# METHODS OF SNOW COVER CHANGE SCENARIOS DESIGN FOR SLOVAKIA IN 1951-2100

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***Snowfall and snow cover have several routine characteristics, such as new snow cover depth or daily fresh snow accumulation, total snow cover depth, number of days with snowfall, number of days with snow cover with depth one cm and more (5 cm, 10 cm, 25 cm, 50 cm and more), the first and the last day with snowfall or snow cover etc. These characteristics can be calculated (observed) in winter season (Dec. 1 to Feb. 28/29, Nov. 1 to March 31, July 1 to June 30 etc.). On the other hand the snowfall and the snow cover data or climatic characteristics are frequently used in the practice or requested by user from several sectors. Recently it was found significant decrease in snow cover characteristics in the majority of Slovakia, but except the altitudes above 1200 m a.s.l. Reduction of snow cover is especially noteworthy below 800 m a.s.l. By the reason of expected significant increase of air temperature as well as precipitation totals in winter season during the next decades, we prepared methods to estimate possible scenarios of snow cover development change in Slovakia up to the end of the 21st century. The first method is based on the modified GCMs and RCMs outputs and the second one on the regression (analogue) estimation. According to the comprehensive comparison of measured and modeled data it was found that air temperature and precipitation daily data by GCMs (CGCM3.1 and ECHAM5) and RCMs (KNMI and MPI) are the most reliable for such analysis. Mean daily temperature below +2°C resulted at precipitation as predominantly solid phase and above +2°C as predominantly liquid phase. Comparison of measured monthly snow cover data with air temperature and precipitation in the period 1951-2010 enabled to prepare simple method for monthly snow cover characteristics scenarios design in 2011-2100 period. It was found that there are serious differences among altitudes below 500 m a.s.l., 500 to 1000 m a.s.l. and above 1000 m a.s.l. Very important for the snow cover persistence is the occurrence of mild weather spells during winter (with temperature above +5°C) as well as high liquid precipitation totals. We analyzed such episodes in the modified GCMs and RCMs outputs data in 1951-2100 and compared them with measured ones in 1951-2017. Another possibility of temperature change scenarios and snow cover conditions analysis is the evaluation of technical (artificial) snow producing at the ski resorts. It seems that the suitable temperature (from 0°C to -10°C) occurrence will decline significantly mainly in altitudes below 1000 m a.s.l.***

***Keywords:** snow cover changes, climate change scenarios, snow change scenarios, snowmelt, technical snow*

## INTRODUCTION

Snowfall and snow cover have several routine characteristics, such as daily new snow cover depth or daily fresh snow accumulation, daily total snow cover depth and winter (annual) sum of daily snow cover depths, number of days with snowfall, number of days with snow cover with depth one cm and more (5 cm, 10 cm, 25 cm, 50 cm and more), the first and the last day with snowfall or snow cover etc. These characteristics can be calculated (observed) in winter season (Dec. 1 to Feb. 28/29, Nov. 1 to March 31, July 1 to June 30 etc., Faško et al., 1997).

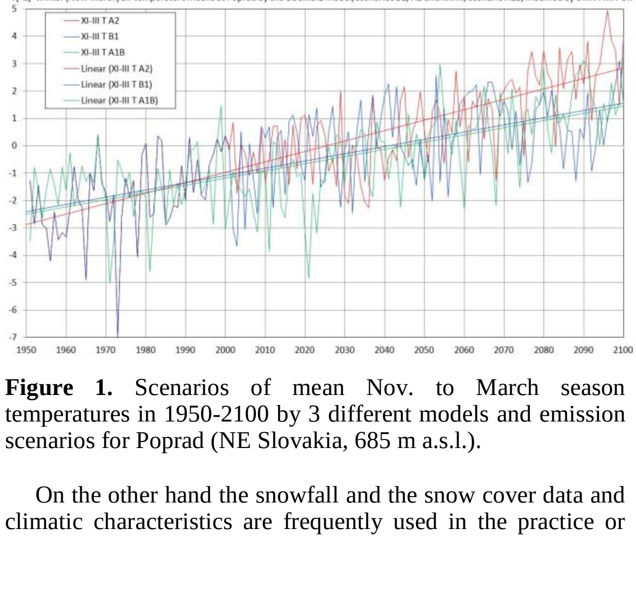


**Figure 1.** Scenarios of mean Nov. to March season temperatures in 1950-2100 by 3 different models and emission scenarios for Poprad (NE Slovakia, 685 m a.s.l.).

