Atmospheric icing at the high-mountain sites in the Low and High Tatras

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***Abstract*–To study the seasonal variability of atmospheric icing at high-mountain conditions in Slovakia, the icing measurements at the mountain localities 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 1957-2007 period are used. Measurements are performed on a horizontal pair of orthogonal (N-S and E-W) wooden rods located at standard height of 2 m. The diameter of the rods is 32 mm and length is 1 m. Data are acquired 3 times a day at 7, 14, 21 hrs.**

By processing the extensive experimental material many statistical characteristics of the number of icing days, as well as the atmospheric icing masses in the Low and High Tatra Mountains were obtained. For example, it was shown that at Chopok, there are more suitable meteorological conditions for the atmospheric icing accretion than at Lomnický štít, and that the annual amplitude of the number of icing days is twice as much at Chopok than at Lomnický štít. The monthly and annual values of the number of icing days vary depending on the air masses which occurred in our territory. Cold and moist air masses are the reason for the more frequent icing accretion, whereas the warmer, and in the winter season, freezing and dry air masses, respectively, have a consequence that the atmospheric icing does not create.

Keywords: atmospheric icing, mass of atmospheric icing: annual course, occurrence of ice, number of icing days

I. Introduction

Atmospheric icing in the higher mountain positions represents an important contribution to its precipitation regime. For example Rink writes [17], the amount of melted water from atmospheric icing at Snežka was 5.25 times higher than the precipitation total which was measured during the period from 2 November 1936 up to 18 June 1937. Another results from Lomnický štít [15] showed, the annual amount of atmospheric icing during the 1941-1944, 1947-1962 period represented 59% precipitation measured by normal rain-gauge. According to our results, the atmospheric icing amount at Lomnický štít represents 61% and at Chopok, 177% from the precipitation in the long time period 1957-2007. Hence, the ice yield is considerable at the high-mountain positions and ought to be also accounted at the calculation of the total water budget of the specific locality. Therefore, the study of the meteorological conditions during the ice accretion has an adequate importance in the problems of the mountain meteorology.

II. Material and Methods

Measurements of the atmospheric icing are systematically carried out at the high-mountain observatories of the Low and High Tatras [7], [9] since 1957. Measurements are performed on a horizontal pair of orthogonal (N – S and E – W) wooden rods at the standard height of 2 m above ground [2]. Diameter of the rods is 0.032 m with a length of 1 m. It follows that the whole cylindrical surface of one rod is 1000 cm^2, i.e. 0.1 m^2. After the melting of icing and its measurement in a cup of normal rain-gauge with the receiving-area of 500 cm^2, the number of millimetres precipitation, which specifies the measuring cup, ought to be multiplied by factor 0.5, to get the value of atmospheric icing in $kg \cdot m^{-2}$. The calculated average value of the both rods is put down into the records. The measurements are carried out 3 times a day at 7, 14, and 21 h of the local time.

Some theoretical works are focused to the modeling of the atmospheric icing creation [5], [6], but our solution of the investigated problem is based on experiment. The necessary experimental data 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 1957–2007 period.

Methods of mathematical statistics [1], [3], [8] were applied in the calculated characteristics of daily, monthly, and annual sums of atmospheric icing.

III. Results and Discussion

By processing of the extensive material of the atmospheric icing measurements at Chopok and Lomnický štít many statistical characteristics were obtained and published [10], [11], and [13].

A. *Annual Masses of Icing*

Mean annual masses of atmospheric icing at Chopok (1924.7 $kg \cdot m^{-2}$) and at Lomnický štít (906.5 $kg \cdot m^{-2}$) confirm that at the Chopok meteorological and other conditions are essentially more suitable for icing creation than at Lomnický štít, in general. The mean annual sum of atmospheric icing at Lomnický štít represents only 47% of

the total amounts at Chopok in the studied period. This difference is partly due to by the higher total windiness at Chopok, where the annual mean of wind speed is 8.0 m $\cdot s^{-1}$ [14], while at Lomnický štít it is only 3.3 m$\cdot s^{-1}$ [12]. The remaining part of the different masses of icing can be mainly assigned to the different thermo-hydrometric conditions. The quantitative ratio of the particular meteorological factors on the higher icing total at Chopok cannot be strictly estimated according to present results of icing measurements.

