

CHANGES IN THE HIGH-ALTITUDE CLIMATE OF HIGH TATRA MTS. EVALUATED BY CLIMATIC NORMALS FROM THE SKALNATÉ PLESO OBSERVATORY

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The Skalnaté Pleso Observatory (1778 m a.s.l.) is situated at the alpine treeline ecotone of the High Tatra Mts. (Western Carpathians). In this study, the climatological normals (CLINOs) 1961–1990 and 1991–2020 calculated from conventional measurements at this observatory were analysed. We used CLINO 1961–1990 as a reference for determining temporal changes in the normal period 1991–2020. The changes in principal climatological surface parameters were used to indicate the extent of the climate change-induced alteration between normal periods. The results of this study indicate an increase in the annual normals of all parameters in the CLINO 1991–2020. The annual precipitation rose by 195.6 mm and the total annual number of days with precipitation above 1 mm increased by 6 days. The steepest increase was detected in the annual maximum air temperature (1.2 °C), the mean air temperature increased by 1.1 °C, and the minimum air temperature increased by 0.8 °C. The mean vapour pressure increased by 0.6 hPa. The annual geopotential height increased by 7.1 m and the total number of hours of sunshine rose by 52 hours..

Observatórium Skalnaté Pleso (1778 m n. m.) sa nachádza v ekotóne medzi subalpínskym a alpínskym stupňom Vysokých Tatier (Západné Karpaty). Klimatické normály (CLINO) 1961–1990 a 1991–2020, ktoré boli analyzované v tejto práci, boli vypočítané z konvenčných meraní na tomto observatóriu. CLINO 1961–1990 sme použili ako referenčný rámec pre určenie zmien v normálovom období 1991–2020. Odchýlky hlavných klimatologických parametrov (PCSP) medzi normálovými obdobiami identifikovali rozsah zmien spôsobených zmenou klímy. Výsledky prezentované v tejto štúdiu udávajú nárast ročných normálov všetkých parametrov v CLINO 1991–2020. Ročný úhrn zrážok sa zvýšil o 195,6 mm a taktiež pribudlo 6 dní v roku so zrážkami nad 1 mm. Najvyšší nárast bol zaznamenaný v prípade ročnej maximálnej teploty vzduchu (o 1,2 °C), priemerná teplota sa zvýšila o 1,1 °C, a v prípade minimálnej teploty sme zaznamenali nárast o 0,8 °C. Priemerný tlak vodnej pary stúpol o 0,6 hPa. Priemerná ročná geopotenciálna výška sa narástla o 7,1 m a celkový počet hodín slnečného svitu sa zvýšil o 52 hodín.

Key words: climatological normal, precipitation, air temperature, vapour pressure, geopotential height, sunshine duration

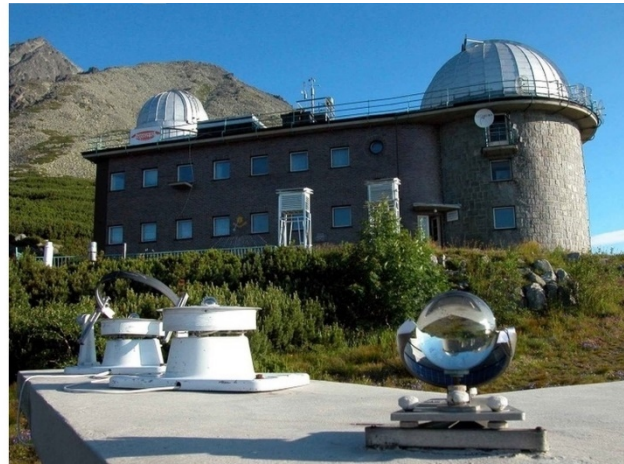
INTRODUCTION

Throughout the world, mountain regions experience more rapid changes in air temperature than environments located at lower elevations. Rising air temperature and changes in precipitation patterns are likely to accelerate the rate of change in various systems with significant consequences for humans and ecosystems (Beniston, 2003; Pepin et al., 2015; Středová et al., 2020). Continuous warming at high altitudes can significantly modify the hydrologic cycles in mountainous regions (Nijssen et al., 2001; Vido et al., 2015) and cause a reduction in winter and spring snowpack leading to changes in the temporal pattern of streamflow (Arnell, 2003). Shifts in the precipitation regime may potentially jeopardize the resources of freshwater (Beniston et al., 1997). Evapotranspiration brought by rising air temperature induces severe droughts in the vegetation period (Overpeck and Udall, 2010) leading to increases in the frequency and intensity of wildfires (Korená Hillyayová et al., 2023).

