Variability of the air temperature and atmospheric precipitation in the high-mountain positions of the Low and High Tatras in winter

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Abstract: On the basis of the fifty three-year time series of air temperature and precipitation in three levels of the atmospheric layer the seasonal variability of air temperature and precipitation in the Low and High Tatras regions are studied. Measurements of the air temperature and precipitation at the meteorological observatories Lomnický štít, Skalnaté Pleso and Chopok during the 1955–2007 period were used to analyse the time series in winter season, and compared with the corresponding results from the normal period 1961–1990. By processing of the extensive experimental material many statistical characteristics of the precipitation in the Low and High Tatra Mts were obtained.

Key words: air temperature, amount and occurrence of precipitation, statistical characteristics, methods of mathematical statistics

1. Introduction

Recently a great attention has been paid to the problem of the long-term variability of the air temperature and the atmospheric precipitation, because temperature and precipitation belong to the responsive indicators of climatic changes. Extreme fluctuations in air temperature, precipitation, but also other meteorological elements in various parts of the world have aroused an increased interest of experts and wide public (*Hrvoľ, 2006; Lapin, 1993; Závodská and Závodský, 1991*). This interest is paid not only to the extreme fluctuations in weather, but also to the factors that cause these fluctuations, such as solar activity, volcanic activity, anthropogenic factors and many others, in the earth-atmosphere-ocean system. Air temperature and precipitation appear to be the most sensitive indicators of climatic variations. Seasonal and annual fluctuations in air temperature and precipitation are in direct relationship to the fluctuations in the general atmospheric circulation that might be brought about by various factors.

Precipitation regime in Slovakia has been significantly changed in the 20$^{\mathrm{th}}$ century. It was probably due to the changes in the atmospheric circulation regime above Central Europe. Possible changes in the air pressure fields above Europe and the North Atlantic in the 21$^{\mathrm{st}}$ century can essentially influence the position and variability of the polar frontal zone as well as the general circulation patterns (*Hrvoľ et al., 2001; Lapin et al., 2003; Niedźwiedź, 2000*). This is a factor which determines many characteristics of the climatic system, including precipitation.

The different altitude, as well as the distinguished topographical conditions at the meteorological observatories Lomnický štít ($\varphi = 49°12'$N, $\lambda = 20°13'$E, h = 2634 m a.s.l.), Skalnaté Pleso ($\varphi = 49°12'$N, $\lambda = 20°14'$E, h = 1778 m a.s.l.), and Chopok ($\varphi = 48°56'$N, $\lambda = 19°35'$E, h = 2004 m a.s.l.) enable to study the variability of air temperature and precipitation in different altitudes of the Low and High Tatras in winter season. From the climatic point of view the sites are situated in the Central Europe where the influence of the Atlantic Ocean declines, whereas the effects of the Baltic Sea and of the Mediterranean prevail and the continental character of the climate manifests itself.

2. Material and methods

Solution of the investigated problem is based on experiment. Mean monthly values of air temperature and precipitation at Lomnický štít, Skalnaté Pleso, and Chopok during the 1955–2007 period were used for the study of the investigated problem, in winter season. Measurements are carried out 3 times a day at 7, 14, and 21 h. Obtained results were compared with the results of the normal period 1961–1990.

The methods of mathematical statistics (*Anděl, 1985; Brooks and Carruthers, 1953; Conrad and Pollak, 1962; Kendall and Stuart, 1968; Nosek, 1972*) were applied for the evaluation of described experimental data with focus on time series analysis.

It is very difficult to study trends and other statistical characteristics of extreme meteorological and climatological elements such as precipitation totals. This is caused, in particular, by their very high temporal and spatial variability (*Faško et al., 2006*). The study is focused to the analysis of air temperature and atmospheric precipitation ($R \geq 0.1$ mm) in the high-mountain positions of the Western Carpathian Mountains.

3. Results and discussion

By processing the extensive experimental data, many statistical characteristics of the air temperature and precipitation at Lomnický štít, Skalnaté Pleso, and Chopok were obtained. Some of them have already been evaluated and published in numerous works (*Chomicz and Šamaj, 1974; Lapin et al., 2003; Ostrožlík, 2006*).

