AIR TEMPERATURE CHANGES IN THE PERIOD 1991 – 2020

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In the article, we provide a detailed description of the preparation and execution, evaluation of air temperature norms for the period 1991 – 2020. WMO international procedures were taken into account during the selection and completion of individual meteorological elements and their characteristics. In the work there were used mathematical and statistical procedures that take into account breaks and inhomogeneity (MASH) in the time series so that it was possible to create the largest possible number of places (points on the map) representing the territorial units of Slovakia with the values of the relevant characteristics. In the end, 88 points were created for the average air temperature, for the average maximum and minimum air temperature, for the number of summer, tropical, frost and ice days, as well as for the number of days with a tropical night, 56 points for the absolute maximum and minimum air temperature. Base on obtaining homogeneous data, normal of the average start and end of days with 5, 10 and 15 °C were subsequently prepared. All the values calculated in this way will serve for at least 10 years (WMO) as a benchmark for comparison with current (self-corresponding) values (characteristics). However, the results (trend) expected, are worrying for the further development of humanity.

This paper further investigates the relationships between elevation and warming across Slovakia to understand the spatial and temporal behavior of annual and seasonal air temperatures and to test the hypothesis of increased warming with elevation. Over the 60 years of the data set (1961 – 1990 and 1991 – 2020), temperature trend and elevation warming analyzes were performed. Slovakia is under visible annual and seasonal warming (stronger in summer and winter), both during the day and at night. These results could serve as a reference for further investigation of the effects of climate warming not only in Slovakia, but also in the wider region (e. g. The Carpathians) especially in relation to increased summer heat stress (e.g. more frequent and intense heat waves and milder winters), which we also documented by analyzing changes in the number of summer, tropical days and frost and ice days.

V článku podávame podrobný popis prípravy a vyhotovenia, zhodnotenia normálov teploty vzduchu za obdobie 1991 – 2020. Pri výbere a kompletizácii jednotlivých meteorologických prvkov a ich charakteristík boli zohľadnené medzinárodné postupy WMO. V práci boli využité matematické a štatistické postupy riešiace prerušenia a nehomogenity (MASH) v časovom rade tak, aby bolo možné vytvoriť čo najväčší počet miest (bodov na mape), reprezentujúce územné celky Slovenska s hodnotami príslušných charakteristík. V konečnom dôsledku tak bolo vytvorených 88 bodov pre priemernú teplotu vzduchu, pre priemerné maximum a minimum teploty vzduchu, pre počty letných, tropických, mrazových a ľadových dní, ako aj pre počty dní s tropickou nocou, 56 bodov pre absolútne maximum a minimum teploty vzduch. Na základe získania homogénnych údajov boli následne pripravené normály priemerného nástupu a ukončenia dní s 5, 10 a 15 °C. Všetky takto vypočítané hodnoty budú slúžiť minimálne 10 rokov (WMO) ako etalón pre porovnávanie s aktuálnymi (sebe odpovedajúcimi) hodnotami (charakteristikami). Výsledky, (trend) akokoľvek očakávané, sú pre ďalší vývoj ľudstva znepokojujúce.

Táto práca ďalej skúma vzťahy medzi nadmorskou výškou a otepľovaním na Slovensku, aby sme pochopili priestorové a časové správanie ročných a sezónnych teplôt vzduchu a otestovali hypotézu zvýšeného otepľovania s nadmorskou výškou. Počas 60 rokov súboru údajov (1961 – 1990 a 1991 – 2020) sa vykonali analýzy trendu teplôt a výškového otepľovania. Na Slovensku je viditeľné ročné a sezónne otepľovanie (silnejšie v lete aj v zime), cez deň aj v noci. Tieto výsledky by mohli slúžiť ako referencia pre ďalšie skúmanie dôsledkov otepľovania klímy nielen na Slovensku, ale aj v širšom regióne (napr. Karpaty), najmä v súvislosti so zvýšeným letným tepelným stresom (napr. častejšie a intenzívnejšie vlny horúčav a miernejšie zimy), čo sme zdokumentovali aj analýzou zmien v počte letných, tropických, mrazových a ľadových dní.

Key words: normal air temperature, climate change, MASH, summer, tropical, frost and ice days, 1991 – 2020

INTRODUCTION

Leaving aside the very early records that mankind has observed for millennia, but not always with accurate or continuous records, often mixed with other subsequent events (this does not detract from their importance in the historical context, even for historical climatology), often kept in national libraries and archives, here we focused on regular measurements. Early records in manuscript form were kept in daily, weekly or monthly journals. Since the 1940s, and especially following the establishment of WMO, standardized forms and procedures have gradually become prevalent, and national meteorological archives have been designated as the storage site for these records.

Chronological record, constantly updated, in sequential order, methodical and careful tracking and record keeping enabled easier collection, archiving and subsequent use of records. Since the late twentieth century, most weather information has been transmitted digitally to centralized national collection centers. As the messages have been intended primarily for operational weather forecasting, it has been common practice to rely on the original observing documents for the creation of the climate record in climate centers around the world. The collection, transmission, processing and storage of operational meteorological data however, being dramatically improved by rapid advances in computer technology, and meteorological archives are increasingly being populated with data that have never been recorded on paper. The power and ease of use of computers, the ability to record and transfer information electronically, and the development of international exchange mechanisms such as the Internet have given climatologists new tools to rapidly improve the understanding of climate. Absorbing all the knowledge mentioned above and using archival digitized records, we performed analyzes of meteorological data and calculations based on the recommendations of the WMO Guidelines on the Calculation of Climate Normals (2017) and WMO Guide to Climatological Practices (2018).

DATA

The observed daily maximum (t_max), minimum (t_min) and average (t_avg) air temperatures were analyzed at 88 meteorological stations of the Slovak Republic for the period 1991 – 2020 (Fig. 1 – Fig. 3). The selection of stations was prepared according to the following WMO criteria (2017):

"Complete" - All climatological stations have a **completed daily and monthly series measurements**.

"WMO Guide" – Climatological stations that **meet requirements of the WMO Guide**.

Figure 1. Location of analyzed stations for period 1991 – 2020.

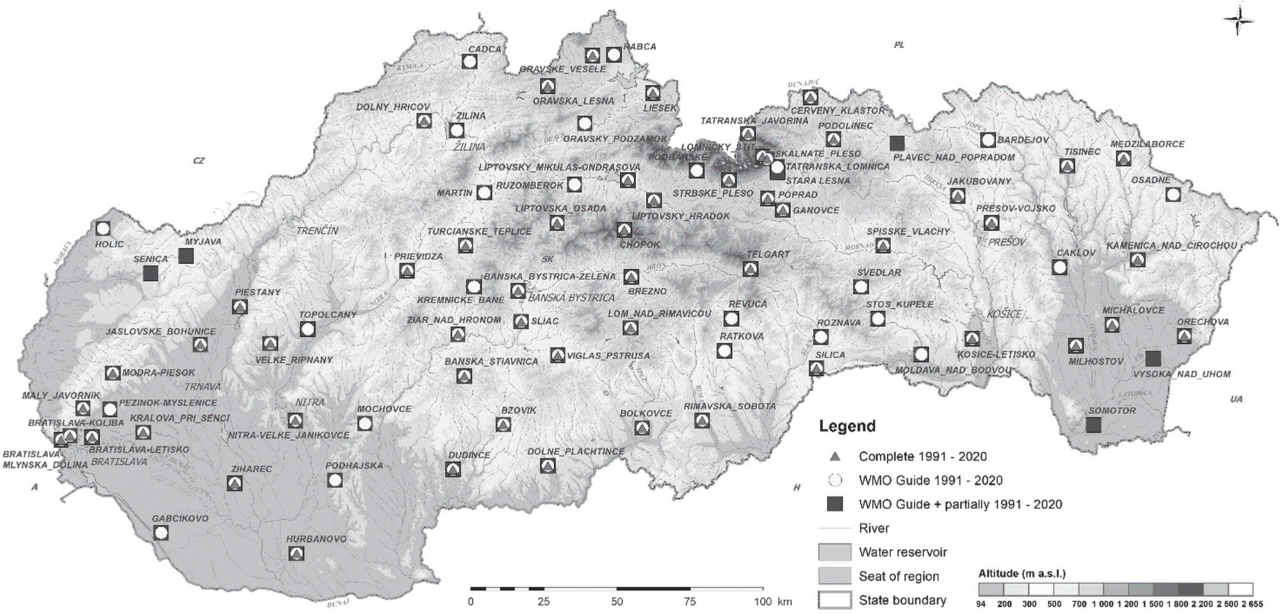


Figure 2. Complete analyzed station network for preparing climate normal for period 1991 – 2020.