The information on the climatic conditions of certain mountain regions originates primarily from the data measured at mountain observatories. The first systematic meteorological observations in the High Tatra Mts. began during the Austro-Hungarian monarchy when a basic network of

meteorological stations was established. In the 19th century, the foundation of new tourist lodges and climate-therapeutic resorts required the building of the meteorological stations in Tatranská Lomnica (in 1897), Štrbské Pleso (in 1902) and Starý Smokovec (in 1905) (Bičárová et al., 2013). The construction of the cable car from Tatranská Lomnica through Skalnaté Pleso to Lomnický štít (Lomnický peak) in 1939 enabled the build-up of a mountain meteorological station near the tarn Skalnaté Pleso at 1769 m a.s.l. (Smolen, 1990). In 1943, Dr Antonín Bečvář (1901–1965), a climatologist working for the climatic resort at Štrbské Pleso, initiated the construction of a new observatory at an altitude of 1778 m a.s.l., where the staff worked under the guidance of the Military Air Force Weather Station (Bičárová et al., 2013). Since then, a unique, almost 80-year-long database of manually measured meteorological data at the Skalnaté Pleso Observatory (SPO) has been recorded. At present, SPO serves as the experimental workplace of the Earth Science Institute of the Slovak Academy of Sciences. The data from this observatory cover two climatological standard normals (CLINOs) 1961–1990 and 1991–2020 and represent the climate of the border between the subalpine and alpine zone of the High Tatra Mts.

Figure 1. Photography of the south-facing slopes of the High Tatra Mts. The position of the Skalnaté Pleso Observatory is marked in black rectangle.



The data from SPO provides significant information about how the high-altitude climate evolved in the Western Carpathians between the two recent normals. Using this dataset, we investigated climate change in the High Tatra Mts (Western Carpathians) by comparing the CLINOs 1961 – 1990 and 1991 – 2020. We analysed changes in principal climatological surface parameters (PCSP) defined by the World Meteorological Organization (WMO, 2017).

DATA AND METHODS

Meteorological observations at Skalnaté Pleso Observatory

The Skalnaté Pleso Observatory (SPO, Fig. 1) is located at an altitude of 1778 m in the Skalnatá dolina (Skalnatá Valley) on the southern slopes of the High Tatra Mts., Slovakia (49.18928°N; 20.23410°E) on the border between subalpine and alpine zone (Škvarenina et al., 2004). The vegetation of this alpine treeline ecotone (Bader et al., 2020) is primarily composed of shrub species dominated by *Pinus mugo* Turra. The topography of the area has a high-relief character with tarns (small mountain lakes without a tributary), gables, rock walls and towers. According to Konček's climate classification (Konček, 1974), the altitude of SPO (1778 m a.s.l.) belongs to the cold and wet climate zone with the July isotherm below 16 °C. The primary mission of this observatory is to carry out long-term monitoring of high-altitude climate (<http://www.geo.sav.sk/en/structure-of-the-institute/laboratories/meteorological-observatory-skalnate-pleso/>). The observations made at this observatory are used for interdisciplinary research related to the alpine tree line ecotone.

Climatic parameters and their measurements

This study is focused on principal climatological surface parameters (PCSP), which were defined by the WMO (2017) and WMO (1989). The individual monthly values were calculated as:

- Mean parameter, which is the mean of the daily values during the month: mean air temperature (T_{mean}), mean

maximum temperature (T_{max}), mean minimum temperature (T_{min}), mean geopotential height (GPH) and mean vapour pressure (VP).

