Changes in the Sums of Active Temperatures and Absolute Minimum Temperatures in 1931-2020 in Slovakia

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Abstract

The air temperature is increasing worldwide, Europe and especially Slovakia are no exception. This increase is more than double here. The years 2015-2022 represent the eight warmest years in the history of measurements. The aim of this work is to point out the increasing areas of the territory of Slovakia with sums of active temperatures (TS ≥ 5 °C) and with absolute minimum temperatures during the years 1931-1960, 1961-1990 and 1991-2020. The results show an increase mainly in the last 30 years when the area of the territory with temperatures above 3,400 °C increased by 50 % (compared to the years 1931-1960) and the area of the territory with temperatures up to 2,200 °C decreased by 88 %. The change is also visible at absolute minimum temperatures when the area with T_{min} ≤ -24 °C decreased by 93 % and the area with T_{min} ≥ -18.1 °C increased by 203 %. These facts affect the development of plants - droughts in the spring and summer months, but also the occurrence of diseases caused by insufficient freezing of the soil and the lack of moisture from the snow cover, which has hardly occurred in the southern parts of Slovakia in recent years. Therefore, it is necessary to adapt to these changes, as the situation is expected to worsen.

Keywords: sum of active temperature, absolute minimum temperature, vegetation period, climate change
1. Introduction

Climate change is a problem these days. With accelerating climate change, the probability that the deviation of the annual global temperature will reach 1.5 °C (compared to the years 1850-1900) in the period 2022-2026 is increasing. This represents an increase of 38 % compared to the years 2017-2021 (Pecho & Markovič, 2022). The average global air temperature was 1.15 °C higher in 2022 (compared to the years 1850-1900), while the years 2015-2022 represent the 8 warmest years in the history of measurements (Markovič, 2023). In Europe, the temperature increase is twice as high as compared to the global average. In the period 1991-2021, it represents an average temperature increase of 0.5 °C per decade (Markovič & Pecho, 2022).

With climate change, winters are also changing. In recent years, the Slovak Hydrometeorological Institute (SHMI) has repeatedly recorded extremely long uninterrupted periods without the occurrence of ice days (T_max < 0°C). Among the thirty longest periods without ice days in the overall order, up to 25 have occurred since the end of 2006. At the local level, even extremely long periods without ice days in Slovakia are increasing significantly in the current warmer climate conditions (Pecho, Výberči, 2022).

The aim of this work is to point out these changes also in relation to plants. As the temperature increases, the vegetation periods are lengthened and thus the sum of active temperatures (T_S ≥ 5 °C) also increases. There are also more and more frequent periods with mild winters, which affects the wintering of plants. In this contribution, we compared the sums of active temperatures (SAT) and absolute minimum temperatures for the period 1931-1960, 1961-1990 and 1991-2020 in Slovakia.

2. Material and Methods

2.1 Study Area

The subject of the research was the Slovak Republic (northern latitudes from 47°44´21˝ up to 49°36´48˝ and eastern longitudes from 16°50´56˝ up to 22°33´53˝). It is located in the centre of Europe and has an area of 49,036 km² (Fig. 1). The surface of Slovakia increases from the lowlands in the south (Záhorská Lowland, Danube Lowland, Východoslovenská Lowland) to the highest mountains in the centre and in the north (Carpathian Mountains). Slovakia is located in the northern temperate zone. The climate is influenced by both continental and oceanic climates. The most precipitation falls in the High Tatras in the north (around 2,000 mm/year) and the least in the lowlands (550 mm/year). The average annual temperature is from 9 °C to 11 °C, in the valleys and basins the temperature reaches 6 °C to 8 °C (Bunčák et al., 2006).
2.2 Data Analysis

For this study were analysed daily and monthly air temperatures in periods 1931-1960, 1961-1991 and 1991-2020 at 38 meteorological stations in Slovak Republic (Fig. 2). The dataset for period 1931-1960 was obtained from the publication “Agroclimatic conditions of the Czechoslovak Socialist Republic” (Kurpelová, 1975) and for years 1961-2020 was dataset obtained from SHMI.
2.2.1 Sum of Active Temperatures

The sum of active temperatures combines the temperature value with its duration and is calculated as the sum of average daily temperatures during the vegetation period (Kowalski & Nawalany, 2019).