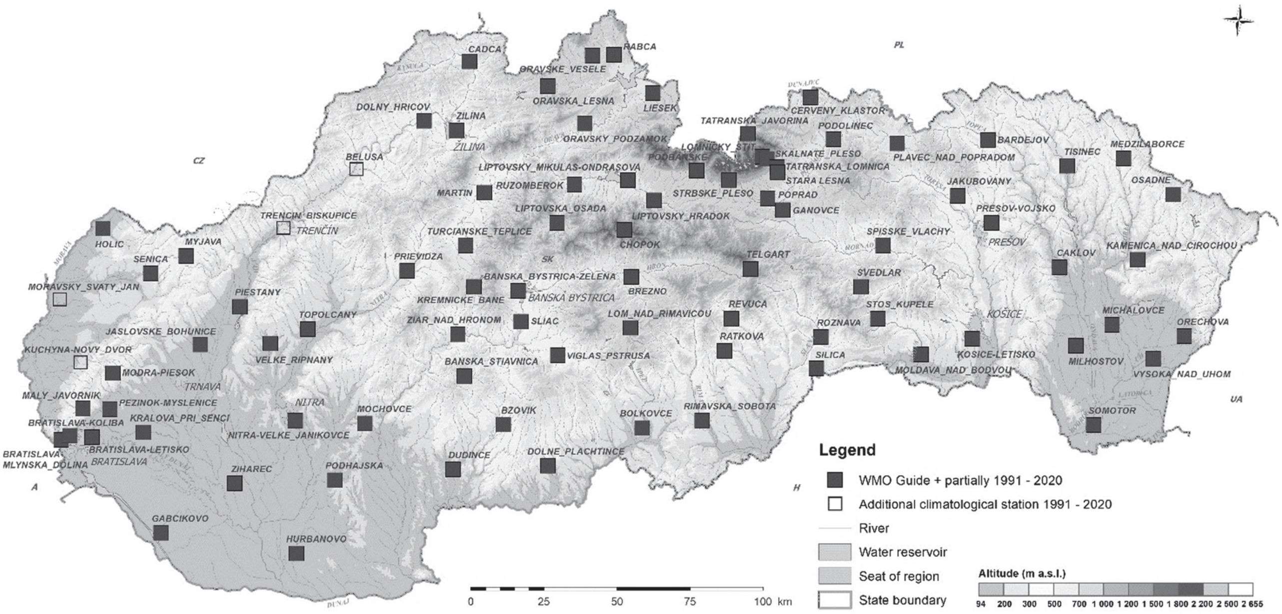
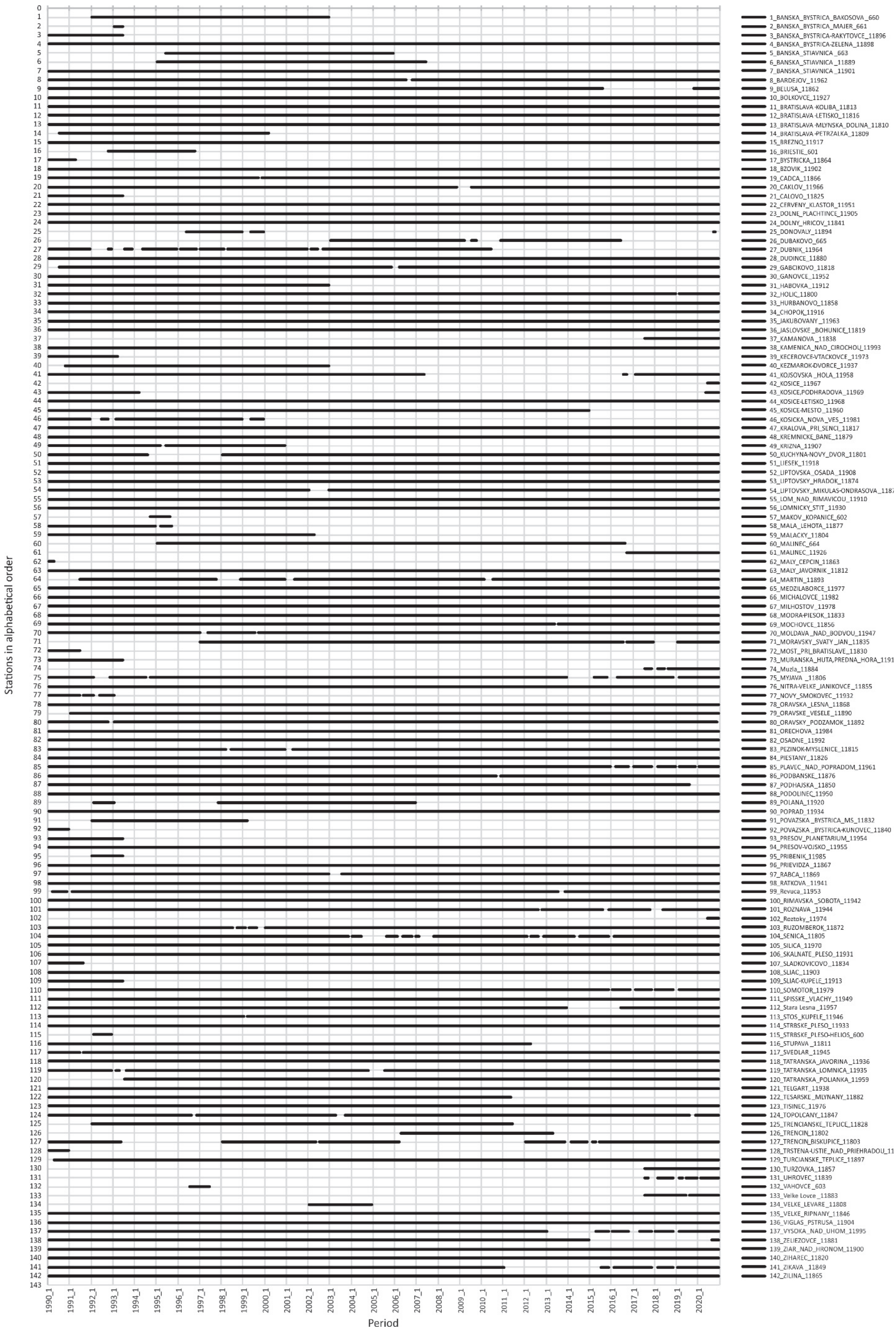


Figure 3. Data availability by meteorological station name in the period 1991 – 2020.



"WMO Guide + partially" – Climatological stations meeting the conditions of the **WMO GUIDE only in a certain part of the series** (understood the months for 1991 – 2020).

"According to the position extreme" – Climatological stations, meeting the conditions of the **WMO GUIDE only in number of years** its inclusion is possible under the assumption of the same year of occurrence of the extreme (for a given month in the period 1991 – 2020) as at the surrounding stations.

"Note to daily data" – at climatological stations, their daily records, there are incomplete time series (the month has an incomplete number of daily measurements).

Timelines of station measurement history

Because some territorially important stations dropped out of the list, we also built a graph of the occurrence of data in the timeline arranged by:

a) Alphabetically order (station name, Fig. 3);
b) Meteorological station indicator.

This helped us to construct some other time series that fulfil the gap in station map

METHODS

MASH methods

Possible break points and shifts detect and adjust through mutual comparisons of series within the same climatic area. The candidate series chose from the available time series and the remaining series consider as reference series. The role of series changes "step by step" in the course of the procedure. Depending on the climatic elements, additive or multiplicative models are applied. The second case transform into the first one by logarithmization.

Several difference series construct from the candidate and weighted reference series. The optimal weighting is determined by minimizing the variance of the difference series, in order to increase the efficiency of the statistical tests. Assuming that the candidate series is the only common series of all the difference series, we assign the boundary points found in all the difference series to the candidate series. A new multiple break points detection procedure has been developed which takes the problem of significance and efficiency into account. We formulate significance and effectiveness according to conventional statistics regarding errors of the first and second type. This test obtains not only estimated break points and shift values, but the corresponding confidence intervals as well. We adjust the series using point and interval estimates. This version is evolving towards automation. Some developments connect with special problems of the homogenization of climatic time series. One of them is the relation of monthly, seasonal and annual series. The problem arises from the fact, that the signal to noise ratio is probably less in case of monthly series than in case of derived seasonal or annual ones. Thanks to this, we can more easily detect inhomogeneity in the derived series, even if we plan to adjust the monthly series. Another issue concerns the use of metadata during the homogenization process. The developed version of MASH system makes possible to use the metadata information – in particular the probable dates of break points - automatically. This new version also includes a new transformation procedure that the author developed for the multiplicative model in order to solve the problem arising from values approaching zero. A new part of MASH system is a verification procedure (MASHVERI.BAT) which makes possible to evaluate the actual or the final stage of the homogenization. We think the verification is an important part of the topic of homogenization since all over the world there are a many so-called homogenized series however their reliability sometimes is doubtful. The basic concept of the verification procedure is that we can increase the reliability in homogenized series by joint comparative mathematical examination of the original and homogenized set of series.