The additional statistical characteristics are presented in the tables and figures to follow. For example, Table 1 contains some characteristics of air temperature at Lomnický štít, Skalnaté Pleso, and Chopok, such as: average, median, extreme values, standard deviation, coefficient of variation, etc., over winter period. From data in this Table it can be seen that the mean winter air temperature varies from $-10.5\,^\circ$C at Lomnický štít, $-8.2\,^\circ$C at Chopok, up to $-5.0\,^\circ$C at Skalnaté Pleso. It follows that the mean air temperature in winter season decreases with altitude. In individual years the extreme values of mean winter air temperature exhibited variations of about $7\,^\circ$C. The standard deviation is highest at Skalnaté Pleso ($1.603\,^\circ$C) and represents about 32% of the long-term average. Further characteristics of this element are introduced in Table 1.

To estimate the trend of the air temperature (T) with time (t) (variable t denotes the corresponding year in the time series) the method of regression analysis (*Anděl, 1985*) was applied to the deviations. In the first approximation a simple linear model and a quadratic model were applied and by the method of the least squares the regression coefficients were calculated.

Based on our calculations, we can analytically express the mean winter values of air temperature [°C] at Lomnický štít, Skalnaté Pleso, and Chopok in the form

Table 1. Statistical characteristics of air temperature (T) in °C at Lomnický štít, Skalnaté Pleso, and Chopok during the 1955–2007 period and winter season

Variable	Air temperature in °C		
	Lomnický štít	Skalnaté Pleso	Chopok
Sample size	53	53	53
Average	–10.5	–5.0	–8.2
Median	–10.4	–4.9	–8.3
Mode	–10.3	–4.6	–8.4
Geometric mean	–10.4	–4.8	–8.1
Variance	2.165	2.569	2.068
Standard deviation	1.471	1.603	1.438
Standard error	0.202	0.220	0.198
Minimum	–14.3	–9.3	–12.2
Maximum	–7.4	–1.6	–4.9
Range	6.9	7.7	7.3
Lower quartile	–11.5	–6.1	–9.2
Upper quartile	–9.4	–3.9	–7.2
Interquartile range	2.1	2.2	2.0
Skewness	–0.222	–0.309	–0.298
Kurtosis	0.167	0.376	0.613
Coeff. of variation	14.1	31.781	17.478
Sum	–556.5	265.0	–434.6

$T = 0.02492\,t - 49.36191,$ Lomnický štít
$T = 0.03516\,t - 69.65031,$ Skalnaté Pleso
$T = 0.02377\,t - 47.08922.$ Chopok

Correct to the second order, this trend can be written as:

$T = 0.00002\,t^2 - 0.04576\,t + 20.63839,$ Lomnický štít
$T = 0.00012\,t^2 - 0.42771\,t + 388.79351,$ Skalnaté Pleso
$T = -0.00044\,t^2 + 1.74746\,t - 1754.09503.$ Chopok

The course of deviations of the mean air temperature values from the long-term average, the linear trend, as well as polynomial trend of second order are presented in Fig. 1. More detailed analysis shows that the deviations of air temperature from the long-term average do not lie on the curves but are scattered. Despite of this fact from the course of the curves, it is evident