On the other hand the snowfall and the snow cover data and climatic characteristics are frequently used in the practice or requested by many users from several sectors. Recently it was found significant decrease in snow cover characteristics in the majority of Slovakia, but except the altitudes above 1200 m a.s.l. (4% of the territory). Reduction of snow cover is especially noteworthy below 800 m a.s.l. (Šťastný et al., 2017).

By reason of expected significant increase of air temperature as well as precipitation totals in winter season during the next decades (Figs. 1 and 2), we prepared methods to estimate possible scenarios of snow cover development change in Slovakia up to the end of the 21st century.

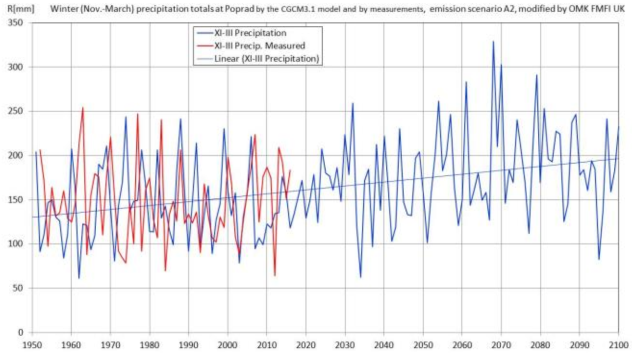


**Figure 2.** Scenario of Nov. to March precipitation totals in 1950-2100 by CGCM3.1 model and emission scenario SRES A2 for Poprad (blue line, NE Slovakia, 685 m a.s.l.) and measured totals for Poprad in 1951-2017 (red line).

The first method is based on the modified GCMs and RCMs outputs (snow cover water equivalent values in mm and new snow cover amount in mm at mean daily air temperature below +2°C) and the second one on the regression (analogues) estimation.

## MATERIALS, METHODS AND RESULTS

In Slovakia there are about 100 meteorological station with complete measurements and about 700 stations with daily measurements of precipitation, new and total snow cover since 1950. These data can be used for detail analysis.

According to the comprehensive comparison of measured and modeled data it was found that air temperature and precipitation daily data by Global General Circulation Models - GCMs (CGCM3.1 and ECHAM5) and Regional Circulation Models - RCMs (KNMI and MPI) are the most reliable for such analysis (Lapin et al., 2012). In the model outputs we have daily data of air temperatures, precipitation totals and water equivalent of snow cover. Mean daily temperature below +2°C resulted at precipitation as predominantly solid phase and above +2°C as predominantly liquid phase. In Fig.3 we present the share of precipitation occurred at mean daily temperature below +2°C in Oct. to March season. I can be seen significant decrease of solid precipitation also for the Poprad site (695 m a.s.l.). For higher altitudes is decrease of RS lesser, for lower altitudes even greater.

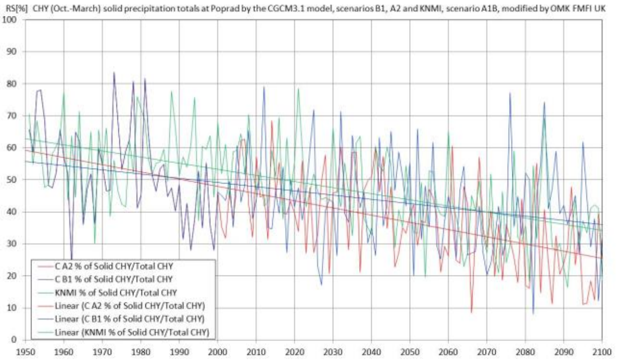


**Figure 3.** Share of solid precipitation (RS) from all precipitation totals by 3 scenarios (CGCM3.1, SRES A2 and B1, KNMI, SRES A1B) for Poprad (NE Slovakia, 695 m a.s.l.) and Oct. to March season in 1951-2100.