The author of MASH connects the latest development with a certain automation of procedures.

Basic principles of MASH procedure:

- Relative homogeneity test procedure.
- Step by step procedure: the role of series (candidate or reference series) changes "step by step" in the course of the procedure.
- Depending on the climatic elements, we will use an additive or cumulative model.
- It is possible to homogenize monthly, seasonal or annual time series.
- In case you have monthly series for all 12 months, we can choose to homogenize the monthly, seasonal and annual series together.
- Derive daily inhomogeneities from monthly ones.
- Meta data (probable dates of break points) can be used automatically.
- There is a possibility to verify the actual or final stage of homogenization.

The mathematical basis of 'MASH' procedure

Statistical modelling:

Additive Model (for example temperature)
Examined series:

$X(t) = C_j(t) + IH_j(t) + \varepsilon(t) \qquad (j = 1, 2 \ldots N;\ t = 1, 2 \ldots . n)$

C: climate change; IH: inhomogeneity, ε: noise

Multiplicative Model
(for example monthly or seasonal precipitation)
Examined series:

$X_j^*(t) = C_j^*(t).\, IH_j^*(t).\, \varepsilon_j^*(t) \qquad (j = 1, 2 \ldots N;\ t = 1, 2 \ldots . n)$

C^*: climate change; IH^*: inhomogeneity, ε^*: noise

Logarithmization for Additive Model

$X_j(t) = C_j(t) + IH_j(t) + \varepsilon(t) \qquad (j = 1, 2 \ldots N;\ t = 1, 2 \ldots . n)$

where: $X_j(t) = \ln X_j^*(t) \qquad C_j(t) = \ln C_j^*(t)$
$IH_j(t) = \ln IH_j^*(t) \qquad \varepsilon_j(t) = \ln \varepsilon_j^*(t)$

Basic characteristics of normal values 1991 – 2020 and statistics

Processing was carried out using standard procedures for calculating monthly, seasonal and annual values in tabular form for 88 meteorological stations and for meteorological characteristics (mean air temperature, mean maximum and mean minimum air temperature, absolute minimum and maximum air temperature. Later on number of days with characteristic temperatures for a summer day (t_max ≥ 25 °C), tropical day (t_max ≥ 30 °C), day with tropical night (t_min ≥ 20 °C), frost (t_min < 0 °C), ice (t_max < 0 °C) and arctic day (t_max < –10 °C) were processed as well. The result is tabular outputs for individual stations as well as an overview table of normal values. Other statistics such as standard deviation, skewness, kurtosis, minimum and year of occurrence of minimum, maximum and year of occurrence of maximum and climatic certainty of occurrence as well as previous normal values for the periods 1981 – 2010, respectively, 1961 – 1990 were processed relied on WMO recommendations (WMO 2017, 2018).

RESULTS

Research on decadal air temperature averages

We converted the homogenized data and their characteristics into a standard form comparable to the outputs for previous periods (1981 – 2010, respectively 1961 – 1990).

For a better idea of the trend of air temperature in the historical series, we constructed the values of decade averages of air temperature at professional meteorological stations, which represent Slovakia horizontally and vertically (Fig. 4a, 4b and 4c).

Selected characteristics:

- Average decade air temperature
- Average decade maximum air temperature
- Average decade minimum air temperature

Comparison of decades of air temperature especially the normal period 1991 – 2020

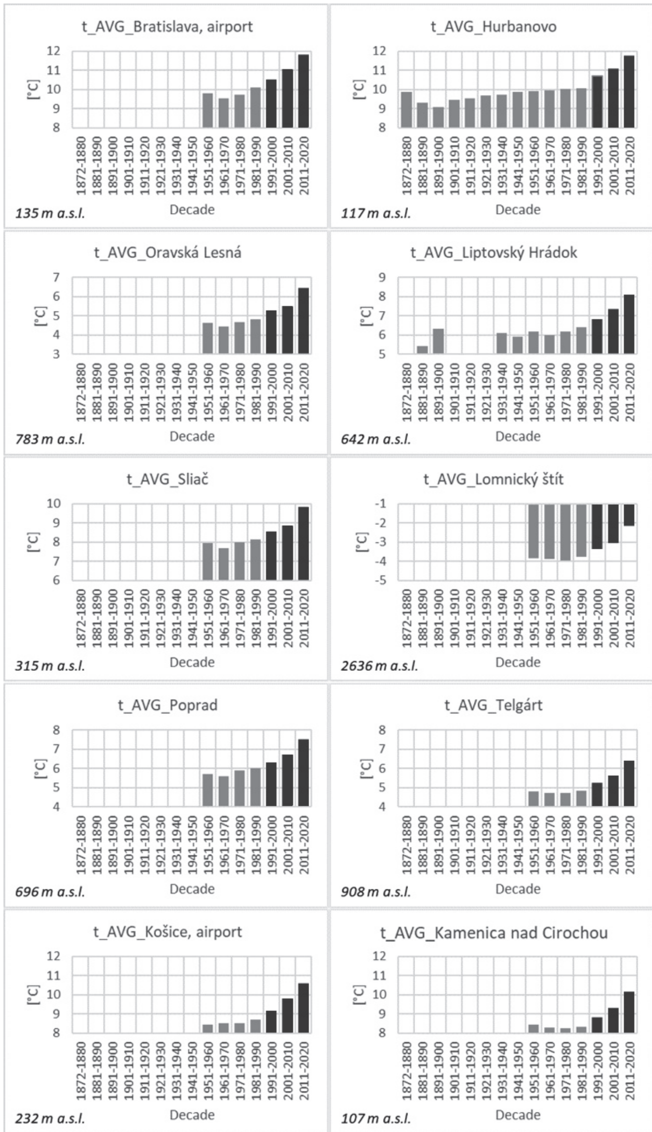
Common facts are that:

- Selected professional station represent Slovakia in latitude, longitude and altitude manner.
- The last 3 decades are the warmest.
- Never in the history of measurement has the last temperature decade been higher.
- The course of air temperature by altitude is exponential.
- The slope of the curve depends on period (season).

Decade air temperature (t_AVG)

The largest decade differences in average air temperature are clearly between the 3^{rd} and the 2^{nd} decade of the period 1991 – 2020, reaching up to 1 °C.

Figure 4a. Average decade air temperature.



Decade maximum air temperature (t_max_AVG)

The most significant decade changes in the maximum air temperature occurred between the 2^{nd} and 3^{rd} decade, reaching up to 1.1 °C.

Decade minimum air temperature (t_min_AVG)

Although the decade difference t_min_AVG between the 2^{nd} and 3^{rd} decades at selected stations was larger, it was not as significant as it was with t_AVG or t_max_AVG.

Comparison of stations of different latitude and longitude and according to altitude and different periods 1991 – 2020 compared to 1981 – 2010 and 1991 – 2020 compared to 1961 – 1990

If it considers the differences in area (longitude, latitude) and vertically (altitude), then the dependencies show the following results (Fig. 5).

Figure 4b. Average decade maximum air temperature.