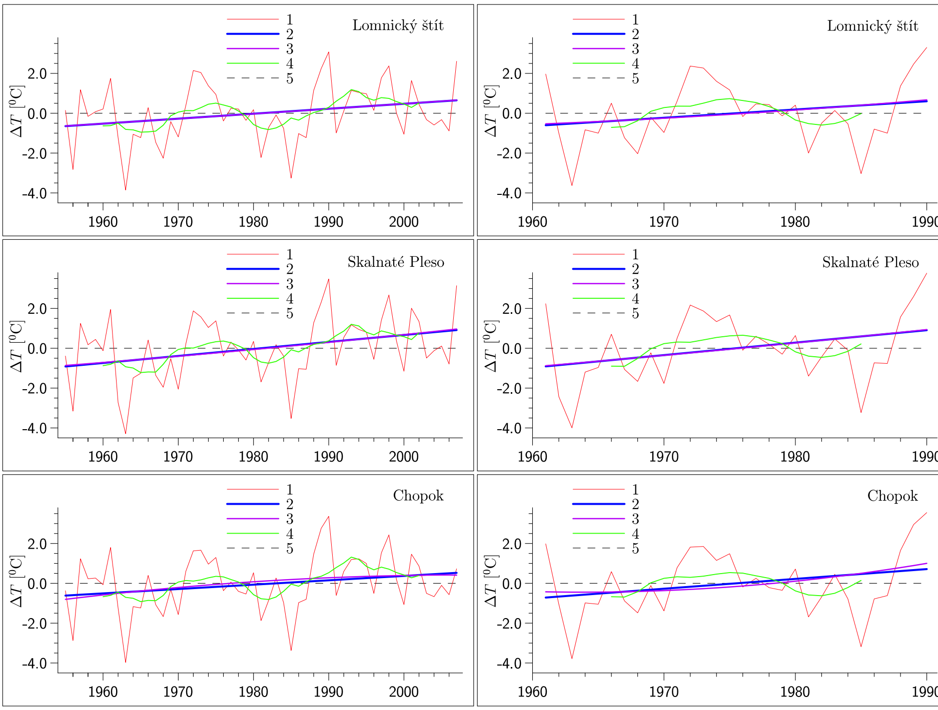

Fig. 1. Course of deviations of air temperature from the long-term average (1), the linear trend component of these deviations (2), the quadratic trend (3), and course of deviations from the long-term average smoothed by eleven-year running averages (4) at Lomnický štít, Skalnaté Pleso and at Chopok during the 1955–2007 period (left) and the normal period 1961–1990 (right). Value of 0 °C refers to the long-term average (5). Winter season.

that the winter air temperature has a weak increasing linear trend in all positions. In all compared positions, the extreme values occurred in the same years: minimum in 1963 and maximum in 1990.

The general trend, the increase of air temperature in the last years, is also confirmed by the other results, which are published by *Bilčík and Janičkovičová (1996), Bochníček (2002), Brázdil and Štepánek (1998), Nieplová et al. (2000), Štekl (1991), Janičkovičová and Bilčík (1996), Kalvová and Brázdil (1993)*. These authors pay attention not only to studying the air temperature trend but also to the analysis of statistical tests of homogeneity.

To find the secular air temperature variations in the investigated period, the course of air temperature anomalies was smoothed by eleven-year running averages (Fig. 1). Wave character of the curves for running averages indicates some characteristic periods of decreasing (1st period – at the beginning of the investigated period till the beginning seventies and the 2nd in the 1980) and growing (in 1970 and 1990) air temperature. Similar situation arises in case of the normal period – the growth of air temperature in 1970.

Mean monthly values of experimental and theoretical courses of air temperature at Lomnický štít, Skalnaté Pleso and Chopok are graphically presented in Fig. 2. Harmonic analysis was used in these calculations (*Brooks*

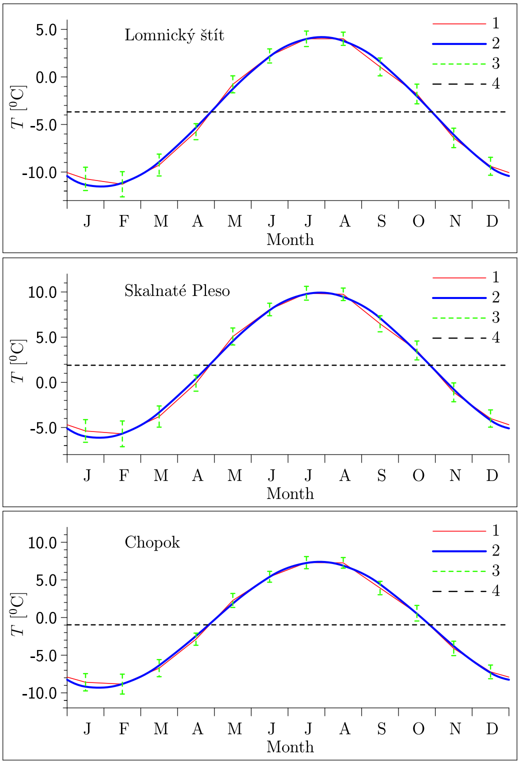

Fig. 2. Annual course of the deviations (1) of air temperature [°C] and its first harmonic component (2) from the annual mean at Lomnický štít, Skalnaté Pleso, and Chopok during the 1955–2007 period. Value of 0 °C refers to the long-term average (3). Error bars represent variance and indicate variability within the month (4).

and Carruthers, 1953; Conrad and Pollak, 1962). Course of the curves shows the existence of a simple annual cycle of air temperature. One maximum is in July and minimum in January – February. Winter months are the coldest of all. Standard deviations indicate some annual course characterized by maximum in the winter months and minimum in the summer months. The greater variability of air temperature in winter depends mainly on the atmospheric circulation and cycles of Sun activity (*Bednarz et al., 1994*).