Another possibility of solid precipitation (or snow cover) scenarios design directly from the GCMs and RCMs outputs is the analysis of daily values of deposited water equivalent of snow cover on the surface (in mm). In Tab.1 we present only data from the KNMI (SRES A1B) model outputs and compare them with measurements of snow cover depth sum (in cm) and snow cover day's number. It is obvious that the water equivalent of snow cover in mm and the depth in cm are different quantities, usually values in mm are much greater especially at older snow cover (in March). Values from the KNMI model are without any modification for the nearest two gridpoints round the meteorological station (grid points resolution is 25x25 km, altitudes are in m a.s.l.).

As it can be seen from data for four stations in Slovakia (Tab.1, Hurbanovo, SW Slovakia, 115 m a.s.l., Sliač Airport, CE Slovakia, 313 m a.s.l., Poprad Airport, NE Slovakia, 695 m a.s.l. and Oravská Lesná, NW Slovakia, 780 m a.s.l.), the nearest gridpoints have sometimes very different altitude than the meteorological station. More over the modeled topography is very simplified in spite of 25x25 km resolution. That is why some upwind and lee effects are not expressed in the outputs. In spite of this the decrease of snow conditions is very clear.

Comparison of measured monthly snow cover data with air temperature and precipitation in the period 1951-2010 enabled to prepare simple method for monthly snow cover characteristics scenarios design in 2011-2100 period. It was found that there are serious differences among altitudes below 500 m a.s.l., 500 to 1000 m a.s.l. and above 1000 m a.s.l.

**Table 1.** Modeled (Kxxx) and measured (Myyy) annual sums of daily snow cover depths (Sum) and annual snow cover days (N) for 4 stations in Slovakia (Kxxx represent outputs for the nearest two gridpoint by the KNMI model, SRES A1B emission scenario, xxx and yyy are altitudes in m a.s.l., modeled values are in mm for Sum and ≥0.4 mm for N, % is a relative value in 2051-2100 compared to 1951-1980 average)

| Hurbanovo | 1951 -980 | 1961 -990 | 1981 -010 | 2001 -050 | 2051 -100 | % |
|---|---|---|---|---|---|---|
| K113 Sum [mm] | 253 | 260 | 224 | 193 | 84 | 33.3 |
| K113 N [days] | 37.9 | 38.8 | 39.5 | 32.7 | 15.8 | 41.7 |
| K161 Sum [mm] | 288 | 286 | 254 | 227 | 92 | 32.0 |
| K161 N [days] | 43.3 | 43.6 | 43.8 | 36.3 | 18.1 | 41.7 |
| M115 Sum [cm] | 332 | 327 | 268 | | | |
| M115 N [days] | 36.4 | 36.6 | 34.1 | | | |

| Sliač Airport | 1951 -980 | 1961 -990 | 1981 -010 | 2001 -050 | 2051 -100 | % |
|---|---|---|---|---|---|---|
| K477 Sum [mm] | 1090 | 1226 | 1148 | 938 | 364 | 33.4 |
| K477 N [days] | 88.4 | 92.4 | 87.5 | 73.6 | 45.4 | 51.4 |
| K701 Sum [mm] | 1709 | 2034 | 2042 | 1613 | 604 | 35.3 |
| K701 N [days] | 112.9 | 114.3 | 107.8 | 95.8 | 64.9 | 57.5 |
| M313 Sum [cm] | 934 | 906 | 783 | | | |
| M313 N [days] | 68.2 | 64.9 | 60.8 | | | |

| Poprad Airport | 1951 -980 | 1961 -990 | 1981 -010 | 2001 -050 | 2051 -100 | % |
|---|---|---|---|---|---|---|
| K707 Sum [mm] | 1886 | 2443 | 2720 | 1827 | 854 | 45.3 |
| K707 N [days] | 119.2 | 120.8 | 115.6 | 102.4 | 72.0 | 60.5 |
| K777 Sum [mm] | 2114 | 2563 | 2832 | 2072 | 1097 | 51.9 |
| K777 N [days] | 128.6 | 128.7 | 123.9 | 111.8 | 81.6 | 63.5 |
| M695 Sum [cm] | 933 | 855 | 785 | | | |
| M695 M [days] | 78.6 | 80.1 | 80.5 | | | |