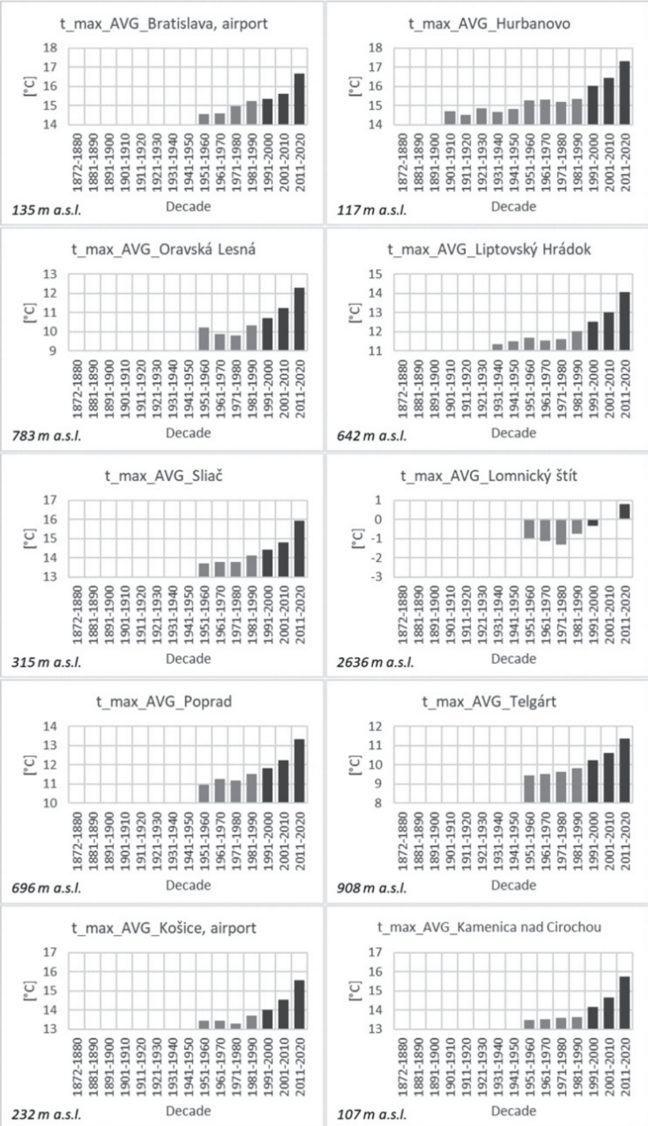
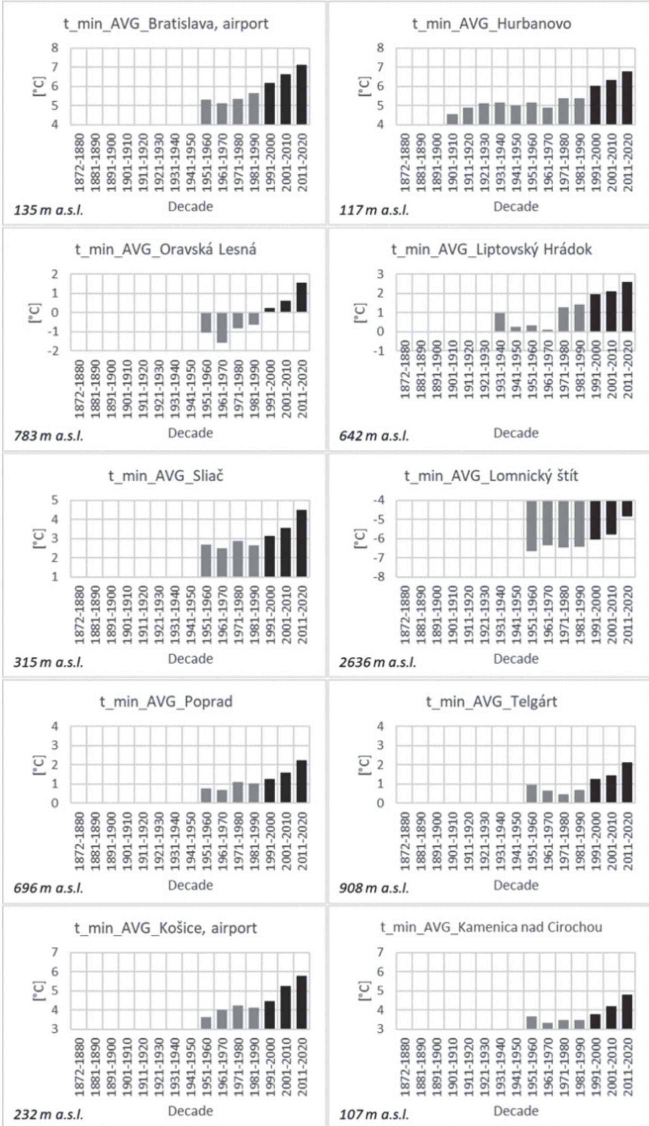


Figure 4c. Average decade minimum air temperature.



Comparing the periods 1991 – 2020, 1981 – 2010 and 1961 – 1990, we state:

- The difference in temperatures increases with time. More significantly in 1991 – 2020 compared to 1961 – 1990.
- Changing air temperature is important for various sectors (transport, tourism, agriculture, etc.). Therefore, we prepared the course of air temperature with height for comparison with the periods 1961 – 1990, 1981 – 2010. In both comparisons (1991 – 2020 versus 1961 – 1990 and 1981 – 2010), a positive difference in temperature can be seen in the corresponding altitudes. The dependence of air temperature with altitude indicates an exponential dependence in months, seasons and in the year.

Important facts:

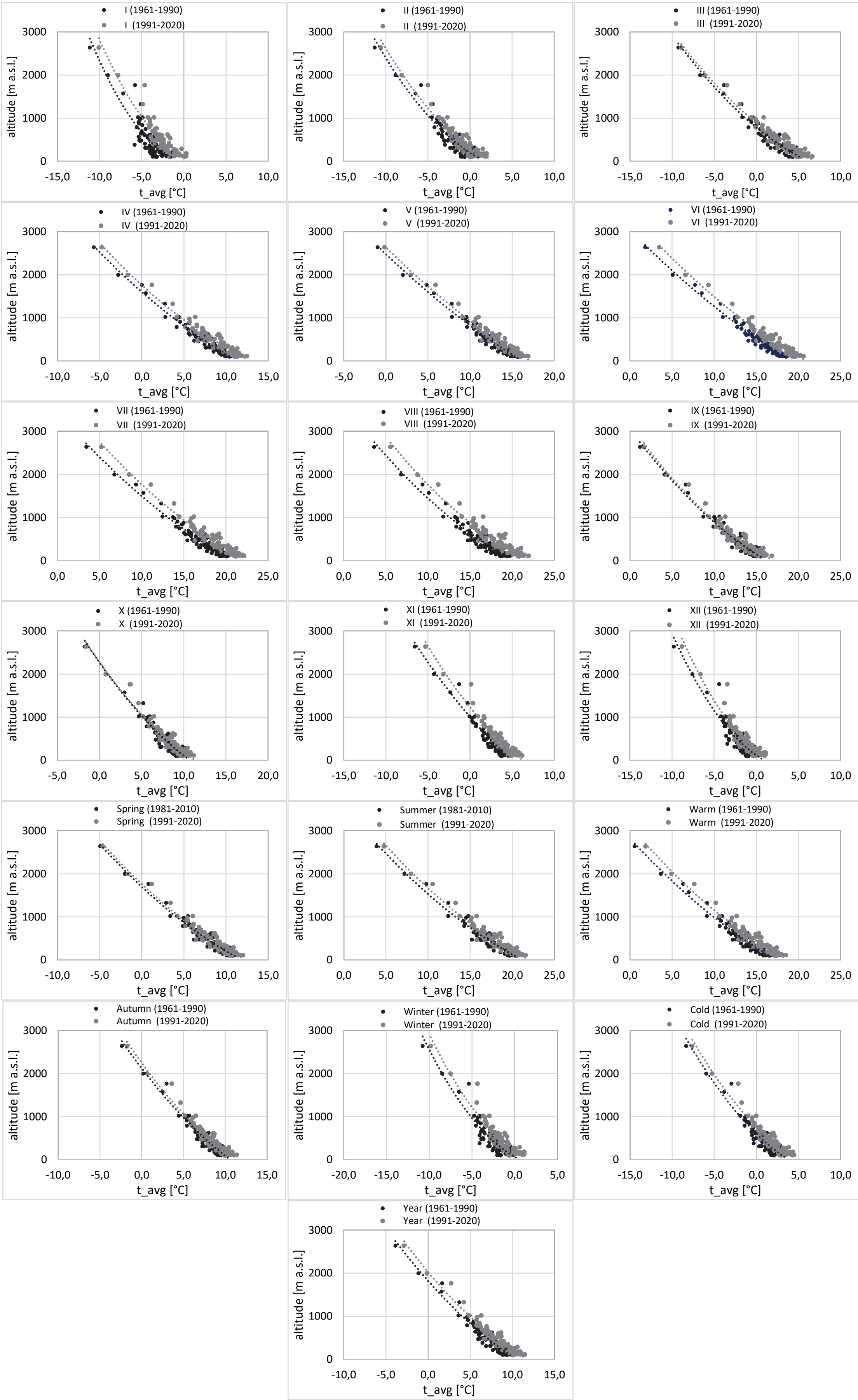
- Slope of the curve and the distance between the two curves within the month are important.
- In the winter months and in the cold half-year - a slower drop in temperature with altitude.
- In the summer months, in the spring and in the warm half-year - a faster drop in temperature with altitude.

Comparison of 1991 – 2020 and 1961 – 1990

Large (+) differences in temperature occur in: “JAN”, “JUN”, “JUL”, “AUG”, “NOV”, “DEC”.

In order to document at least some of the processes here in graphic form, we present the average air temperature in the coldest month of the year (January, Fig. 6) and in the warmest month of the year (July, Fig. 7). We used the additive model of the MASH program for homogenization. To homogenize the number of summer (Fig. 8) days (tropical, days with tropical night) or of frost (Fig. 9) days (ice, arctic) we used the multiplicative model of the MASH program and all this for the period 1991 – 2020.

Figure 5. Monthly (seasonal, yearly) average of air temperature comparison.