Using experimental data periodic annual course of air temperature at Lomnický štít, Skalnaté Pleso and Chopok can be expressed by the first harmonic component in the form

$$T = -3.67767 + 7.84096 \sin(x + 257^\circ\, 54'), \qquad \text{Lomnický štít}$$
$$T = 1.88836 + 8.01856 \sin(x + 259^\circ\, 24'), \qquad \text{Skalnaté Pleso}$$
$$T = -0.96698 + 8.34533 \sin(x + 259^\circ\, 47'). \qquad \text{Chopok}$$

where x is a time angle. It is computed from $x = iz$, $z = 360^\circ/P$, $i = 0, 1, 2.....P - 1$, if P denotes the length of the period investigated. For example, in our case $P = 12$ months and $z = 360^\circ/12 = 30^\circ$.

Table 2 shows the characteristics of the amount and occurrence of precipitation at Lomnický štít, Skalnaté Pleso, and Chopok: average, median, extreme values, standard deviation, coefficient of variation, etc. in annual sense. In winter season, the long-term mean of precipitation is 360.6 mm at Lomnický štít, 233.9 mm at Chopok, and 202.4 mm at Skalnaté Pleso. Based on these results, we can state that the winter precipitation in the high-mountain positions of Slovakia is abundant and increases with altitude. Similarly, the amplitude of extreme values has an increasing tendency with altitude. Extreme winter precipitation totals were in 1978 (minimum) and 2007 (maximum), except Chopok (1997, 1966, respectively). These extreme values also confirmed that the precipitation is a very variable meteorological element, changing in wide ranges. The values of the standard deviation take of 33.7% (Chopok) to 39.1% (Lomnický štít) of the long-term average.

Regarding the homogeneity, the time series of precipitation at Lomnický štít showed that there were expressive marks of in-homogeneity around the early 1960s and above all at the beginning of 1990s. It is an interesting feature but apparently not of natural origin (*Faško et al., 2006; Štepánek, 2005*).

Table 2. Statistical characteristics of amounts of precipitation (R) in mm and number of days with precipitation (n) in winter season at Lomnický štít, Skalnaté Pleso, and Chopok during the 1955–2007 period

Variable	Atmospheric precipitation					
	Total in mm	Number of days	Total in mm	Number of days	Total in mm	Number of days
	Lomnický štít		Skalnaté Pleso		Chopok	
Sample size	53	53	53	53	53	53
Average	360.6	54.6	202.4	50.7	233.9	51.8
Median	325.8	56.0	192.3	52.0	220.3	52.0
Mode	256.3	58.8	172.1	54.6	193.2	52.5
Geometric mean	335.5	53.8	187.4	49.7	220.6	51.0
Variance	19888.720	79.094	5871.640	90.876	6197.397	76.371
Standard deviation	141.027	8.893	76.627	9.533	78.724	8.739
Standard error	19.372	1.222	10.525	1.309	10.814	1.2
Minimum	130.6	33.0	74.9	29.0	92.6	31.0
Maximum	757.0	70.0	366.0	68.0	395.1	69.0
Range	626.4	37.0	291.1	39.0	302.5	38.0
Lower quartile	253.5	50.0	146.5	45.0	179.8	46.0
Upper quartile	454.1	61.0	260.9	58.0	279.5	59.0
Interquartile range	200.6	11.0	114.4	13.0	99.7	13.0
Skewness	0.873	–0.606	0.302	–0.352	0.468	–0.264
Kurtosis	0.376	–0.312	–0.654	–0.397	–0.280	–0.500
Coeff. of variation	39.113	16.293	37.861	18.810	33.663	16.879
Sum	19111.8	2894	10727.2	2687	12396.7	2745

The course of deviations of the winter precipitation values from the long-term average, the linear trend, polynomial trend of second order, as well as the course of the secular precipitation variations are presented in Fig. 3 and compared with the curves of corresponding cycles of the normal period.