| Oravská Lesná | 1951 -980 | 1961 -990 | 1981 -010 | 2001 -050 | 2051 -100 | % |
|---|---|---|---|---|---|---|
| K810 Sum [mm] | 2323 | 2621 | 2563 | 1997 | 1053 | 45.3 |
| K810 N [days] | 122.4 | 123.8 | 119.8 | 108.3 | 78.5 | 64.1 |
| K755 Sum [mm] | 2397 | 2655 | 2606 | 2055 | 1172 | 48.9 |
| K755 N [days] | 123.2 | 124.1 | 120.5 | 108.4 | 79.8 | 64.7 |
| M780 Sum [cm] | 4764 | 4918 | 4874 | | | |
| M780 N [days] | 131.3 | 129.6 | 126.1 | | | |

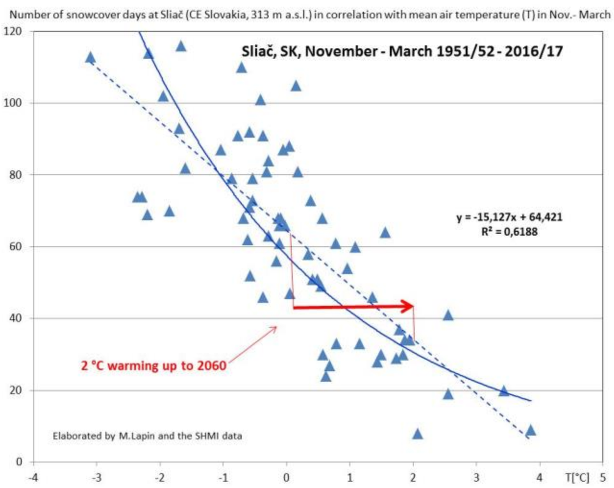


**Figure 4.** Correlation of number of snow cover days and mean air temperature in Nov. to March seasons in 1951/52 to 2016/17 years. Linear regression seems represent well the conditions up to 2°C mean warming of climate. Nonlinear regression is better above 2°C of mean temperature conditions at any station.

Based on such correlations for 3 snow characteristics (sum of total daily snow cover depths, number of snow cover days and sum of daily new snow cover depths) with mean air temperature a precipitation totals we calculated scenarios for Slovak mountains and some lower localities. Here we present only a sample from widen elaboration and only for winter season Dec. to Feb. (XII-II) and longer winter season Nov. to March (XI-III). Kysuce and Orava are the mountainous regions in northwestern Slovakia with high precipitation in winter, Lomnica in SE of the High Tatras is a region with low precipitation in winter, Jasná in N of the Low Tatras is a region with high precipitation in winter, Sliač is a hollow in central Slovakia and Hurbanovo lies on a lowland in SW Slovakia.

**Table 2.** Scenarios of change in snow cover characteristics at increase of mean temperature by 1°C in winter (XII-II) and long winter (XI-III) at some regions in Slovakia (significance very good at all characteristics)

a) Number of snow cover days ≥0.4 mm of snow

| Region | H | XII-II | XI-III | H | XII-II | XI-III |
|---|---|---|---|---|---|---|
| Kysuce | 600 | -7 | -10 | 1200 | 0 | -3 |
| Orava | 600 | -7 | -10 | 1200 | 0 | -3 |
| Lomnica | 850 | -10 | -14 | 1500 | -1 | -2 |
| Jasná | 1000 | -5 | -6 | 1500 | -1 | -2 |
| Sliač | 313 | -17 | -24 | | | |
| Hurbanovo | 115 | -27 | -32 | | | |

b) Sum of total daily snow cover depths

| Region | H | XII-II | XI-III | H | XII-II | XI-III |
|---|---|---|---|---|---|---|
| Kysuce | 600 | -15 | -28 | 1200 | -8 | -14 |
| Orava | 600 | -15 | -29 | 1200 | -8 | -14 |
| Lomnica | 850 | -20 | -35 | 1500 | -7 | -15 |
| Jasná | 1000 | -17 | -25 | 1500 | -7 | -15 |
| Sliač | 313 | -26 | -39 | | | |
| Hurbanovo | 115 | -37 | -48 | | | |