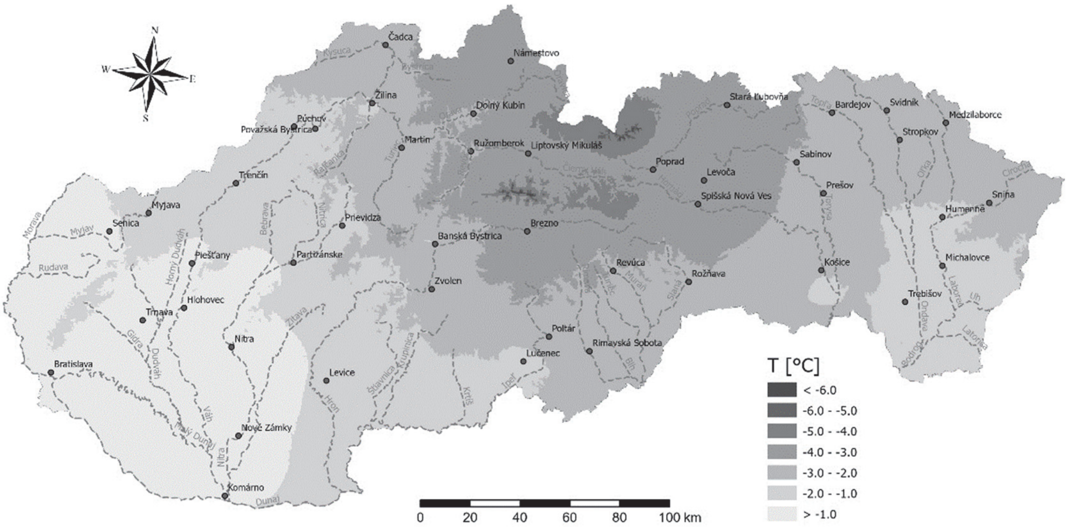


Figure 6. Map processing of January air temperature (mean monthly) in the period 1991 – 2020.

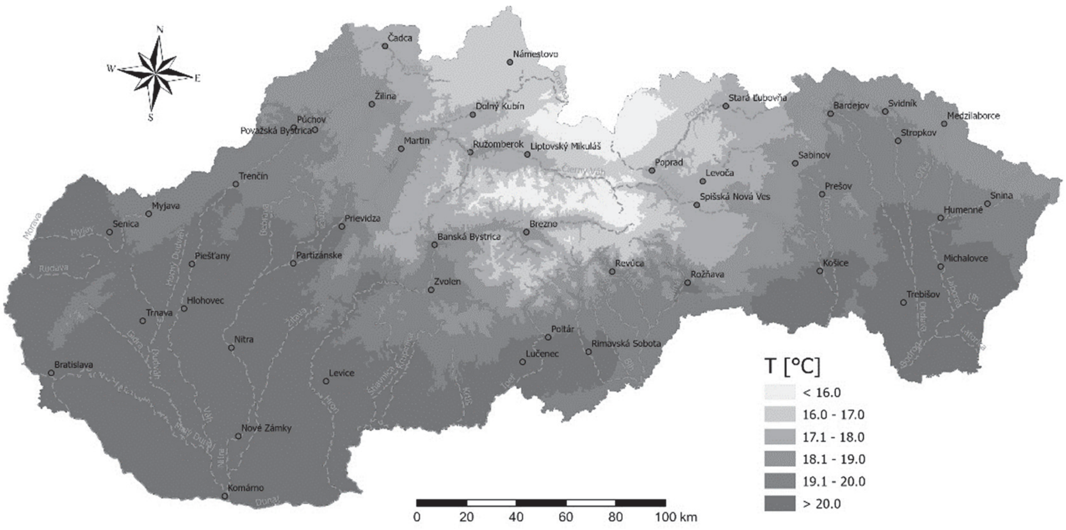


Figure 7. Map processing of July air temperature (mean monthly) in the period 1991 – 2020.

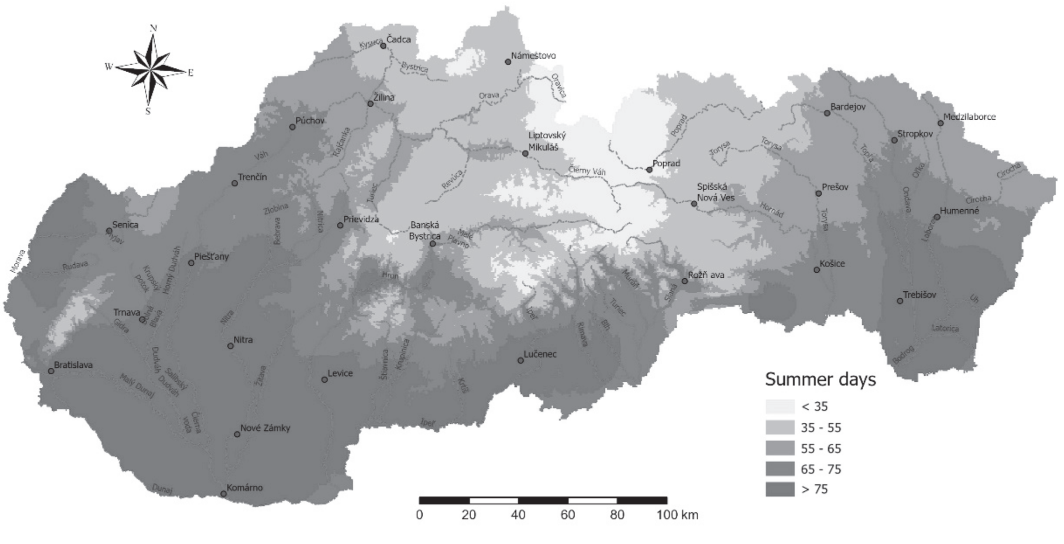


Figure 8. Map processing of summer days (annual account) in the period 1991 – 2020.

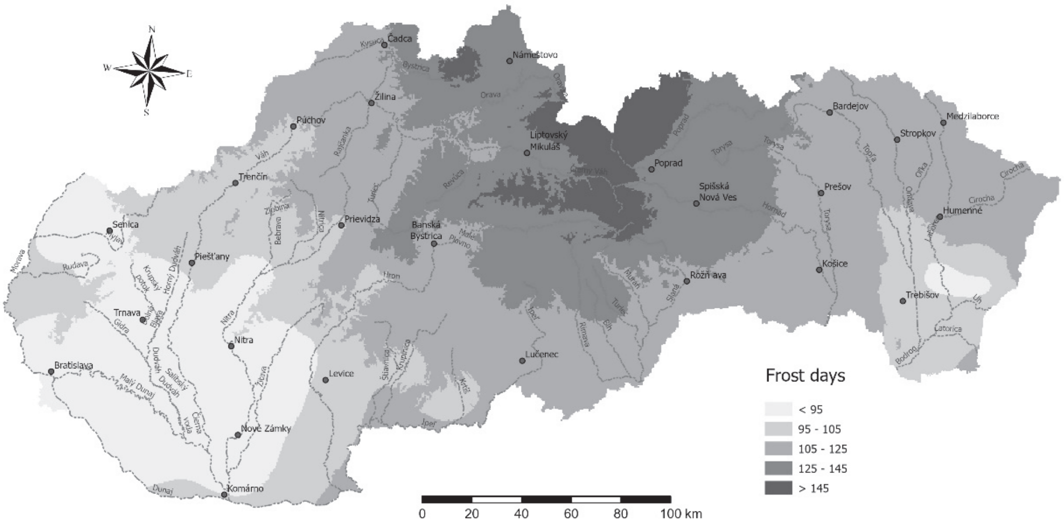


Figure 9. Map processing of frost days (annual account) in the period 1991 – 2020.

Evaluation of the change in average air temperature in the period 1991 – 2020

From a statistical (Tab. 1 and Tab. 2) point of view, the **January** trend of air temperature change turned out to be statistically insignificant (correlation coefficient (r) reached lower values of p = 0.1 (r = 0.2573) see Nosek (1972), where p is a level of significance. In January, we did not observe temperature changes during 1991 – 2020. In **February**, only at meteorological stations (from a selected number of stations) in Piešťany, Prievidza, Ružomberok, Liptovský Hrádok, Dudince, Sliač, Boľkovce and in the east of the country in Košice, airport, Medzilaborce, Milhostov, Somotor and in Kamenica nad Cirochou the changes (increase in air temperature) were statistically significant. In February, we recorded an average increase in air temperature of +2.3 °C, with maximums of 1.5 °C to 2.8 °C, especially in the east of Slovakia. In **March**, the number of statistically significant changes (increase in air temperature) expressed in the number of locations increased even more, while in some locations they were more significant (p = 0.05 (r = 0.3044)), e.g. in Bratislava at the airport, in Liptovský Hrádok, Boľkovce, Poprad, Košice at the airport, Medzilaborce, or in Kamenica nad Cirochou. In March, we observed an average increase in air temperature of +1.7 °C with a maximum in Boľkovce and Košice, airport of +2.2 °C. In **April**, with the exception of Bratislava, airport the increase in air temperature was statistically very significant (p = 0.01 (0.3932)). In April, we recorded an average increase in air temperature of +2.5 °C with a maximum in Liptovský Hrádok of +3.2 °C. On the contrary, in **May** we observed statistically insignificant changes (no trend). There was no change in air temperature behavior in May. **June** was statistically the most significant (at all locations the dependence was higher than p = 0.01 (0.3932). We recorded the closest dependence for Košice, airport (r = 0.642) and for Kamenica nad Cirochou (r = 0.627). In June, we noted an increase in air temperature on average by +2.3 °C with a maximum in Prievidza of +2.8 °C. **July** (similar to March, but with a relatively closer dependence), showed a statistically significant increase in air temperature in most places, but not as significant as in June. In July, we observed an average increase in air temperature of +1.2 °C with a maximum in Bratislava, airport of +2 °C. **August** as well as **September** showed a statistically significant trend (dependency) of an increase in air temperature. In August, we recorded an average increase in air temperature by +1.5 °C, with a maximum of +2.4 °C at Lomnický štít, and +1.9 °C at Chopok. In September, we observed an average increase in air temperature of +1.8 °C with a maximum in Košice, airport of +2.5 °C.