In individual years the annual masses of atmospheric icing varied in large ranges. For example, at Chopok the annual total of icing achieved the highest values 4347.1 kg m^{-2} in 1966 what represents 227% from long-term average. Minimal annual mass occurred in 1986 with the value of 1154.6 kg m^{-2} what represents about 60% of the mean annual total. In the same period maximal value of icing at Lomnický štít was recorded in 1971 1389.6 kg m^{-2} what represents 154% of the arithmetic average. On the other side, at Lomnický štít the minimal annual mass was measured in the same year as at Chopok (1963), 414.3 kg m^{-2} what is 46% of the long-term annual average. It follows, that the absolute and relative size of annual masses of atmospheric icing is considerably higher at Chopok than at Lomnický štít. Based on this fact we can deduce that in mountain regions of central Europe the absolute and relative amplitude of the annual totals of atmospheric icing are the highest in the localities where the most abundant icing is created.

Although upon a score of results at Chopok and at Lomnický štít we cannot specify the dependence of icing on altitude in the mountains of central Europe, nevertheless these results as well as the results published in literature allow at least a rough estimate of the tendency of this dependence. At the same time it is also necessary to take into attention the local topographical effects to ice creation. The annual total of atmospheric icing increases relatively quickly up to a certain altitude and after that a slow decline occurs. According to the obtained results we can state, that Chopok is in the layer or on the rank of this layer in which the maximal annual masses of atmospheric icing create.

B. Monthly Masses of Icing

In Figure 1 the annual course of atmospheric icing masses is illustrated. At Chopok, it is characterized by the expressive winter maximum and summer minimum. Obtained results showed that this tendency of the annual course of icing at Chopok is well-preserved also in individual years. Minimum occurs in the summer months and maximum in any month from November to March.

According to the total tendency, the mean annual course of icing masses at Lomnický štít is similar to the one at Chopok, e.g. it is characterized by simple course with the winter maximum and summer minimum. However, this course at Lomnický štít is less expressive and in individual years can be quite different. The maximal monthly masses of icing can occur at any month of the year. Obtained results showed that the minimal values of atmospheric icing can also appear at any month, even if the highest probability for that is in the period from March to August. The ratio of the mean monthly sums of icing in December and August is 56.1 p.u. at Chopok while at Lomnický štít the corresponding portion is only 2.1 p.u. in the investigated period.

Using the measured data, only in the warm part of the year – from June to September, the mean monthly masses of icing are smaller at Chopok than at Lomnický štít. In the remaining part of the year, the masses are higher at Chopok. At the same time, the highest differences of mean monthly masses of icing between both localities are in the months which are the most abundant on icing from November to February.

Similar dependence of icing on altitude as in annual mean sense is also in tendency of annual course, however it is more regular. In accordance with air temperature conditions the atmospheric icing does not occur at all in months of the warm part of the year. From a certain level, where the negative temperatures occur during the invasions of the cold air mass, the atmospheric icing occurs also in the summer months, and with the rising altitude the icing mass increases, even if, as it was mentioned the annual total of icing decreases from a certain altitude. In accordance with changes of annual and monthly sums of atmospheric icing in summer months with altitude the mean portion between winter maximum and summer minimum also decreases. In consequence of this tendency of annual course of icing at Chopok and Lomnický štít we can expect that the more expressive annual course will be in the layer with the highest annual total of icing. However, this hypothesis can not be accurately confirmed based on these results.