c) Sum of daily new snow cover depths

| Region | H | XII-II | XI-III | H | XII-II | XI-III |
|---|---|---|---|---|---|---|
| Kysuce | 600 | -8 | -9 | 1200 | -4 | -5 |
| Orava | 600 | -8 | -9 | 1200 | -4 | -5 |
| Lomnica | 850 | -8 | -12 | 1500 | -3 | -5 |
| Jasná | 1000 | -4 | -7 | 1500 | -3 | -5 |
| Sliač | 313 | -14 | -21 | | | |
| Hurbanovo | 115 | -24 | -29 | | | |

Very important for the snow cover persistence is the occurrence of mild weather spells during winter (with temperature above +5°C) as well as high liquid precipitation totals. We analyzed such episodes (days with mean temperature above +5°C) in the modified GCMs and RCMs outputs data in 1951-2100 and compared them with measured ones in 1951-2016. Here only a sample from all results is presented and only for winter season Dec. to Feb., CGCM3.1 model, SRES A2.

Another possibility of temperature change scenarios and snow cover conditions analysis is the evaluation of technical (artificial) snow producing at the ski resorts. It seems that the suitable temperature (from 0°C to -10°C) occurrence will decline significantly mainly in altitudes below 1000 m a.s.l. Here only occurrence of winter days with mean temperature below -1°C and below 0°C is presented and only by the CGCM3.1 model, SRES A2 scenario (the warmest).

**Table 3.** Scenarios of change in snow cover characteristics at increase of mean precipitation totals by 10% in winter (XII-II) and long winter (XI-III) at some regions in Slovakia (significance low, good new snow cover depths sum)

a) Number of snow cover days ≥0.4 mm of snow

| Region | H | XII-II | XI-III | H | XII-II | XI-III |
|---|---|---|---|---|---|---|
| Kysuce | 600 | 1.5 | 1.1 | 1200 | 0.4 | 0.3 |
| Orava | 600 | 1.5 | 1.1 | 1200 | 0.4 | 0.3 |
| Lomnica | 850 | 1.0 | 0.8 | 1500 | 0.3 | 0.3 |
| Jasná | 1000 | 0.5 | 0.4 | 1500 | 0.3 | 0.3 |
| Sliač | 313 | 1.7 | 1.6 | | | |
| Hurbanovo | 115 | 3.4 | 3.1 | | | |

b) Sum of total daily snow cover depths

| Region | H | XII-II | XI-III | H | XII-II | XI-III |
|---|---|---|---|---|---|---|
| Kysuce | 600 | 5 | 3 | 1200 | 4 | 2 |
| Orava | 600 | 5 | 3 | 1200 | 4 | 2 |
| Lomnica | 850 | 5 | 4 | 1500 | 3 | 2 |
| Jasná | 1000 | 4 | 2 | 1500 | 3 | 2 |
| Sliač | 313 | 4 | 3 | | | |
| Hurbanovo | 115 | 5 | 4 | | | |

c) Sum of daily new snow cover depths

| Region | H | XII-II | XI-III | H | XII-II | XI-III |
|---|---|---|---|---|---|---|
| Kysuce | 600 | 5.5 | 3.8 | 1200 | 3.8 | 2.4 |
| Orava | 600 | 5.5 | 3.8 | 1200 | 3.8 | 2.4 |
| Lomnica | 850 | 7.0 | 3.5 | 1500 | 3.5 | 2.0 |
| Jasná | 1000 | 4.0 | 2.5 | 1500 | 3.5 | 2.0 |
| Sliač | 313 | 4.5 | 3.5 | | | |
| Hurbanovo | 115 | 8.1 | 5.6 | | | |