Based on our calculations, we can analytically express the mean winter values of precipitation [mm] at Lomnický štít, Skalnaté Pleso, and Chopok in the form

$$R = 0.65071\,t - 1289.05461, \qquad \text{Lomnický štít}$$
$$R = 0.11445\,t - 226.71779, \qquad \text{Skalnaté Pleso}$$
$$R = -0.46748\,t + 926.07983. \qquad \text{Chopok}$$

Correct to the second order, this trend can be written as:

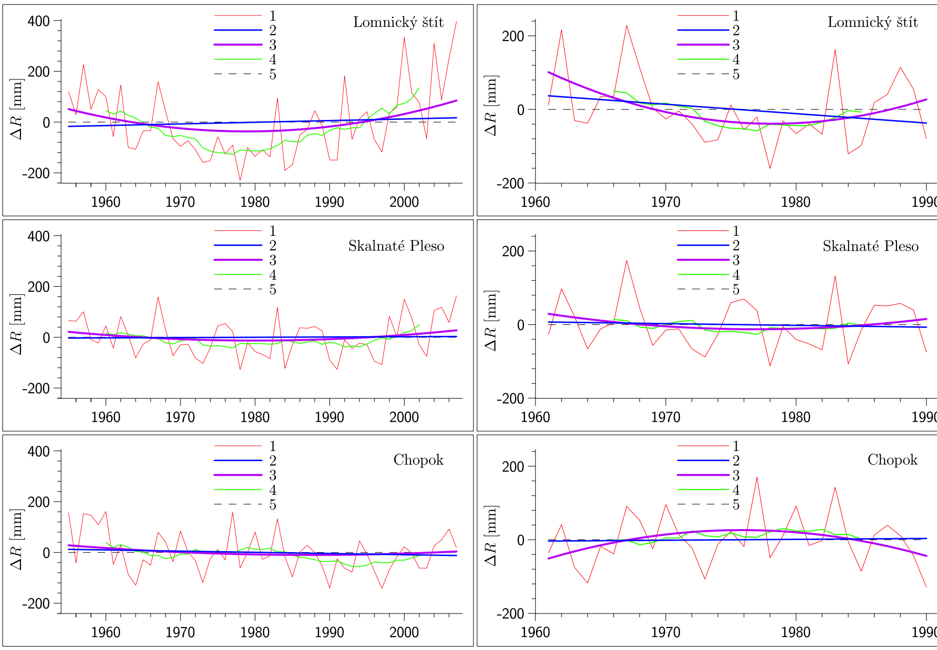

Fig. 3. Course of deviations of precipitation from the long-term average (1), the linear trend component of these deviations (2), the quadratic trend (3), and course of deviations from the long-term average smoothed by eleven-year running averages (4) at Lomnický štít, Skalnaté Pleso, and Chopok during the 1955–2007 period (left) and the normal period 1961–1990 (right). Value of 0 mm refers to the long-term average (5). Winter season.

$R = 0.15382\,t^2 - 608.78581\,t + 602321.81866,$ Lomnický štít
$R = 0.05515\,t^2 - 218.38225\,t + 216181.35391,$ Skalnaté Pleso
$R = 0.03609\,t^2 - 143.43770\,t + 142529.63783.$ Chopok

From the course of the curves (Fig. 3) it is evident that the winter precipitation has a weak increasing linear trend at Lomnický štít, and Skalnaté Pleso, while at Chopok a decreasing one. A very interesting is the sample of precipitation at Lomnický štít. As mentioned before the time series of atmospheric precipitation is characterized by in-homogeneity in this site, in annual sense.