On the basis of the annual course of the mean monthly masses of icing at Chopok and at Lomnický štít we can also characterize dependence of relative portion of monthly masses upon the annual total with altitude in Western Carpathians in zone above 2000 m a.s.l. (Fig. 2). In this

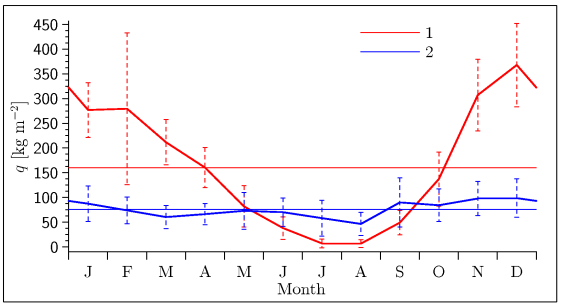

Fig. 1. Annual course of mean monthly masses of icing at Chopok (1) and Lomnický štít (2) during the 1957-2007 period. Error bars represents variance and indicate variability within the month.

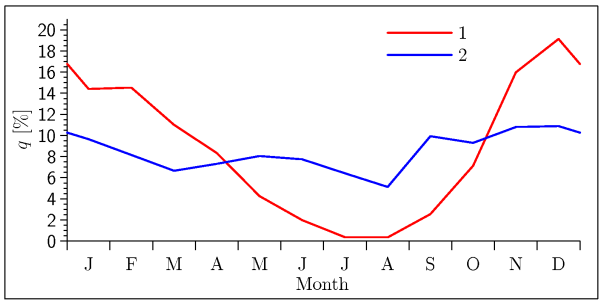

Fig. 2. Relative portion [%] of the mean monthly masses of atmospheric icing on annual total of icing at Chopok (1) and Lomnický štít (2) during the 1957-2007 period.

high-mountain region the relative portion of monthly masses of icing on its annual total increases with altitude in the warm part of the year from May to October, and on the contrary, decreases with altitude in the cold part of the year from November to April. This rule is evidently also executed with a certain shifting of the time limits for the lower mountain localities of the Western Carpathians. According to the circulation and thermo-hydrometric conditions in the central Europe it can be assumed this dependence validity in general statement for the all Alps and Carpathians regions, as well as for the other massifs of the central Europe. At the same time, the length of the warm and cold part of the year depends mainly on the altitude and latitude.

Large differences in monthly masses of icing during the individual years are caused by the variability of circulation conditions and by the air masses exchange in central Europe.

C. *Dependence of Icing on Weather Types*

To evaluate of the general circulation conditions during the atmospheric icing creation the Konček-Rein classification [4], [16] was applied.

From the course of the curves in Fig. 3, the general tendency of the annual cycle of icing at Chopok under

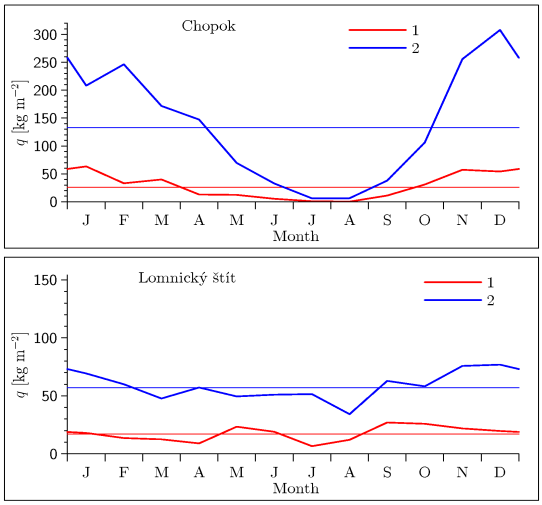

Fig. 3. Annual course of the mean monthly masses of icing under the anti-cyclonic (1) and the cyclonic weather situations (2) at Chopok and Lomnický štít during the 1957-2007 period.

cyclonic and anti-cyclonic weather types is similar as in case of all types, although the annual course under the anti-cyclonic situations is essentially less expressive than at the cyclonic ones. A comparison with the Fig. 1 indicates the annual course of the mean monthly mass of icing at Chopok is mainly due to by annual course under the cyclonic weather types. At Lomnický štít the annual course under the anti-cyclonic and cyclonic situations is not expressive. Such annual courses of the icing mass due to a little expressive general annual course of the icing (regardless of weather types Fig. 1). From the Fig. 3 is evident that the corresponding annual course of icing under the anti-cyclonic and cyclonic weather types is essentially different at Chopok and Lomnický štít, above all under the cyclonic types. This difference between both localities can be explained especially by the different thermal conditions during the year.