**Table 4.** Average number of warm days (with mean temperature above +5°C (days)) in winter (Dec.-Feb., 90 days) and sum of precipitation (mm) during these warm days by CGCM3.1 model, SRES A2 scenario (H – Hurbanovo, SW Slovakia, 115 m a.s.l., P – Poprad Airport, 695 m a.s.l., O – Oravská Lesná, NW Slovakia, 780 m a.s.l., % - share of warm days from all days in winter and precipitation during warm days from all precipitation in winters 2071-2100 in %).

| Station | 1951-1980 | 1961-1990 | 1981-2010 | 2011-2040 | 2041-2070 | 2071-2100 | % |
|---|---|---|---|---|---|---|---|
| H days | 11.5 | 11.6 | 14.9 | 21.4 | 26.2 | 40.9 | 45.4 |
| H mm | 26.5 | 27.7 | 34.1 | 45.5 | 59.6 | 106.3 | 62.7 |
| P days | 1.4 | 1.4 | 2.4 | 4.4 | 6.9 | 12.1 | 13.4 |
| P mm | 2.7 | 3.3 | 5.6 | 6.9 | 10.7 | 18.2 | 18.2 |
| O days | 2.2 | 2.3 | 3.6 | 6.7 | 8.8 | 14.3 | 15.9 |
| O mm | 9.9 | 13.0 | 22.2 | 28.3 | 37.9 | 65.4 | 21.8 |

**Table 5.** Average number of days with temperature < -1°C and < 0°C by the CGCM3.1 model, SRES A2 scenario in the long winter season Nov. to March (totally 161 days) for the stations Hurbanovo, Sliač Airport, Poprad Airport, Oravská Lesná, Štrbské Pleso (N Slovakia, 1360 m a.s.l.) and Chopok (CE Slovakia, 2008 m a.s.l.), % - share of such days in 2071-2100.

a) Average number of days with mean temperature < -1°C

| Station | 1951-1980 | 1961-1990 | 1981-2010 | 2011-2040 | 2041-2070 | 2071-2100 | % |
|---|---|---|---|---|---|---|---|
| Hurban | 43.2 | 40.7 | 32.0 | 24.6 | 19.8 | 8.0 | 4.9 |
| Sliač | 65.1 | 61.6 | 52.1 | 44.2 | 36.1 | 21.9 | 13.6 |
| Poprad | 84.4 | 80.3 | 70.4 | 62.1 | 50.7 | 32.7 | 20.3 |
| OLesná | 79.5 | 75.9 | 66.5 | 58.3 | 47.7 | 31.6 | 19.6 |
| ŠPleso | 100.9 | 97.0 | 85.1 | 75.8 | 62.1 | 40.0 | 24.9 |
| Chopok | 139.2 | 137.7 | 132.5 | 129.9 | 119.2 | 102.6 | 63.7 |

a) Average number of days with mean temperature < 0°C

| Station | 1951-1980 | 1961-1990 | 1981-2010 | 2011-2040 | 2041-2070 | 2071-2100 | % |
|---|---|---|---|---|---|---|---|
| Hurban | 53.7 | 51.3 | 42.0 | 32.8 | 26.5 | 13.7 | 8.5 |
| Sliač | 75.6 | 72.3 | 63.4 | 54.7 | 44.5 | 28.8 | 17.9 |
| Poprad | 96.7 | 92.4 | 81.8 | 74.2 | 60.5 | 41.9 | 26.0 |
| OLesná | 91.3 | 87.3 | 76.9 | 70.5 | 57.3 | 40.1 | 24.9 |
| ŠPleso | 112.7 | 109.4 | 98.6 | 89.6 | 75.8 | 53.1 | 33.0 |
| Chopok | 143.3 | 142.6 | 139.8 | 137.5 | 129.0 | 115.3 | 71.6 |

## SUMMARY OF RESULTS

As seen from the Tabs.1 – 5 and Figs.1 – 4, snow conditions in Slovakia have changed and the negative tendency will continue probably up to 2100 at least. The most dramatic changes are expected in lower altitudes, mainly below 800 m a.s.l. and only above 1000 m a.s.l. (5.4% of Slovak territory) will have unchanged or something better conditions for winter sports, namely skiing (increase of accumulated snow cover is expected only above 1200 m a.s.l., about 4% of the territory).