The course of the curves in Fig. 4 indicates that at both localities the annual course of the precipitation is not monotonic. There are two maxima

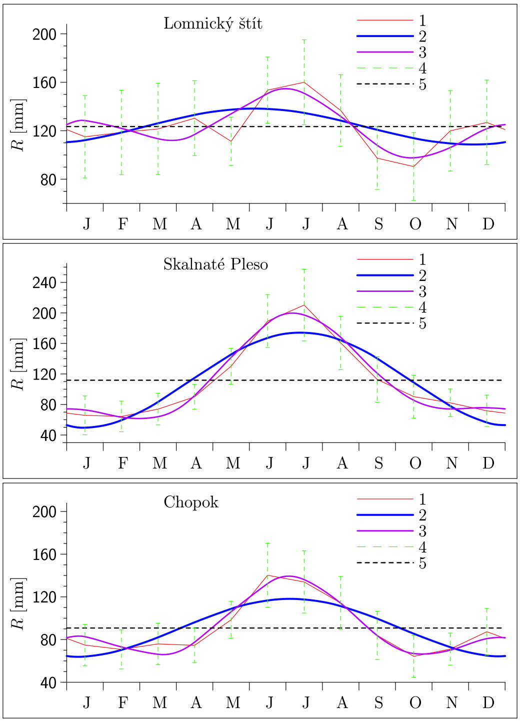

Fig. 4. Annual course of mean monthly sums of precipitation (1), its first (2) and the first two (3) harmonic components, error bars (4) that represent variance and indicate variability within the month, and (5) refers to the long-term average at Lomnický štít, Skalnaté Pleso, and Chopok during the 1955–2007 period.

during the year – the main maximum in summer and a weak subsidiary maximum in winter. However, in individual years the course can be quite disturbed. The maximum monthly amount of precipitation may occur at any month of the year. Up to now the highest monthly amount was measured at Skalnaté Pleso 490.2 mm in July 2001, at Lomnický štít 429.4 mm in March 2000, and at Chopok 390.1 mm in June 1960. Likewise, the minimum monthly amount of precipitation can fall to any month within a year although the highest probability is from September to March. It was shown that the driest month was October 1951 at Lomnický štít and Skalnaté Pleso with the amounts 0.6 mm and 1.8 mm, respectively, whereas January 1964 at Chopok with the amount of 3.4 mm.

Analytical expression of the first harmonic component can be written as

$R = 123.45629 + 14.77619 \sin(x + 310°32')$, Lomnický štít
$R = 111.77405 + 62.29489 \sin(x + 272°48')$, Skalnaté Pleso
$R = 90.81116 + 27.24742 \sin(x + 281°15')$. Chopok

Analytical expression of the first two harmonic components can be written in the form

$R = 123.45629 + 14.77619 \sin(x + 310°32') + 17.06230 \sin(x + 108°27')$, Lomnický štít
$R = 111.77405 + 62.29489 \sin(x + 272°48') + 24.87001 \sin(x + 110°58')$, Skalnaté Pleso
$R = 90.81116 + 27.24742 \sin(x + 281°15') + 20.07433 \sin(x + 112°08')$. Chopok

Comparing the curves in Fig. 4 – measured and calculated – we can see that in case of the annual course of precipitation the fitted curves of the first two harmonic components give a better agreement between the observed and calculated values than in case of its first harmonic component.

In Fig. 5, the trend of number of days with precipitation is illustrated for all investigated positions. Generally, there are great fluctuations of the winter values from the long-term average. Nevertheless, it can be seen that the tendency has a very week increasing trend. According to our processing, an increase of the number of the days with precipitation from the beginning of the investigation period is from 0.4 day at Skalnaté Pleso to 2.2 day at Lomnický štít.

An analytical expression for the precipitation (n) as a function of the number of days with at Lomnický štít, Skalnaté Pleso, and Chopok can be written in the form

$n = 0.04150\, t - 82.21661$, Lomnický štít
$n = 0.00677\, t - 13.41464$, Skalnaté Pleso
$n = 0.02938\, t - 58.19575$. Chopok

Correct to the second order, this trend can be written as:

$n = 0.00265\, t^2 - 10.46411\, t + 10322.96927$, Lomnický štít
$n = 0.0189\, t^2 - 7.48335\, t + 7405.10523$, Skalnaté Pleso