D. *Number of Icing Days*

Number of icing days belongs to the fundamental icing characteristics, similar look like the other climate elements and phenomena of the weather.

The analysis of the number of days with atmospheric icing at Chopok and Lomnický štít shows that there are 165.2, eventually 121.3 icing days in a year, in annual mean sense.

A comparison of icing occurrence in individual years shows the number of icing days at Chopok is higher than at Lomnický štít in every year. The monthly and annual values of the number of days with atmospheric icing vary with dependence on the air masses which occurred in our territory. Cold and moist air masses are the cause of a more frequent icing accretion whereas the warmer and in the winter season freezing and dry air masses respectively have a consequence, that the atmospheric icing situation does not exist. The most frequent occurrence of atmospheric icing was at Chopok in 1974 (196 days) and at Lomnický štít in the year 1985 (152 days). It was calculated that the maximal occurrence at Chopok represents 119% and at Lomnický štít 125% of the annual average. On the other side, the rarest occurrence was in 1996 (125 days) at Chopok and in 1968 (85 days) at Lomnický štít which represents about 76% and 70% of the long-term average, respectively.

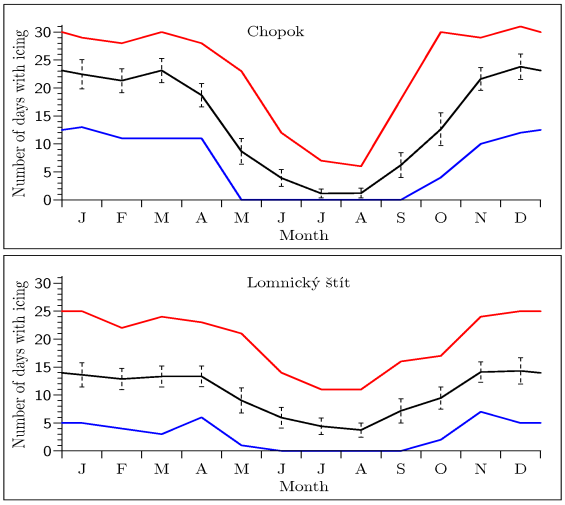

Fig. 4. Annual cycles of the mean, maximal, and minimal number of icing days at Chopok and Lomnický štít during the 1957-2007 period. Error bars represents variance and indicate variability within the month.

E. *Annual Course of Number of Icing Days*

The annual course of the number of days with atmospheric icing is illustrated in Fig. 4. From this picture and its comparison with the Fig. 1 it can be seen, that similar as in case of the icing mass, the number of icing days at Chopok has a very expressive annual course with summer minimum in July and August (about 4% of all days) and expressive winter maximum. Similar situation is also in individual years of the investigated period when the maximum of number icing days falls on any winter month and minimum on some summer month. The highest number of icing days (31 days) was recorded in December 1993 (100%). On the other side, the absolute and relative

minimum of icing days (0 days) was in total 65 days from May to September.

At Lomnický štít, the annual course of the number of icing days has similar character as at Chopok with a winter maximum and summer minimum but the annual amplitude is approximately half that at Chopok. It was shown that only in three summer months the number of icing days is higher at Lomnický štít that at Chopok. A comparison of the courses in Fig. 4 with the corresponding courses of the mean monthly masses of atmospheric icing (Fig. 1) shows the annual course of the number of icing days is substantially more regular and more expressive than the annual course of the mean monthly masses of icing. Similar differences can be also noticed in individual years, namely in the sense, that, unlike the ice mass, the maximal number of icing days occurs in a some month of the cold part of the year from November to April and the minimum usually is in any month from May to October. According to our processing the highest number of days with atmospheric icing was 25 days in January 1976 and December 1988. On the other side, the smallest number of the icing days (0 days) was recorded 13 times, in the period from June to September.