At most meteorological stations, **October** showed a significant or strongly significant dependence on the increase in air temperature from 1991 to 2020. In October, we recorded an increase in air temperature on average by +1.5 °C (maximum at Lomnický štít up to +2.0 °C, +1.9 °C in Chopok and Bratislava, airport). In **November** and **December**, we observed a very close to extremely close dependence (except mountain stations in December) when the air temperature increased above p = 0.02 (0.3578), respectively above p = 0.01 (0.3932). In November, we recorded an increase in air temperature by +2.7 °C on average, with a maximum of +3.6 °C at Chopok and +3.5 °C at Lomnický štít. In December, we observed an average increase in air temperature of up to +3.1 °C with a maximum in Kamenica nad Cirochou up to +4.5 °C (+3.5 °C in Somotor and Milhostov). **Seasonal** values (except in winter) showed a statistically extremely significant trend of air temperature increase above p = 0.01 (0.3932) with an average of the correlation coefficient in spring of 0.467 and a maximum of 0.588, in summer with an average of 0.537 and a maximum of 0.653, and in autumn with an average of 0.581 and a maximum of 0.705. In winter (Fig. 10), depending on the course of the air temperature from 1991 to 2020, we observed a statistically less significant closeness of the relationship than in other seasons, nevertheless more pronounced in the east of the country. In spring (Fig. 11), we recorded an average increase in air temperature by +1.5 °C with a maximum of +1.9 °C in Poprad. In the summer (Fig. 12), we observed an average increase in air temperature by +1.7 °C with a maximum in Prievidza of +2.1 °C.

Table 1. Change in average air temperature in the period 1991 – 2020.

Ind. (short)	Name	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	spring	summer	autumn	winter	Wp	Cp	year
805	Senica	0.3	1.9	1.5	2.1	0.3	2.3	1.4	1.6	1.5	1.7	2.8	3.0	1.3	1.7	2.0	1.4	1.5	1.9	1.7
816	Bratislava, airport	0.1	2.2	2.0	2.6	0.2	2.5	2.0	1.2	1.8	1.9	2.4	3.0	1.6	1.9	2.1	1.5	1.7	1.9	1.9
826	Piešťany	0.2	2.4	1.6	2.3	0.0	2.5	1.6	1.3	1.3	1.5	3.0	3.2	1.3	1.8	1.9	1.6	1.5	2.0	1.7
835	Moravský sv. Ján	0.5	1.9	1.5	2.3	0.1	2.3	1.3	1.5	1.6	1.3	2.7	3.0	1.3	1.7	1.9	1.5	1.5	1.8	1.6
858	Hurbanovo	0.2	2.1	1.4	2.3	0.0	2.1	1.6	1.2	1.5	1.3	2.6	2.9	1.2	1.7	1.8	1.4	1.4	1.7	1.6
862	Beluša	-0.1	2.2	1.7	2.6	0.0	2.3	1.3	1.5	1.5	1.5	2.7	3.3	1.4	1.7	1.9	1.5	1.5	1.9	1.7
866	Čadca	-0.2	1.8	1.8	1.9	-0.2	2.1	0.8	1.0	1.0	1.2	2.7	3.1	1.2	1.3	1.7	1.3	1.1	1.8	1.4
867	Prievidza	0.0	2.4	1.8	2.9	0.8	2.8	1.7	1.9	1.9	1.7	2.7	3.0	1.8	2.1	2.1	1.5	2.0	1.9	1.9
868	Oravská Lesná	0.1	2.0	1.5	2.8	0.3	2.4	1.1	1.6	1.8	1.4	3.0	3.2	1.5	1.7	2.0	1.5	1.7	1.9	1.8
872	Ružomberok	-0.3	2.5	1.6	2.6	-0.2	2.2	0.8	1.3	1.6	1.0	2.5	2.8	1.3	1.4	1.7	1.4	1.3	1.7	1.5
874	Liptovský Hrádok	0.1	2.7	2.0	3.2	0.2	2.6	1.4	1.7	2.0	1.4	2.5	3.4	1.8	1.9	2.0	1.8	1.8	2.1	1.9
880	Dudince	0.3	2.7	1.6	2.1	0.1	2.3	1.3	1.3	1.6	1.4	2.7	3.1	1.2	1.7	1.9	1.6	1.5	1.9	1.7
903	Sliač	-0.2	2.6	1.7	2.5	0.0	2.4	1.2	1.7	2.0	1.8	2.6	3.0	1.4	1.8	2.2	1.3	1.6	1.8	1.8
916	Chopok	-1.2	1.2	1.5	3.0	0.6	2.6	0.9	1.9	2.4	1.9	3.6	2.0	1.7	1.9	2.6	0.4	1.9	1.5	1.7
927	Boľkovce	0.2	2.5	2.2	2.5	0.4	2.1	1.2	1.6	2.0	1.5	2.7	3.0	1.7	1.7	2.0	1.4	1.6	1.9	1.8
930	Lomnický štít	-1.1	1.6	1.5	3.0	0.6	2.4	0.7	2.4	2.3	2.0	3.5	1.6	1.7	1.8	2.6	0.4	1.9	1.5	1.7
934	Poprad	-0.4	1.9	2.1	3.0	0.5	2.5	1.3	1.6	2.0	1.5	2.7	3.4	1.9	1.8	2.1	1.4	1.8	1.9	1.9
938	Telgárt	-0.5	1.8	1.7	2.8	0.5	2.1	1.2	1.5	1.9	1.5	2.8	2.4	1.6	1.6	2.1	0.9	1.7	1.6	1.6
962	Bardejov	0.0	2.1	1.5	1.9	-0.3	1.7	0.5	1.1	1.9	1.1	2.6	3.4	1.0	1.0	1.1	1.9	1.6	1.1	1.7
968	Košice, airport	0.4	2.8	2.2	2.8	0.7	2.6	1.3	2.2	2.5	1.7	2.9	3.6	1.9	2.0	2.4	2.0	2.0	2.3	2.1
977	Medzilaborce	0.5	2.8	2.1	2.3	0.5	2.3	0.9	1.1	1.9	1.8	2.7	3.8	1.6	1.7	2.3	2.2	1.7	2.3	2.0
978	Milhostov	0.3	2.6	1.7	2.0	0.1	2.0	1.0	1.8	2.4	1.1	2.4	3.5	1.3	1.6	2.0	1.9	1.6	1.9	1.8
979	Somotor	0.5	2.8	1.6	1.6	-0.4	1.4	0.0	0.8	1.7	0.7	2.4	3.5	0.9	0.7	1.6	2.0	0.9	1.9	1.4
993	Kamenica n/C	0.8	2.8	2.0	2.5	0.7	2.5	1.1	1.8	1.9	1.3	2.6	4.5	1.7	1.8	1.9	2.5	1.8	2.3	2.1

Legend: *JAN - January, FEB - February, MAR - March, JUN - June, JUL - July, AUG - August, SEP - September, OCT - October, NOV - November, DEC - December, spring - March to May, summer - June to August, Autumn - September to November, Winter - December to February, Wp - April to September, Cp - October to March, year - January to December.*

Table 2. Correlation coefficient of change in average air temperature in the period 1991 – 2020.