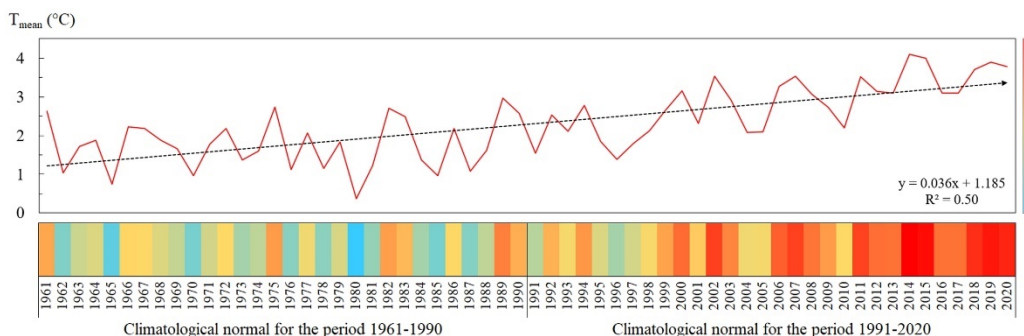
- Sum parameters, which are the sum of the daily values during the month: precipitation total (P), and the total number of hours of sunshine (SD).
- Count parameter: number of days with precipitation above 1 mm (P_d).

At SPO, the observations of these parameters are carried out by qualified observers using conventional manual methods and measurement equipment. According to the applicable standards in Slovakia, meteorological measurements are performed three times a day: at 0700, 1400 and 2100 LMT (Local Mean Time). Based on the geographical position of SPO, the LMT is shifted by 21 minutes against CET (Central European Time), i.e. 0700 LMT corresponds to 6:39 CET.

Calibrated mercury-in-glass thermometers with manual read-out are used as standard instruments to measure the actual air temperature (dry-bulb thermometer) and diurnal maximum temperature (maximum thermometer). The minimum temperature is measured by a spirit thermometer (minimum thermometer) twice daily. The thermometers are placed in a fixed position inside a standardized wooden meteorological shelter (Stevenson screen) at a height of 2 meters above the ground. In addition, the August psychrometer is installed in the interior of the meteorological shelter. This device consists of a dry-bulb and wet-bulb thermometer. The bulb of the wet-bulb thermometer is wrapped in cloth that is kept wet with distilled water via wicking action. The direct visual read-outs of temperature provided by the dry-bulb and wet-bulb thermometers are used to determine relative humidity and vapour pressure by employing psychrometric tables.

A conventional rain gauge (METRA) is installed at the observatory to measure the amount of precipitation (liquid water) and dissolved solid precipitation (snow, hail, or settled precipitation). Precipitation is accumulated in a metal container. The volume of water is measured three times a day (0700, 1400 and 2100 LMT) using a graduated cylinder. The capture area of the gauge is 500 cm².

Figure 2.
Increase in mean annual air temperature from 1961 to 2020.



The mean sea level pressure is measured by a mercury barometer where the atmospheric pressure balances the column of mercury. Measurements by the mercury barometer are corrected to compensate for the effects of ambient temperature and the local gravity anomaly, which is $9.80576513 \text{ ms}^{-2}$ at SPO. Since SPO is located at a high altitude, according to the recommendation of the WMO (2017), the mean sea level pressure was substituted by the mean geopotential high at 850 hPa. The method described in Technical note No. 61, WMO (1964) and WMO (2021) were applied to calculate the geopotential height.

A Campbell-Stokes sunshine recorder is installed at SPO to measure the total number of hours of sunshine. The principle of operation of this device is based on concentrating sunlight through a glass sphere onto a recording paper strip placed in the focal point. The length of the sunburned trace along the paper strip represents the duration of sunshine in hours per day.

Following the guidelines of the WMO (2017), all climatological elements observed at the SPO are subject to quality control and homogenized before the calculation of CLINO using the template available at <https://www.ncei.noaa.gov/pub/data/normals/WMO>.

The climate-change-induced alterations in the PCSPs were assessed by calculating differences between the CLINO 1991–2020 and the reference normal CLINO 1961–1990.