This conclusion comes from the detail analysis of measured snow characteristics and also from the models output. Some differences among modeled results are based on different scenarios of air temperature and precipitation increase in winter seasons Dec. to Feb. or Nov. to March. Generally higher increase of air temperature is expected at the SRES A2 emission scenario and the least at the SRES B1 scenario. Deviations in results are quite low at the same SRES emission scenario and different models. Deviations in precipitation scenarios by different models is greater and do not have any regular specifics. In the northern half of Slovakia will be the winter precipitation increases probably greater than in the southern one. Now have a look at the up to present development of 30-year characteristics of some climatic elements for 6 stations as preliminary verifying of presented scenarios.

**Table 6.** Measured averages of air temperature (in °C, top), precipitation totals (in mm, center) and new snow cover sums (in cm, bottom) at 6 stations in the Nov. to March winter season (H – altitude in m a.s.l., * recalculated means at Štrbské Pleso to the 1951-1992 site, * precipitation totals and new snow cover sums are influenced by wind at Chopok).

| Temperature | H | 1951-1980 | 1961-1990 | 1981-2010 | 1988-2017 |
|---|---|---|---|---|---|
| Hurbanovo | 115 | 2.0 | 2.0 | 2.4 | 2.9 |
| Sliač Airport | 313 | -0.2 | -0.1 | 0.1 | 0.6 |
| Poprad Airp. | 685 | -2.0 | -1.9 | -1.5 | -1.0 |
| Or. Lesná | 780 | -2.7 | -2.7 | -2.4 | -1.8 |
| Štrb. Pleso* | 1360 | -3.2 | -3.0 | -2.8 | -2.4 |
| Chopok | 2008 | -7.2 | -7.2 | -6.9 | -6.4 |

| Precipitation | H | 1951-1980 | 1961-1990 | 1981-2010 | 1988-2017 |
|---|---|---|---|---|---|
| Hurbanovo | 115 | 192 | 188 | 186 | 185 |
| Sliač Airport | 313 | 262 | 254 | 237 | 238 |
| Poprad Airp. | 685 | 151 | 149 | 142 | 146 |
| Or. Lesná | 780 | 370 | 383 | 443 | 449 |
| Štrb. Pleso | 1360 | 326 | 326 | 366 | 373 |
| Chopok* | 2008 | 390 | 364 | 373 | 390 |

| New snow | H | 1951-1980 | 1961-1990 | 1981-2010 | 1988-2017 |
|---|---|---|---|---|---|
| Hurbanovo | 115 | 53 | 51 | 46 | 37 |
| Sliač Airport | 313 | 97 | 95 | 81 | 69 |
| Poprad Airp. | 685 | 101 | 97 | 91 | 84 |
| Or. Lesná | 780 | 286 | 300 | 348 | 315 |
| Štrb. Pleso | 1360 | 359 | 353 | 383 | 360 |
| Chopok* | 2008 | 422 | 378 | 353 | 339 |

From Tab. 6 it follows that the last 30-year period 1988-2017 was by 0.8 to 1.0°C warmer than the period 1951-1980. This is in accordance with the SRES A2 scenario. Precipitation totals increased irregularly but more in the northern Slovakia (Oravská Lesná had in 1988-2017 by 21.4% more precipitation in winter than in 1951-1980). This influenced also new snow cover sum in winter – decrease at Hurbanovo, Sliač Airport and Poprad Airport (localities below 700 m a.s.l.) and no change or increase at Oravská Lesná and Štrbské Pleso (mountainous meteorological station Chopok, 2008 m a.s.l., is problematic).

## CONCLUSION

Snow cover and snow characteristics are very important factors also from the point of view of natural ecosystems, agriculture, forestry, hydrology, hydrogeology, water management, transport, sports and recreation. Negative or rapid changes in snow characteristics can affect adversely all mentioned sectors. That is why reliable scenarios of climatic elements connected with snow cover and the snow cover as well are very important. Our paper is only a review from much broader elaboration of climatic scenarios for Slovakia. Even at snow cover we prepared 7 different scenarios by 4 modeling centers and the time period from 1951 to 2100. We are ready to present these results in a form of comprehensive papers or chapters in monograph.

## Acknowledgement

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