Ind. (short)	Name	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	spring	summer	autumn	winter	Wp	Cp	year
805	Senica	0.045	0.203	0.250	0.398	0.054	0.489	0.296	0.287	0.288	0.313	0.422	0.458	0.410	0.483	0.567	0.253	0.539	0.431	0.615
816	Bratislava, airport	0.014	0.238	0.324	0.014	0.051	0.524	0.401	0.221	0.352	0.374	0.392	0.480	0.488	0.516	0.623	0.269	0.604	0.458	0.664
826	Piešťany	0.024	0.271	0.263	0.403	0.006	0.554	0.350	0.254	0.257	0.267	0.433	0.466	0.405	0.537	0.530	0.282	0.550	0.451	0.651
835	Moravský sv. Ján	0.059	0.212	0.256	0.401	0.017	0.481	0.280	0.287	0.349	0.256	0.415	0.422	0.395	0.500	0.554	0.249	0.550	0.419	0.651
858	Hurbanovo	0.026	0.223	0.245	0.428	0.004	0.469	0.356	0.238	0.299	0.256	0.380	0.439	0.387	0.498	0.556	0.247	0.543	0.424	0.631
862	Beluša	0.014	0.255	0.270	0.458	0.008	0.541	0.297	0.300	0.301	0.281	0.401	0.450	0.438	0.531	0.553	0.262	0.590	0.429	0.674
866	Čadca	0.028	0.200	0.266	0.358	0.046	0.509	0.187	0.230	0.233	0.228	0.398	0.386	0.369	0.453	0.525	0.213	0.480	0.399	0.573
867	Prievidza	0.003	0.277	0.282	0.483	0.145	0.595	0.347	0.366	0.360	0.316	0.384	0.423	0.521	0.626	0.579	0.252	0.697	0.429	0.706
868	Oravská Lesná	0.008	0.218	0.242	0.496	0.057	0.534	0.265	0.382	0.371	0.254	0.415	0.417	0.469	0.587	0.589	0.257	0.680	0.429	0.674
872	Ružomberok	0.037	0.273	0.265	0.458	0.050	0.494	0.187	0.284	0.326	0.185	0.364	0.373	0.410	0.485	0.491	0.230	0.519	0.399	0.607
874	Liptovský Hrádok	0.010	0.288	0.309	0.551	0.039	0.605	0.324	0.399	0.406	0.285	0.348	0.439	0.543	0.611	0.562	0.292	0.690	0.452	0.706
880	Dudince	0.033	0.289	0.296	0.386	0.026	0.527	0.306	0.271	0.341	0.293	0.412	0.414	0.430	0.537	0.588	0.261	0.570	0.437	0.674
903	Sliač	0.028	0.276	0.293	0.472	0.004	0.589	0.290	0.365	0.401	0.361	0.392	0.373	0.476	0.589	0.629	0.214	0.641	0.397	0.670
916	Chopok	0.156	0.172	0.242	0.501	0.108	0.566	0.195	0.394	0.388	0.261	0.294	0.282	0.521	0.586	0.609	0.094	0.701	0.407	0.702
927	Boľkovce	0.020	0.274	0.369	0.494	0.074	0.530	0.307	0.340	0.391	0.315	0.413	0.365	0.555	0.561	0.637	0.233	0.628	0.432	0.700
930	Lomnický štít	0.156	0.213	0.240	0.485	0.117	0.497	0.163	0.530	0.360	0.267	0.504	0.229	0.513	0.591	0.566	0.081	0.708	0.394	0.731
934	Poprad	0.046	0.192	0.323	0.551	0.107	0.639	0.339	0.398	0.399	0.286	0.375	0.435	0.588	0.653	0.614	0.234	0.724	0.420	0.720
938	Telgárt	0.087	0.219	0.269	0.513	0.110	0.545	0.291	0.355	0.358	0.266	0.422	0.386	0.521	0.578	0.597	0.196	0.656	0.401	0.711
962	Bardejov	0.003	0.243	0.238	0.369	0.065	0.473	0.114	0.316	0.392	0.239	0.379	0.450	0.336	0.336	0.429	0.622	0.273	0.487	0.394
968	Košice, airport	0.065	0.342	0.343	0.519	0.132	0.642	0.284	0.457	0.456	0.343	0.455	0.473	0.560	0.624	0.705	0.352	0.673	0.519	0.779
977	Medzilaborce	0.066	0.329	0.308	0.455	0.107	0.578	0.206	0.316	0.471	0.338	0.378	0.488	0.565	0.624	0.664	0.376	0.706	0.499	0.794
978	Milhostov	0.041	0.319	0.278	0.394	0.022	0.558	0.230	0.405	0.459	0.251	0.390	0.473	0.452	0.527	0.647	0.336	0.610	0.452	0.716
979	Somotor	0.071	0.325	0.250	0.327	0.069	0.412	0.005	0.179	0.322	0.151	0.397	0.475	0.306	0.252	0.557	0.353	0.335	0.443	0.595
993	Kamenica n/C	0.105	0.294	0.306	0.473	0.141	0.627	0.266	0.435	0.389	0.249	0.333	0.533	0.551	0.610	0.582	0.379	0.677	0.479	0.595

Legend: *Correlation coefficient values for the significance limit $p = 0.1$; 0.05; 0.02 and 0.01.*
$p = 0.1$ (0.2960); $p = 0.05$ (0.3494); $p = 0.02$ (0.4093) $p = 0.01$ (0.4487)

Figure 10. Map processing of average air temperature change (winter) in the period 1991 – 2020.

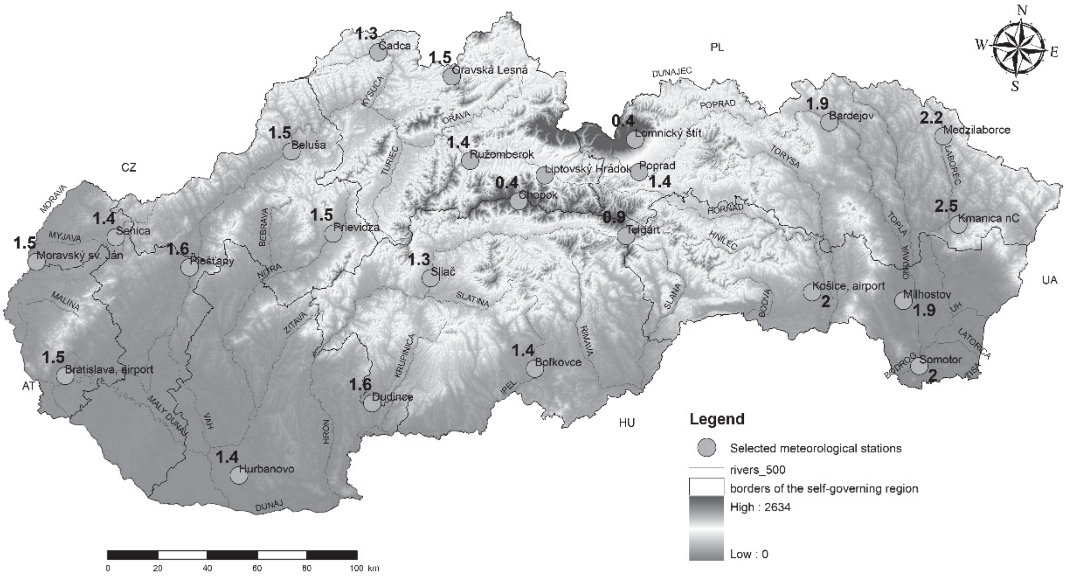


Figure 11. Map processing of average air temperature change (spring) in the period 1991 – 2020.

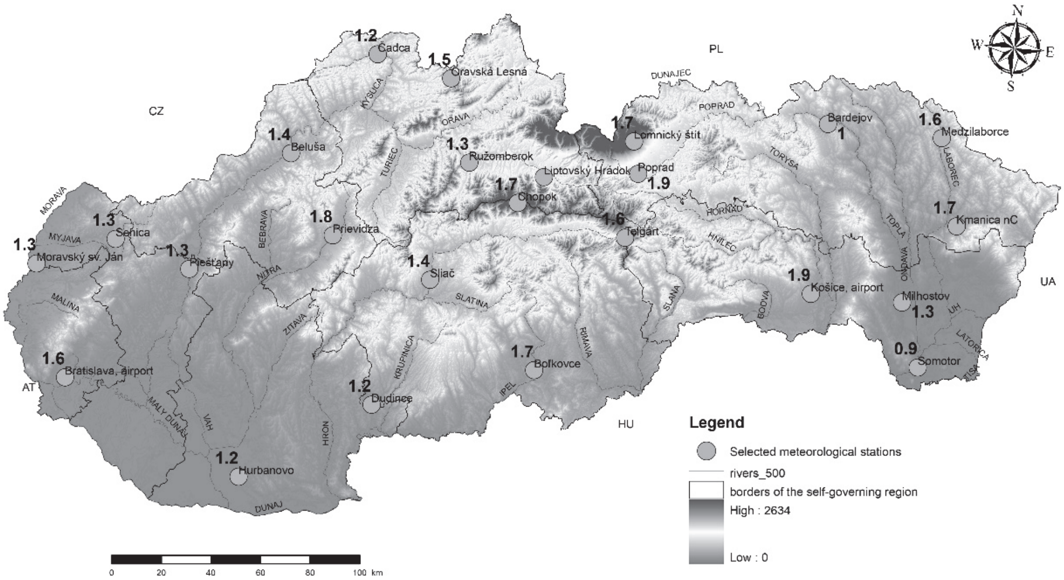


Figure 12. Map processing of average air temperature change (summer) in the period 1991 – 2020.