RESULTS AND DISCUSSION

Temperature and vapour pressure normals of 1961–1990 and 1991–2020

The warming at the Skalnaté Pleso Observatory is unprecedented, which is shown in Fig 2. Concretely, the increase in the maximum temperature (T_{\max}) between the CLINOs has been observed in all months of the year (Fig. 3). The average annual T_{\max} increased from $5.3 \text{ }^\circ\text{C}$ to $6.5 \text{ }^\circ\text{C}$ (Tab. 1). The highest increases in T_{\max} were above $2 \text{ }^\circ\text{C}$ observed in July and August. The lowest increases were observed in the months of September and October with T_{\max} of 0.4 and $0.2 \text{ }^\circ\text{C}$, respectively. Considering minimum temperature (T_{\min}), the temperature shifts were lower compared to T_{\max} . The highest increases in July and August were $1.6 \text{ }^\circ\text{C}$ for both. During the last CLINO, T_{\min} remained unchanged in October. In September and March, it increased only by 0.2 and $0.3 \text{ }^\circ\text{C}$, respectively. Analysing the mean monthly

temperature (T_{mean}), the increase in T_{mean} has been observed throughout the whole year similarly to previous temperature parameters. Changes in T_{mean} below $1 \text{ }^\circ\text{C}$ were detected only in February and March, and in September and October (Fig. 3). Generally, all three temperature parameters point to a profound increase in air temperature within the warm half of the year (IV–IX, Fig. 3). In the period of June–August T_{\max} increased by $2.0 \text{ }^\circ\text{C}$, T_{\min} by $1.4 \text{ }^\circ\text{C}$ and T_{mean} by $1.7 \text{ }^\circ\text{C}$. In these three summer months, the mean increase in vapour pressure (VP) was high as well (1.1 to 1.3 hPa). The positive differences in VP were observed throughout the whole year in CLINO 1991–2020 (Fig. 3). The most important meteorological variables affecting the VP are air temperature and relative humidity (Shi et al., 2019), therefore the rising air temperature at SPO was accompanied by increasing water vapour pressure (Fig. 3). The increasing temperature and atmospheric moisture content may cause the atmospheric lapse rate profiles to become shallower (Collins et al., 2013). When air temperature decreases less sharply with increasing altitude, warming in high mountains is more pronounced (Pepin and Lundquist, 2008).

Figure 3. Differences in principal climatological surface parameters between the CLINO 1991–2020 and the reference period 1961–1990.: daily maximum (T_{\max}), minimum (T_{\min}) and mean air temperature (T_{mean}), and vapour pressure (VP).

	T_{\max} ($^\circ\text{C}$)	T_{\min} ($^\circ\text{C}$)	T_{mean} ($^\circ\text{C}$)	VP (hPa)
I	1.2	1.0	1.2	0.4
II	0.9	0.5	0.8	0.2
III	0.6	0.3	0.4	0.2
IV	1.6	0.8	1.2	0.5
V	1.4	0.7	1.1	0.5
VI	1.9	1.2	1.5	1.1
VII	2.0	1.6	1.7	1.3
VIII	2.1	1.6	1.8	1.2
IX	0.4	0.2	0.4	0.4
X	0.2	0.0	0.1	0.4
XI	1.4	1.3	1.4	0.4
XII	1.0	1.0	1.0	0.1
III-V	1.2	0.6	0.9	0.4
VI-VIII	2.0	1.4	1.7	1.2
IX-XI	0.7	0.5	0.6	0.4
XII-II	1.0	0.8	1.0	0.2
X-III	0.9	0.7	0.8	0.3
IV-IX	1.6	1.0	1.3	0.8
Annual	1.2	0.8	1.1	0.6

Table 1. Climatological standard normals (CLINOs) 1961 – 1990 and 1991 – 2020 of temperature parameters in °C and vapour pressure in hPa calculated for Skalnaté Pleso Observatory.