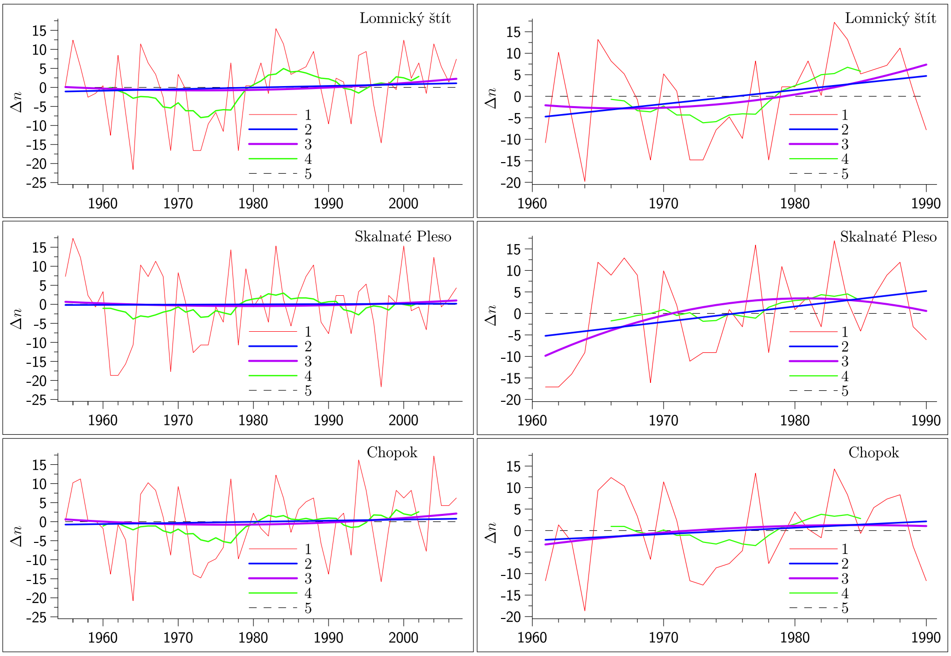

Fig. 5. Course of deviations of number of precipitation days from the long-term average (1), the linear trend component of these deviations (2), the quadratic trend (3), and course of deviations from the long-term average smoothed by eleven-year running averages (4) at Lomnický štít, Skalnaté Pleso, and Chopok during the 1955–2007 (left) and the normal period 1961–1990 (right). Value 0 refers to the long-term average (5). Winter season.

$$n = 0.00310\,t^2 - 12.24946\,t + 12103.26268. \qquad \text{Chopok}$$

On the other hand, the analysis of the number of days with precipitation shows that precipitation in the high-mountain positions is also frequent, more than 50 days in winter. The monthly and annual values of the number of days with precipitation vary in dependence on the air masses occurring in our territory.

4. Conclusions

Regional climatic variations may differ from global changes in certain time intervals. Hence, it is necessary to study the variations of climate during the same intervals in various geographical areas and to judge their relationship to global variations (*Bloutsos et al., 1990*).

- *Air temperature in the High and Low Tatras in winter season*: Processing of the extensive experimental data confirmed a decrease of temperature with altitude. Extreme values vary in wide ranges with an average of about 7 °C. Regression analysis indicated an increasing tendency at all sites.
- *Amount of precipitation in the High and Low Tatras in winter season*: Processing of the extensive data showed that the amount of precipitation increases with altitude. Extreme values also confirmed that the precipitation is a very variable meteorological element. Absolute and relative amplitudes are the highest at Lomnický štít. Regression analysis showed a weak, insignificant increasing tendency at Lomnický štít and Skalnaté Pleso, while at Chopok a decreasing one.
- *Number of precipitation days in the High and Low Tatras in winter season*: Processing of the extensive data showed that the occurrence of precipitation days is a little more than 50 days, roughly speaking 58% of all days. Regression analysis showed that the precipitation days have a weak increasing trend at all sites. Extreme values vary in the ranges of 37–38 days.

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References

Anděl J., 1985: Mathematical Statistics. SNTL/ALFA, Praha, 346 p. (in Czech).

Bednarz Z., Niedźwiedź T., Obrebska-Starkel B., Olecki Z., Trepinska J., 1994: Natural and anthropogenic fluctuations and trends of climate change in southern Poland. Geographia Polonica, 62, 7–22.

Bilčík D., Janičkovičová Ľ., 1996: Analysis of long-term air temperature changes at Mlyňany. Zeszyty naukowe Uniwersytetu Jagiellonskiego. Práce geograficzne. Cracow, **102**, 341–346.

