.3	2	3	7	5.7	8.7	7.3	8	4.7	2	
2	0.1	0.5	3.5	6.5	8.5	8.5	8.3	6.6	6.5	2.4	0.7
Peak Murgash											
1			1.7	6	4.7	6.3	5.3	6.7	1.7		
2			2.4	4.8	6.9	7.6	8.1	5.4	3.3	0.7	

B. Relation between icing and relative air humidity

As ice accretion assumes a certain saturation of air mass by water vapour there are some relationships between the characteristics of humidity and ice creation. The most easily manner how to study this dependence is according to relative air humidity. The relative humidity is the most used measure of air humidity in atmosphere.

Usually, the works on atmospheric icing are less focused to the relationship between humidity and ice, because the ice regularly occurs under the fog, i.e. at the relative humidity equal or near 100%. It is assumes that between the relative air humidity and ice exists a simple relationship. However, more detail analysis of this relationship at Chopok and Lomnický štít shows, that this relationship is not simple, because in both localities the icing occurs under the relative humidity considerably lower than 100%.

Growing of ice is a complicated process of sublimation and freezing of supercool droplets of water. Therefore, when considering the relationship between ice and the relative humidity should be kept in mind the differences in saturation pressure over the ice and over the supercool water [3]. All three phases of water are in stable thermodynamic equilibrium, only at air temperature of 0

°C. The process of ice growing performs at the label thermodynamic equilibrium state of three phases of water in the air. At the equal values of wind speed, the intensity and shape of atmospheric ice depend on the state saturation (saturation over ice and water amount in gaseous and liquid phase) [3]. In considering of the relationship between relative air humidity and ice in our case should be taken into account that the values of humidity were measured by the hair hygrograph with reference to water (also at negative temperatures).

Obtained results showed that the mean relative humidity at Chopok and Lomnický štít is 93.4 and 93.1% but the relative air humidity less than 80% is not richness. The higher relative air humidity at Chopok than at Lomnický štít is apparently caused especially by the thermal differences under icing between both sites.

The annual course of relative humidity under icing and the course in general are illustrated in Fig. 2. A comparison indicates the annual courses are very similar in both localities characterized by relatively small amplitude.

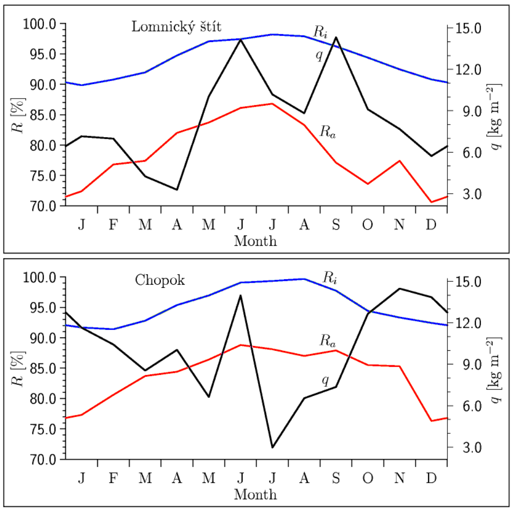

Figure 2. Annual course of the relative air humidity in generally (R_a) and under atmospheric icing (R_i), as well as mean icing masses (q) at Lomnický štít and Chopok during the 1998-2007 period.

A little maximum is in August and minimum in the period from December to March. During the whole year the relative air humidity is higher at Chopok than at Lomnický štít, excepting May. These differences are small and the smallest are in October. From the Fig. 2 is also apparent that during the whole year the average values of relative air humidity under icing (R_i) are substantially higher than the value of relative humidity in general (R_a), regardless of icing.

Distribution of icing occurrence according to its abundance and its relative humidity shows (Table. 1) the same tendency like in case of air temperature. With rising relative humidity the icing yield increases, especially at Chopok. For example, the mean icing masses ≥10 kg m^{-2} were observed at the mean relative humidity ≥86% and a very heavy daily icing ≥30 kg m^{-2} at the relative humidity ≥90%, and so on. It also confirms that the thermal conditions under ice accretion influence the humidity conditions under icing.

In both sites the ice occurrence is the most frequent at the high relative air humidity near 100%. Nearly ½ (~48.5%) cases were at the mean relative humidity ≥94.1%. On the other side, the lower relative humidity under the atmospheric icing ≤84% occurred also, more frequent at Lomnický štít than at Chopok.

C. Wind speed under icing

In addition to thermodynamic conditions the air flow plays an important role at the icing accretion, especially its speed. At the same time, the wind is applied at the ice creation as a circulation factor at the advection of cold and moist air masses, or the wind shares at the ice mass as the meteorological factor on which in a crucial measure depends an intensity of ice growing. In the case given we can consider the relationship between the wind and icing amount, similar as in case of temperature and humidity, on the basis of daily values of icing and the hourly anemograph records of wind.