F. Number of Icing Days under Various Weather Types

From the comparison of Fig. 5 and Fig. 3, it follows that the annual course of the number of icing days under anti-cyclonic and cyclonic weather types has in both localities en bloc more regular course than the annual course of the mean monthly icing mass during the mentioned types. At the same time, the tendency of the annual course of the number of icing days and the course of the mean monthly icing masses at Chopok are in general identical, while at Lomnický štít considerably different, especially under the cyclonic weather types.

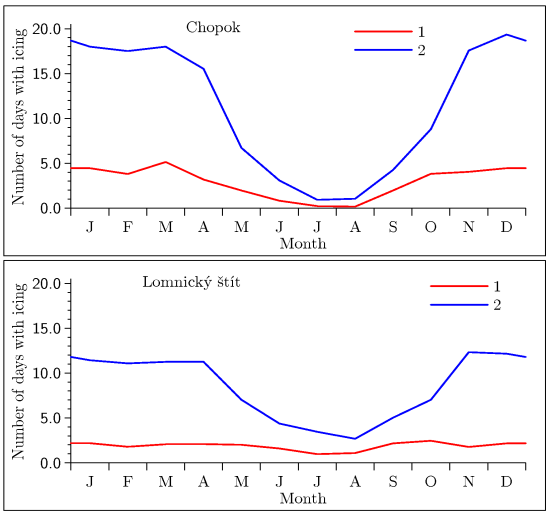

Fig. 5. Annual course of the mean number of icing days under the anti-cyclonic (1) and the cyclonic weather situations (2) at Chopok and Lomnický štít during the 1957-2007 period.

In both localities the number of icing days under anti-cyclonic types is smaller than under cyclonic situations in all months. The differences between number of icing days under anti- and cyclonic situations are the highest in winter months and on the contrary, the smallest in summer months. The higher number of icing days at Lomnický štít than at Chopok is under anti-cyclonic but also cyclonic situations in months May-September.

The previous analysis of seasonal changes of the number of icing days under the various weather types shows that the general annual course of the number of icing days (regardless of weather types) is determined mainly by the annual course of the number of icing days under the cyclonic situations at both localities. It is especially in the winter half-year.

A comparison of the probability of icing occurrence under various weather types leads to the conclusion, that in our mountain regions the probability of icing occurrence is considerably higher under cyclonic weather types than the anti-cyclonic ones. This fact is mainly connected with the more suitable hygro- and hydro-thermal conditions for icing creation under cyclonic weather types. A comparison of the number of icing days under various weather types between Chopok and Lomnický štít shows that it is similar as in case of icing masses and the frequency of icing occurrence in the mountain localities is also dependent not only on altitude but also on the total topography and orientation terrain in the face of air masses movement.

G. Annual Course of Daily Icing Masses

A comparison of the annual course of the mean monthly masses of icing (Fig. 1) and the annual course of the number of icing days (Fig. 5) has already showed that both compared high-mountain sites have a very different annual course of the mean daily yield of icing. This fact also confirms the running of curves in Fig. 6 where is a comparison of the annual courses of the mean daily masses under the days with icing occurrence and under all days (regardless of ice occurrence).