Normal Month	1961 – 1990				1991 – 2020			
	T _{max}	T _{min}	T _{mean}	VP	T _{max}	T _{min}	T _{mean}	VP
I	-2.0	-9.1	-5.8	2.8	-0.8	-8.1	-4.5	3.1
II	-2.0	-8.9	-5.8	2.9	-1.1	-8.4	-5	3.1
III	-0.2	-6.9	-3.9	3.5	0.4	-6.6	-3.3	3.6
IV	3.5	-2.9	0	4.6	5.1	-2.1	1.2	5.0
V	8.4	1.9	4.8	6.8	9.8	2.6	5.9	7.2
VI	11.2	4.8	7.8	8.5	13.1	6.0	9.3	9.5
VII	12.8	6.3	9.4	9.4	14.8	7.9	11.1	10.6
VIII	12.8	6.5	9.4	9.4	14.9	8.1	11.2	10.6
IX	10.1	3.8	6.6	7.7	10.5	4.0	7	8.1
X	7.2	0.7	3.6	5.6	7.4	0.7	3.7	6.0
XI	2.3	-4.2	-1.3	4.1	3.7	-2.9	0.2	4.5
XII	-0.7	-7.7	-4.4	3.1	0.3	-6.7	-3.2	3.3
III-V	3.9	-2.6	-5.2	3.0	5.1	-2.0	-4.3	3.2
VI-VIII	12.3	5.9	4.2	6.6	14.3	7.3	5.5	7.3
IX-XI	6.5	0.1	8.5	8.8	7.2	0.6	9.8	9.8
XII-II	-1.5	-8.5	-0.7	4.3	-0.5	-7.7	0.2	4.6
X-III	0.8	-6.0	-2.9	3.7	1.7	-5.3	-2.0	3.9
IV-IX	9.8	3.4	6.3	7.7	11.4	4.4	7.6	8.5
Annual	5.3	-1.3	1.7	5.7	6.5	-0.5	2.8	6.2

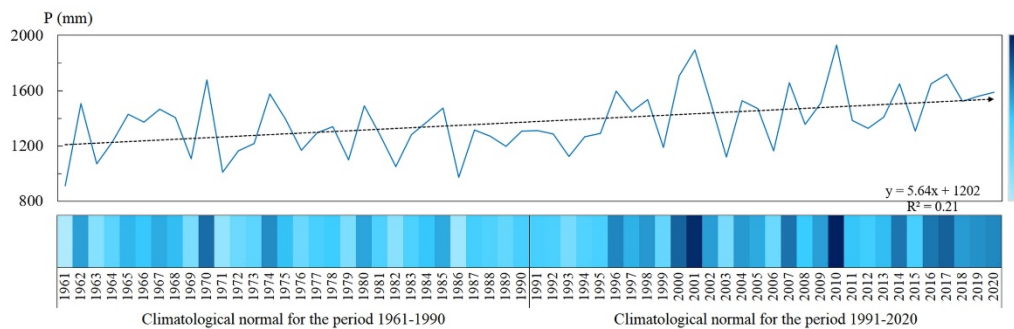
Parameters: T_{max} - daily maximum, T_{min} - minimum and T_{mean} - mean air temperatures, VP - mean vapour pressure

Table 2. Climatological standard normals (CLINOs) 1961 – 1990 and 1991 – 2020 of precipitation parameters calculated for Skalnaté Pleso Observatory.

Normal Month	1961 – 1990		1991 – 2020	
	P	Pd	P	Pd
I	57.5	9.7	81.2	11.8
II	55.7	10.2	74.9	11.3
III	66.6	11.3	82.9	12.1
IV	82.7	12.6	94.3	12.3
V	132.0	14.9	155.1	15.6
VI	188.3	16.4	183.6	15.3
VII	192.2	14.7	237.7	16.7
VIII	163.6	13.6	158.1	12.3
IX	109.7	11.1	127.9	11.2
X	84.3	9.5	117.3	11.5
XI	78.2	11.8	92.2	11.4
XII	70.9	11.7	72.0	12.0
III-V	281.3	38.8	332.3	40.0
VI-VIII	544.1	44.7	579.4	44.3
IX-XI	272.2	32.4	337.4	34.1
XII-II	184.1	31.6	228.1	35.1
X-III	413.1	64.2	520.5	70.1
IV-IX	868.5	83.3	956.7	83.4
Annual	1281.6	147.5	1477.2	153.5

Parameters: P - precipitation total in mm, Pd - number of days with precipitation above 1 mm

Figure 4. Increase in annual precipitation totals from 1961 to 2022.