In both locations the mean annual wind speed under icing is higher than the total annual average speed. At Chopok this difference represents 1.7 m s^{-1}and at Lomnický štít 2.2 m s^{-1}. That demonstrates that ice in our mountain regions occurs under the intensive advection of air masses favourable for ice growth. Similar during the year the mean monthly wind speed under icing is higher than in general. At Chopok the highest differences are in summer months and lowest in the autumn months. Similarly, it is at Lomnický štít, where the wind speed differences in the processing 10-year period are the highest from June to October and the smallest in the rest part of the year. Thus also the annual course of the wind speed under icing is different from the annual course of total wind speed (Fig. 3). The course of the curves in Fig. 3 indicates that at

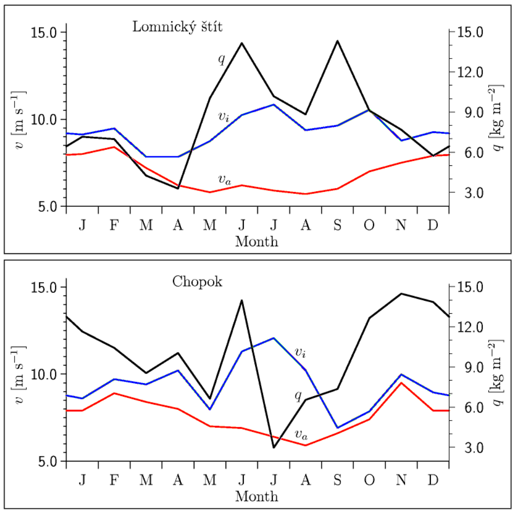

Figure 3. Annual course of the wind speed in generally (v_a) and under atmospheric icing (v_i), as well as mean icing masses (q) at Lomnický štít and Chopok during the 1998-2007 period.

both localities the annual course of the wind speed is not so simple. Unequal annual course of the wind speed under icing is caused by the short processing period and by the small number of cases of icing in the summer. In spite of that the course of the curves it can be seen that at Lomnický štít the mean monthly wind speed under icing (v_i) and corresponding mean daily ice yield (q) have the certain measure analogical seasonal course what is apparently the results of the near relationship between wind speed and ice creation. However, annual course of these characteristics at Chopok suggests that intensity of ice creation is dependent except wind on the other meteorological conditions. This reality is also confirmed by the differences between wind speed under ice (v_i) and daily ice yield (q) between both localities during the year.

From the study of relations between ice mass and meteorological elements it was shown, the graphical relation to the daily ice abundance is more expressive only in case of wind speed. This fact also confirms the results introduced in Table 1. Increasing wind speed is characterized by the rising daily ice masses.

D. Wind direction under icing

High-mountain massifs of High and Low Tatras have a great part on wild field deformation. The mentioned massifs represent a topographical barrier, especially for the northern components of general atmospheric circulation. It also demonstrates the percentage distribution of the surface wind directions in Fig. 4. According to the data in Fig. 4,

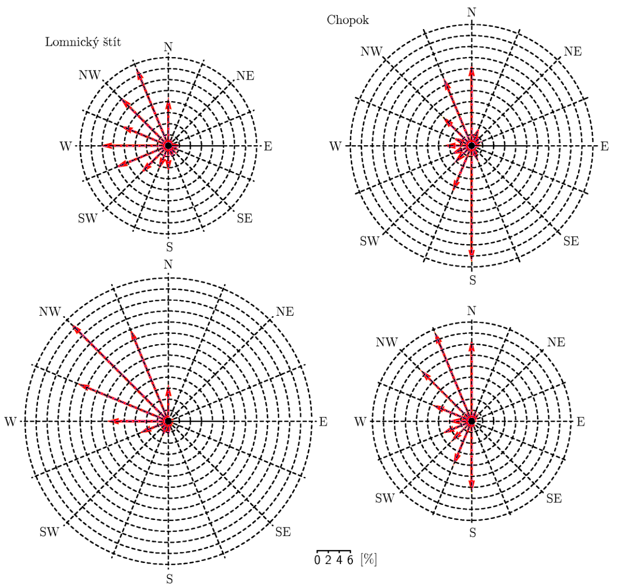

Figure 4. Roses of prevailing wind directions in generally (up) and under atmospheric icing (down) at Lomnický štít (left) and Chopok (right) during the 1998-2007 period.

it can be seen that Lomnický štít is characterized by prevailing north-western air flow components (mainly NNW, NW, and W). On the opposite, the winds with eastern components are at least probably. At Chopok the most frequent winds are with the south and north components (especially S, N and NNW), while the winds with eastern components are again at least probably. This discovery is much more manifested at the ice creation in both sites. It can be seen in Fig. 4 (down) the most frequent occurrence of ice is under the air flow from north-western in both localities and at Chopok in addition at winds with south component (S and SSW). It apparently follows from the complex terrain of this locality.