Bloutsos A. A., Sahsamanoglou H. S., Brázdil R., 1990: Long-term temperature fluctuations in Greece and Czechoslovakia. In: Climatic Change in the Historical and the Instrumental Periods. Brno. Masaryk University, 252–256.

Bochníček O., 2002: Homogenization of the climate time series in the SHMÚ conditions. In: Bulletin SMS pri SAV, Bratislava, 3 s. (in Slovak).

Brázdil R., Štepánek P., 1998: Air temperature fluctuation in Brno during the 1891-1995 period. Geografie – Sborník České geografické společnosti. Praha, **103**, 13–30 (in Czech).

Brooks C. E. P., Carruthers N., 1953: Handbook of Statistical Methods in Meteorology. Majesty's Stationery Office, London, 412 p.

Conrad V., Pollak L. W., 1962: Methods in Climatology. Harvard University Press: Cambridge, Mass., 459 p.

Faško P., Gaál L., Lapin M., Mikulová K., Pecho J., Šťastný P., 2006: The Contribution to the regional Rainfall Distribution for Slovakia. Proceedings from Sixth European Conference on Applied Climatology (ECAC), Ljubljana – Slovinsko, 3–8 September 2006, CD ROM, ISSN: 1812-7053, 7 p.

Hrvoľ J., 2006: Extreme air temperatures in Bratislava, Mlynská dolina for the period 1983-2005. Proceedings of conference abstracts of International Bioclimatological Conference "Bioclimatology and Water in the Land". Slovak Bioclimatological Society at Slovak Academy of Sciences, Strečno, September 11-14, 2006, ISBN 80-89186-12-2, 111 p.

Chomicz K., Šamaj F., 1974: Precipitation conditions. In: Climate of Tatra (Ed. M. Konček), Vydavateľstvo Slovenskej akadémie vied, Bratislava, 855 p. (in Slovak).

Janičkovičová Ľ., Bilčík D., 1996: Long-term changes of daily extremes of air temperature at Mlyňany. In: Bioklimatológia a zmeny klímy. I. Technická bioklimatológia. Nitra, Bratislava, 38–43 (in Slovak).

Kalvová J., Brázdil R., 1993: Global climate change. In: Rizika změny klimatu a strategie jejich snížení. Praha, NKP ČR, **10**, 48–91 (in Czech).

Kendal M. G., Stuart A., 1967: The Advanced Theory of Statistics. Interference and Relationship. Charles Griffin and Co. Ltd., London, **2**, 690 p.

Lapin M., Faško P., Zeman V., 1993: Impacts of air temperature and precipitation variations on the changes of the other climatic elements in the mind of actual scenarios of climatic change till the year 2035 in Slovakia. In: Národný klimatický program SR. Bratislava, SHMÚ, 23 p. (in Slovak).

Lapin M., Damborská I., Gaál L., Melo M., 2003: Possible precipitation regime change in Slovakia due to air pressure and circulation changes in the Euro-Atlantic area until 2100. Contrib. Geophys. Geod., **33**, 3, 161–189.

Nieplová E., Šťastný P., Lapin M., 2000: Air temperature regime in Bratislava. In: Bulletin SMS pri SAV. Bratislava, **11**, 33–37 (in Slovak).

Nosek M., 1972: Methods in Climatology. Academia, Praha, 433 p. (in Czech).

Ostrožlík M., 2006: Some characteristics of precipitation at Skalnaté Pleso. In: Proceedings from Conference on Water Observation and Information Systems for Decision Support – BALWOIS 2008. Ohrid – Macedonia, 27-31 May 2008, CD-ROM, 7 p.

Štekl J., 1991: Temperature series at the observatory Milešovka (Donnersberg). In: Mountainous meteorology, climatology and aerology of the lower layers of troposphere (ed. I. Panenka). Bratislava, 23–29.

Štěpánek P., 2005: AnClim – software for time series analysis. Department of Geography, Faculty of Natural Sciences, Masaryk University, Brno.

Závodská E., Závodský D., 1991: Remarks to the greenhouse effect in the atmosphere. In: Bioklimatológia v praxi. Bratislava, SBkS pri SAV, 148–156 (in Slovak).