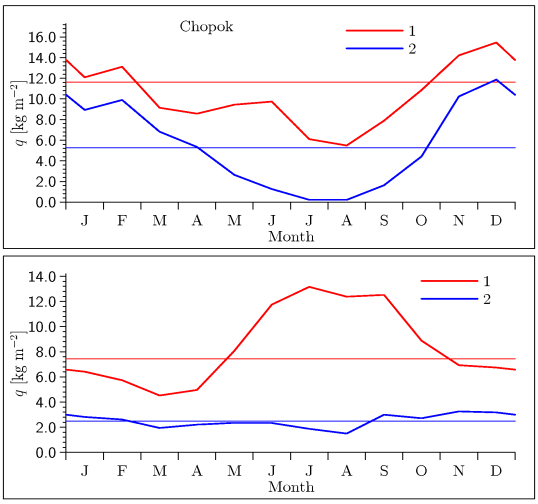

Fig. 6. Annual course of the mean daily masses of icing under the days with icing (1) and under all days in month (2) at Chopok and Lomnický štít during the 1957-2007 period.

At Chopok, annual course of the mean daily masses of icing under the icing days is similar to the annual course of the mean monthly masses of icing although it is in the main a little less expressive and regular. Typical is a split winter maximum with a relative decrease in January (12.3 kg m^{-2}) and an expressive summer minimum in August (5.5 kg m^{-2}). Hence, the mean daily mass of icing in December is approximately 2-3 times higher than the mass in August. This value corresponding to the ratio of the daily icing

masses under all days in mentioned months is naturally higher.

Considerably different thermo-dynamic conditions for ice creation at Lomnický štít are manifested also in the different annual course of the mean daily masses. Therefore the annual course of the mean daily ice masses under the icing days at Lomnický štít is very different from the annual course of the mean monthly icing masses. A comparison with Chopok shows the courses of the mean daily icing masses (Fig. 6) have each other a rough reverse of annual course. The highest mean daily amounts of atmospheric icing during the days with ice are in the months of the warm part of year from June to September with maximum in July (13.2 kg m^{-2}). The other months from October to May have considerably smaller mean daily values of atmospheric icing with minimum in March (4.5 kg m^{-2}).

More detail analysis of icing occurrence according to daily mass showed that the scattering of the values at Chopok is the highest in winter months and the smallest in summer months. In winter the atmospheric icing is not only a frequent event but also the days with the severe icing are very often. Absolute daily maximum of icing was recorded on 17 February 1966, 402.0 kg m^{-2} under the SWc_1 type. Daily masses higher than 100 kg m^{-2} are not rare. In the study period this level of icing masses occurred in 52 days, which means, that the occurrence of the masses higher than 100 kg m^{-2} is once a year mainly from December to May.

Distribution of the number of icing days according to the daily yield during the year at Lomnický štít is essentially different in comparison with Chopok. Maximal daily mass was measured 228.6 kg m^{-2} on 8 September 1996 at the invasion of cold maritime air mass under NEc type. Besides this, similar daily mass of icing higher than 100 kg m^{-2} occurred another 10 times. It follows that the daily masses of icing higher than 100 kg m^{-2} are relatively rare event at Lomnický štít with the mean probability of occurrence approximately once every 5 years.

In both localities the most frequent occurrence of icing days is with the yield of 0.02-5.0 kg m^{-2}, what represents about 21% of the days in a year.

IV. Conclusions

Analysis of long time series of icing measurements at the high-mountain observatories Chopok and Lomnický štít enabled us to obtain new knowledge of the seasonal variability of icing, regularities of its occurrence, and its intensity on the tops of the Low and High Tatra Mountains of the Western Carpathians.

Obtained results showed the conditions for icing creation at both localities are considerably different. The mean annual mass of icing at Lomnický štít represents only 47% of the corresponding mass at Chopok. The monthly and annual values of the number of icing days vary in dependence on the air masses which occurred in our territory. These differences are mainly due to the distinct altitude of both sites, as well as by the different topographical conditions. The vertical difference of 630 m causes first of all essentially different thermal conditions for icing creation under the various weather situations, if the remaining conditions are satisfied for its creation.

V. Acknowledgment

The author is grateful to Grant Agency APVV project APVV - SK-BUL 00306, to the Slovak Grant Agency VEGA (grant No. 2/0036/08) for the partial support of this study and to the Slovak Hydrometeorological Institute in Bratislava for offering data.

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