Wind speed in various wind directions is clearly illustrated in Fig. 5. An analysis of mean speed of wind directions according to wind roses gives a more detailed picture of a dissimilar intensity of flow of individual wind directions in various wind directions. Based on the vector sizes we can take measure the qualitative and partly quantitative dynamic conditions of general air circulation as well as wind speed changes due to by the mountain barrier. From the values of vectors, it can be seen which directions how participate on the whole wind roses in the slope position at Lomnický štít as well as at Chopok. For example, it can be seen that the most numerous wind directions at Lomnický štít (NNW and NW) have also the greatest wind speeds. Similar situation is at Chopok, but here it can be seen that the greatest wind speeds are along the N-S axis. Besides the minimum mean wind speed is at Lomnický štít during the winds with the south-eastern wind components (from E to SW) while at Chopok the minimum wind speed falls to the directions with the western wind components (from WNW up WSW) as well as with the east wind components (from ENE up to SE).

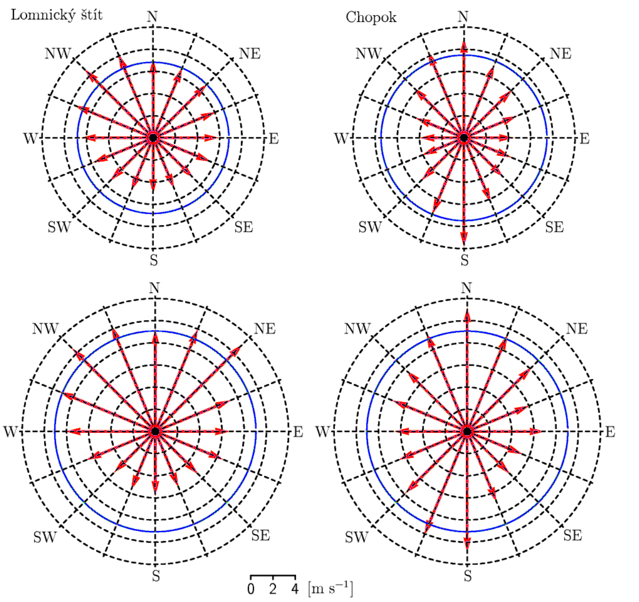

Figure 5. Roses of mean speed of wind directions in generally (up) and under atmospheric icing (down) at Lomnický štít (left) and Chopok (right) during the 1998-2007 period. Mean values of wind speed of the investigated period are depicted by blue circle.

Regarding the wind speed in various wind directions under the icing creation (Fig. 5) the situation is a little different from that one which was presented in Fig. 4. It can be seen that the prevailing winds which are not so frequent in the investigated sites are characterized by the mean wind speed under ice around 6 m s^{-1} while the mean wind speed is 9.06 m s^{-1} and 9.17 m s^{-1} at Lomnický štít and Chopok, eventually. However, the most frequent winds and characteristic with the greatest wind speed have the wind speed under icing equal or over the average. Such winds are at Lomnický štít winds with north-western components (from N up to WNW). It is interesting that ENE and NE winds can be accounted to this group. At Chopok, only 5 wind directions have the mean wind speed equal or over calculated average. They are: NNE, N, ENE, as well as S and SSW.

IV. Estimation of the deposited rime-ice mass

More than 30 cases of icing events for the winter season 2008/09 were registered at peak Murgash with an automated icing sensor. One of them is presented on the figure below as example.

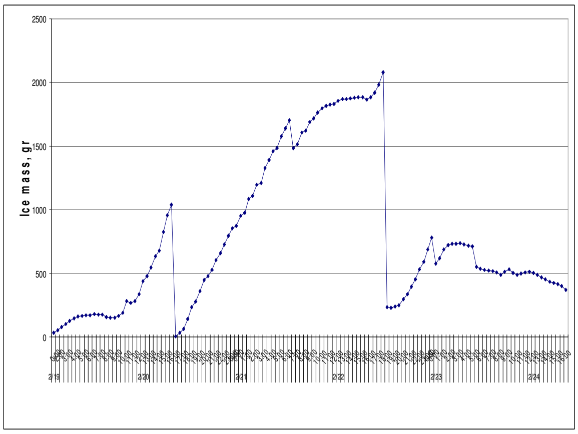

Figure 6 Recorded icing event form 19.02 till 24.02.2009, peak Murgash

The meteorological conditions during this case were: mean air temperature – 9,0 ^{o}C, mean wind velocity – 7,6 m/s with north component, mean horizontal visibility – 50 m.
The results in Table 3 are achieved with a simple rime-icing model.

Table 3 Modeling values of the deposited rime-ice with different return periods

Return period	**2**	**5**	**10**	**20**	**50**
Botev vrah	21	28	35	43	57
Murgash	11	15	18	24	32

V. CONCLUSIONS

Analysis of relationships between atmospheric icing and meteorological parameters (air temperature, relative humidity, wind direction, wind speed) showed the ice mass depends, except these elements, also on parameters like water amount in liquid and solid phase water in air mass. Therefore, the obtained results concerning of the dependence of ice mass on meteorological factors have not character of functional dependence but character of statistical (stochastic) dependence.

VI. ACKNOWLEDGMENT

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