Firstly, it was necessary to calculate the onset and termination of the vegetation period with temperatures $T \geq 5^\circ C$ for each meteorological station. The vegetation periods were calculated for periods 1931-1960, 1961-1990 and 1991-2020 according to formulas (Čimo et al., 2012):

\[
\begin{align*}
\text{onset of temperatures:} & \quad r_v = R \frac{T_n - T_2}{T_1 - T_2} \text{ (days)} \\
\text{termination of temperatures:} & \quad r_p = R \frac{T_1 - T_u}{T_1 - T_2} \text{ (days)}
\end{align*}
\]

Where:

$T_n$ – onset temperature ($^\circ C$),

$T_u$ – termination temperature ($^\circ C$),

$T_1$ – the nearest average monthly temperature above the onset or termination of temp. ($^\circ C$),
T₂ – the nearest average monthly temperature below the onset or termination of temp. (°C),
R – the difference in days between the middle of the months with the average temperature T₂ and the average temperature T₁, can be expressed as an average number R = 30,
rᵥ – difference in days between the middle of the month with temperature T₂ and the date of onset of temperature Tₙ,
rₚ – difference in days between the middle of the month with temperature T₂ and the date of termination of temperature Tᵤ.

Subsequently, when the beginning and ending dates were known, SAT for each station was calculated as:

\[ SAT = \sum_{D_{o}}^{D_{t}} T_d \]  (3)

Where:
Dₒ – day of onset of temperature T ≥ 5 °C,
Dₜ – day of termination of temperature T ≥ 5 °C,
Tₜ – daily mean air temperature (°C).

The sums of active temperatures were classified into 8 categories according to Kurpelová et al. (1975) (Fig. 3).

2.2.2 Agroclimatic Indicator of Wintering

The agroclimatic indicator of wintering represents the long-term average of annual absolute temperature minimums. This characteristic describes the climatic conditions during the winter and is an important factor in the cultivation of winter crops and fruit trees.

The agroclimatic indicator of wintering was classified into 5 categories according to Kurpelová et al. (1975) (Fig. 4).

2.3 Map Processing in ArcGIS
The data was entered into ArcGIS and values for locations between individual stations were calculated by interpolation. The Topo to Raster method was used for interpolation. It is an interpolation method specifically designed for the creation of hydrologically correct digital elevation models (DEMs). It is based on the ANUDEM program developed by Michael Hutchinson (Hutchinson, 1988). Subsequently, the values were divided into categories according to Kurpelová (1975) and map outputs were created.

3. Results and Discussion

3.1 Results

Fig. 3 shows how the areas of the agroclimatic districts have changed. In the period of 1971-1980, there was a cold decade, which also affected the climate normal of 1961-1990, and that also affected the sums of active temperatures. Compared to the period 1931-1960, the area with the sum of active temperatures up to 2,200 °C increased from 198 km² to 281 km², which is an increase of 42 %. On the contrary, the area with the sum of active temperatures above 3,400 °C decreased from 16,809 km² (1931-1960) to 9,148 km², which represents a decrease of 46 %. However, the most significant is the last period of the years 1991-2020, when territories with total temperatures up to 2,200 °C decreased by 88 % (from 198 km² to 24 km²) and territories with total temperatures of 2,200-2,500 °C by 78 % (from 2,219 km² to 499 km²) compared to the years 1931-1960. The increase is significant in the category of the sum of active temperatures above 3,400 °C. Compared to the years 1931-1960, the area increased from 16,809 km² to 25,291 km² (an increase of 50 %) and compared to the years 1961-1990 (9,148 km²), the area increased by up to 176 %.

Changes are also visible in the average absolute minimum temperatures (Fig. 4). The decrease in areas with occurrence of minimum temperatures $T_{\text{min}} \leq -24$ °C is from 5,480 km² to 645 km² (1961-1990) and 128 km² (1991-2020). This represents a decrease of 88 % and 98 % over 1931-1960, despite the fact that 1971-1980 was a cold decade. Also, the territory with occurrence of minimum temperatures $T_{\text{min}}$ -22.1 °C to -24.0 °C decreased by 56 %, and 75 %. On the contrary, areas with $T_{\text{min}} \geq -18.1$ °C increased significantly. From an area of 9,222 km² in 1931-1960 to 17,179 km² (86 %) in 1961-1990 and 27,962 km² (203 %) in 1991-2020.

3.2 Discussion
The increasing temperature due to climate change also means an earlier onset of flowering. A study in Great Britain (Büntgen et al., 2022) confirmed earlier flowering in 1987-2019 by 30 days compared to 1753-1986. This is also confirmed by our research, when the earlier onset of temperatures extends the period with the sum of active temperatures above 5°C.