Precipitation normals of 1961 – 1990 and 1991 – 2020

Over the two CLINO periods, the trend in the annual precipitation was increasing (Fig. 4). The total annual number of days with precipitation above 1 mm increased by 6 days between CLINOs (Tab. 2). The annual precipitation totals increased by 195.6 mm; however, this precipitation increase was not regularly distributed throughout the year. As shown in Fig. 5, the highest increase in precipitation was observed in July (+45.5 mm). On the contrary, precipitation decreased by -4.7 mm in June and -5.5 mm in August when the number of days with precipitation above 1 mm decreased as well. With 16.7 days of precipitation and a total of 237.7 mm, which is approximately 3-times higher than the normal precipitation in winter months (Dec., Jan., Feb., and Mar., Tab. 2), July was the month with the highest precipitation totals in the climatological normal 1991 – 2020. The increase in precipitation agrees with the general increasing trend (statistically significant) in mid-latitudes of the northern hemisphere (30°N to 60°N) over the period 1901 – 2008 and of the shorter period 1951 – 2008, which is also positive but non-significant (Hartmann et al., 2013). However, in Poland on the north slopes of High Tatra Mts., the precipitation totals significantly decreased particularly in the summer and winter months during 2001 – 2018 (Ziernicka-Wojtaszek and Kopcínska, 2020).

Normals of geopotential height and sunshine duration

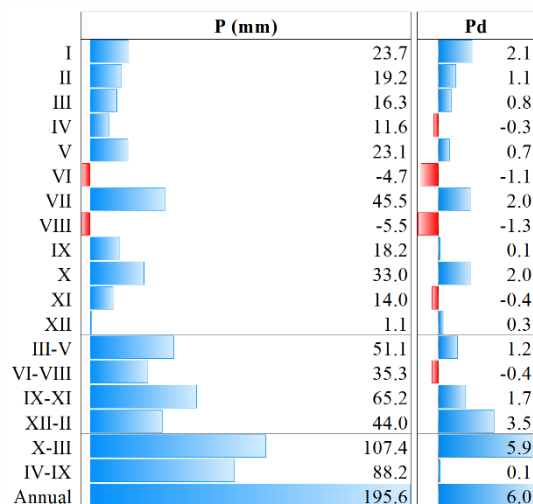
The annual geopotential height (GPH) increased from 1470.8 to 1477.9 m (Tab. 3) between the CLINOs, meaning that the altitude of the horizontal pressure gradient force as the gradient of geopotential along 850 hPa increased by 7.1 m. Looking at the intra-annual changes, and excluding September and October, GPH increased in the period 1991 – 2020 compared to the reference period 1961 – 1990 (Fig. 6). The highest increase was observed in April, November and December. The increase is in accordance with other studies in the mid-latitudes of the northern hemisphere. Generally, after 1960, winter (Dec., Jan., Feb.) and annual means of geopotential height at 850 hPa increased over the mid-latitudes and decreased over high latitudes in the northern hemisphere (Lucarini and Russell, 2002). The geopotential height depends mainly on the prevailing pressure system in the area and the temperature of the air mass since the air pressure vertical gradient is affected by the temperature. At SPO, GPH decreased by -5.3 m and -8.1 m in September and October, respectively. In these months, the mean and extreme temperatures increased only slightly between the normals (Fig. 3), and the total number of hours of sunshine decreased (Fig. 6). The decreases in GPH may point to changes in atmospheric circulation in September and October, but these relationships were not investigated in the present study.

Table 3. Climatological standard normals (CLINOs) 1961–1990 and 1991–2020 of geopotential height (GPH) and sunshine duration (SD) calculated for Skalnaté Pleso Observatory.

Normal Month	1961–1990		1991–2020	
	GPH (m)	SD (h)	GPH (m)	SD (h)
I	1439.1	92.2	1449.0	93.0
II	1428.3	98.9	1440.3	89.1
III	1437.0	124.8	1444.4	128.0
IV	1444.5	131.0	1457.9	146.5
V	1478.3	142.4	1486.0	160.4
VI	1494.1	128.5	1504.1	142.1
VII	1509.3	135.6	1510.7	148.7
VIII	1512.7	139.7	1521.3	153.5
IX	1512.5	127.0	1507.2	124.6
X	1502.5	136.9	1494.4	119.2
XI	1452.2	85.4	1465.2	87.8
XII	1438.8	81.4	1454.4	82.6
III-V	1453.3	398.2	1462.8	434.9
VI-VIII	1505.4	403.8	1512.0	444.3
IX-XI	1489.0	349.3	1488.9	331.6
XII-II	1435.4	272.5	1447.9	264.7
X-III	1449.7	619.6	8747.8	599.7
IV-IX	1491.9	804.2	8987.1	875.8
Annual	1470.8	1423.8	1477.9	1475.5