The sum of active temperatures was processed by Łysiak (2012), but he focused on 'Šampion' and 'Ligol' apple cultivars. In our contribution, we focused on the sums of active temperatures $T \geq 5 \, ^\circ C$ and division into agroclimatic districts. Also, based on the study (Kryza et al., 2014), SAT values changed in the years 1970-2010 in the cross-border region of Poland, the Czech Republic, and Germany.

In comparing temperature conditions, the authors focus on changes in the length of the growing season. In Slovakia, they compared the number of days of the growing season for *Solanum lycopersicum, Brassica oleracea, Daucus carota* (Čimo et al., 2020), *Beta vulgaris, Citrullus lanatus* (Čimo et al., 2022), *Capsicum annum* (Čimo et al., 2020). They also made a prediction of temperature changes for the period up to the year 2100 (Čimo et al., 2020).

When analyzing the frost-free season (the period between the last frost in spring and the first frost in autumn), changes can also be seen. In the USA, this period has shifted by one week since 1980 (Kunkel et al., 2004).
Figure 3: Sum of active temperature (TS ≥ 5 °C) for period a) 1931-1960, b) 1961-1990 and c) 1991-2020

Legend
- State border
- Elevation > 800 m
- Predominantly cold agroclimatic district with TS5 ≤ 2200 °C
- Moderately cold agroclimatic district with TS5 from 2200 °C to 2500 °C
- Weak moderately warm agroclimatic district with TS5 from 2500 °C to 2650 °C
- Relatively moderately warm agroclimatic district with TS5 from 2650 °C to 2800 °C
- Relatively warm agroclimatic district with TS5 from 2800 °C to 3000 °C
- Sufficiently warm agroclimatic district with TS5 from 3000 °C to 3200 °C
- Predominantly warm agroclimatic district with TS5 from 3200 °C to 3400 °C
- Very warm agroclimatic district with TS5 ≥ 3400 °C
Figure 4: Average absolute minimum temperatures for period a) 1931-1960, b) 1961-1990 and c) 1991-2020

From the point of view of the current situation in the winter months (December to February) in 2022 in Slovakia, it did not freeze continuously in Somotor, Michalovce and Vysoká nad
Uhom for 23 days in a row, which represents the longest registered winter frost-free period in the last at least 63 years at any of our climatological stations in areas outside western Slovakia. The station record for the longest frost-free winter period has been achieved so far in the winter 2022/2023 at several climatological stations, including those measuring over 60 years (Pecho & Výberči, 2023). This also supports our claim about the changing conditions of the absolute temperature minimum.

Despite the fact that the growing season is lengthening, the sums of active temperatures are increasing and the period with frosts is shortening, which could sound like a positive for farmers, these changes also have negatives. The main impact of higher temperatures was in the reproductive stage of development, when the grain yield in maize was significantly reduced by up to 80–90% compared to the normal temperature regime (Hatfield & Prueger, 2015).

Early onset of flowering creates the risk of flowers being destroyed by spring frosts and disruption of the food chain. Despite the fact that frosts are not as strong as in the past, they still occur and can destroy crops, especially fruit trees. Also, the period without frost and snow causes a lack of moisture for plants in the spring months and there are frequent periods of drought (Liang et al., 2020). In addition, due to the frost-free period, pathogens occur more often in the soil (Sorensen et al., 2019). Last but not least, the earlier onset of the growing season results in more frequent occurrence of allergies (Anderegg et al., 2021).

In this study, we pointed out precisely these changes in Slovakia and, based on map outputs, to identify locations where it will be necessary to better adapt to these changes.

4. **Conclusion**

In this work, we dealt with the development of temperatures and changes in the sums of active temperatures and changes in absolute minimum temperatures in the period 1931-2020. The results show an increase in the area of the territory with temperatures above 3,400 °C, which caused an extension of the growing season and high average temperatures in the summer months. Conversely, areas with absolute minimum temperatures $T_{\text{min}} \leq -24$ °C decrease significantly. These facts affect the development of plants - droughts in the spring and summer months, but also the occurrence of diseases caused by insufficient freezing of the soil and the lack of moisture from the snow cover, which has hardly occurred in the southern parts of Slovakia in recent years. Therefore, it is necessary to adapt to these changes, as the situation is expected to worsen.
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