Sunshine duration (SD) is a climatological parameter that measures the duration of sunshine for a given location on the Earth. At SPO, the annual total number of hours of sunshine increased from 1423.8 h to 1475.5 h (Tab. 3). SD at SPO is similar to the average annual total of SD of the multi-annual period 1901–2014 on Śnieżka (1603 m a.s.l., Poland), which is 1423.0 h (Urban et al., 2018). At SPO, the most pronounced increase in SD was recorded during the warm part of the year (IV–IX, Fig. 6), when SD increased by 71.6 hours. Adversely, in the cold half of the year, 19.9 hours less SD was recorded in CLINO 1991–2020. The monthly changes in SD (Fig. 6) show an increase of 13 to 18 hours from April to August. On the contrary, SD between CLINOs decreased or only slightly deviated in the period from September to March, with the greatest decline in October (–17.7 h) and February (–9.8 h). Such a decline in September and October agrees with the recent cloud cover analysis over the area of the Carpathian Mountains, which revealed an increasing trend in cloud cover and the global radiation decrease in the regions outside the Carpathian Chain in these months (Cheval et al., 2014).

Figure 5. Differences in principal climatological surface parameters between the CLIMO 1991–2020 and the reference period 1961–1990: precipitation total (P) and the number of days with precipitation above 1 mm (Pd).

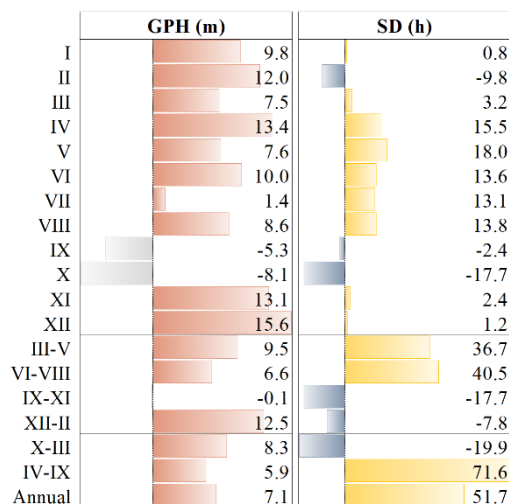


CONCLUSIONS

Mountain meteorological observatories were established in previous centuries to carry out a wide range of services including research in the fields of meteorology, climatology and atmospheric physics. At present, the long-term datasets of meteorological measurements carried out at mountain observatories provide important information on climatic conditions which are used to investigate natural climate variability and anthropogenically induced climate change. However, on a global scale, the number of mountain observatories equipped with conventional (manually operated) instruments is declining due to economic and maintenance issues. This trend is further accelerated by the expansion of automated weather stations. The transition from conventional to automatic instruments brings additional challenges in ensuring the homogeneity of observations. The Skalnaté Pleso Observatory is one of the few mountain observatories in the Western Carpathians with long-term and homogeneous climate observations. The climatological normals calculated in this paper are based on manual measurements. The analysed data covered two climatological standard normals: 1961–1990 and 1991–2020. We attempted to shed light on how the principal climatological surface parameters between the climatological standard normals changed over time. Based on the presented results it can be concluded that the CLINO 1991–2020 of the principal climatological surface parameters increased compared to the baseline CLINO 1961–1990. The main results can be summarised as follows:

- annual precipitation totals rose by 195.6 mm,
- the total number of days with precipitation above 1 mm increased by 6 days,
- annual maximum air temperature increased by 1.2 °C,
- annual minimum air temperature increased by 0.8 °C,
- mean air temperature increased by 1.1 °C,
- mean vapour pressure increment was 0.6 hPa,
- annual geopotential height increased by 7.1 m,
- the total number of hours of sunshine rose by 52 hours.

Figure 6. Changes in principal climatological surface parameters between climatological normals 1991–2020 and baseline period 1961–1990: geopotential height (GPH) and the total number of hours of sunshine (SD).



Future research on changes in the climate of the Western Carpathian Mountains is needed. It would be interesting to compare the results of this study with other high-altitude locations that are monitored by the national weather service. This would give us a broader picture of the ongoing climate change and its peculiarities observed in the Western Carpathians.

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