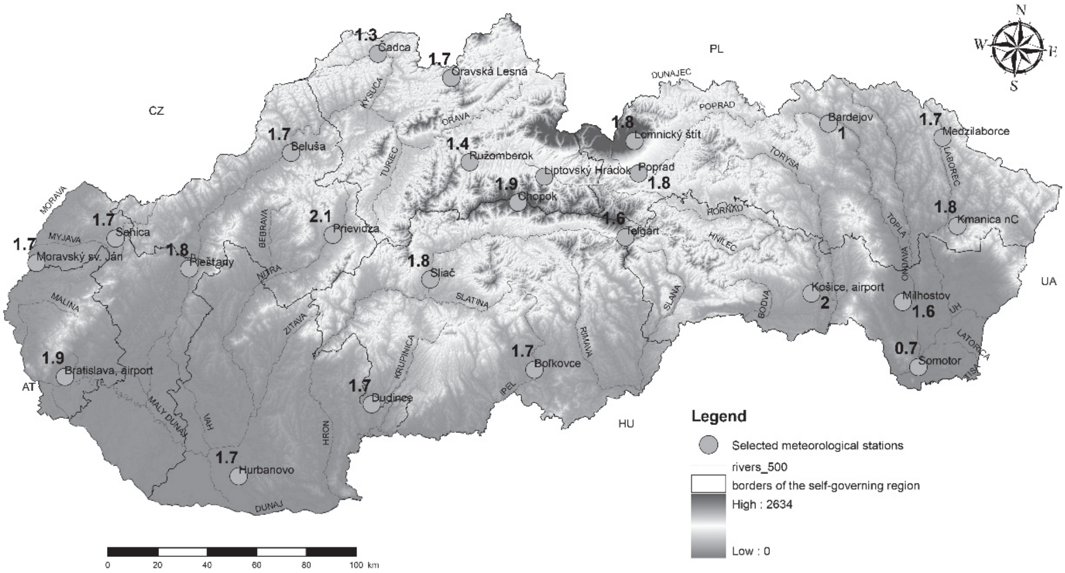


Figure 13. Map processing of average air temperature change (autumn) in the period 1991 – 2020.

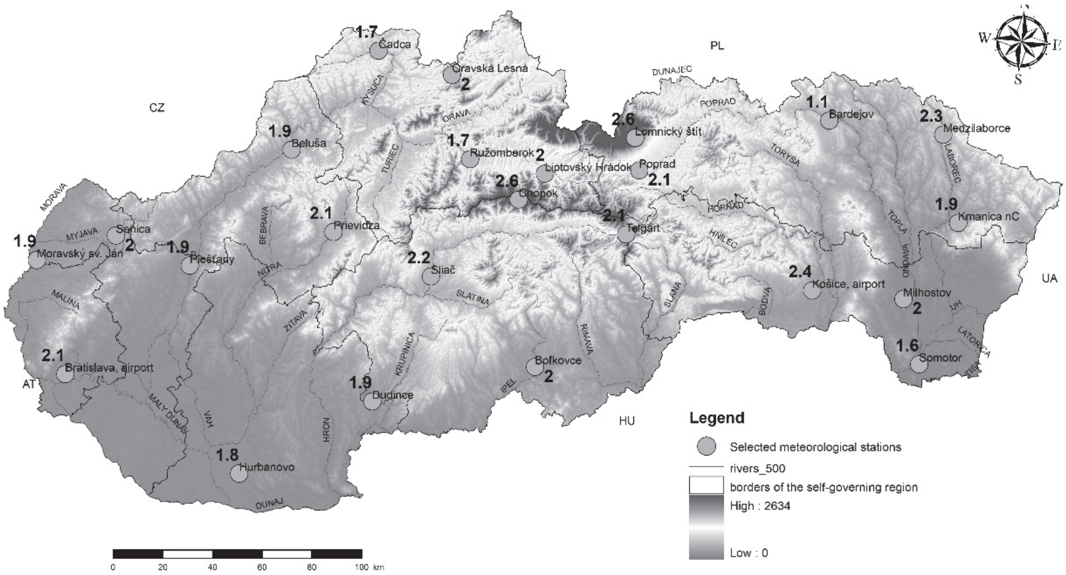
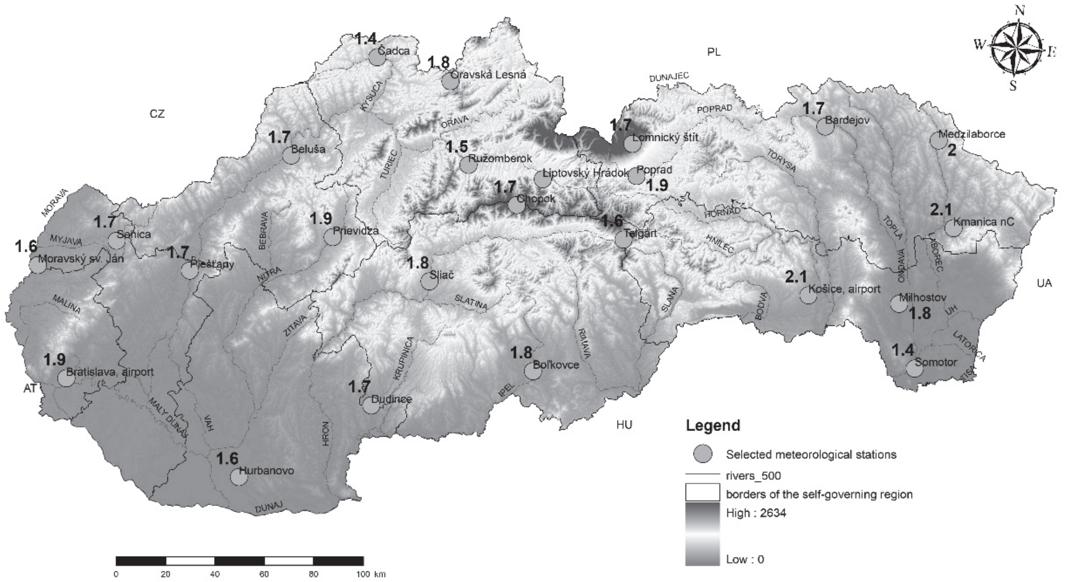


Figure 14. Map processing of average air temperature change (annual) in the period 1991 – 2020.



In autumn (Fig. 13), we recorded an increase in the air temperature by +2 °C on average, with a maximum of +2.6 °C at both Chopok and Lomnický štít. In winter, we observed an average increase in air temperature of +1.5 °C with a maximum in Kamenica nad Cirochou of +2.5 °C. In the **warm** half-year (April to September), we observed a very close to extremely close dependence expressed by the increase in air temperature in the period from 1991 to 2020 (correlation coefficient on average 0.598 and maximum 0.724). In the warm half-year, we recorded an average increase in air temperature of +1.6 °C with a maximum of +2 °C in Prievidza and Košice. In the **cold** half-year (October to March), we observed an extremely close dependence in the period from 1991 to 2020 (correlation coefficient on average 0.437 and maximum 0.519). The dependence is smaller than in the warm half-year, nevertheless extremely significant. In the cold half of the year, we observed an average increase in air temperature by +1.9 °C with a maximum in the east of Slovakia in Košice, airport, Medzilaborce and Kamenica nad Cirochou by +2.3 °C. In the **annual** values of the average air temperature, there was a significant dependence on the growth of the air temperature in the period 1991 to 2020, with an average value of the correlation coefficient of 0.664 and a maximum of 0.794 in the entire territory of Slovakia. In the annual values of the average air temperature (Fig. 14), we recorded an increase in air temperature on average by +1.8 °C with a maximum of +2.1 °C in Kamenica nad Cirochou.

Evaluation of the change in the number of frost days in the period 1991 – 2020

Changes in the number of frost days are observed especially when there are more days with (minimum) temperatures above 0 °C, thus the number of frost days decreases (negative trend). This happens (from a selected number of meteorological stations sufficiently covering the territory of Slovakia) mainly in February, March and April. Also in the highest mountain locations in June and September respectively (Tab. 3 and Tab. 4). With the increasing decrease in temperature, the most pronounced (understand at a significant number of stations) in October (on average a decrease of –4.9 frost days compared to the value from the period 1991 – 2020), in November (–6.6) and in December (–6.5).

During the annual seasons, we observed significant changes in spring with an average decrease of 9.2 days (calculated only from statistically significant decreases, see Tab. 4), respectively at mountain stations and in summer (Chopok –5.8 days and Lomnický štít –13, 2 days). We observed a clear decrease (statistically significant) at all stations in autumn with an average decrease of –11.1 days. In the winter period (December to February), we recorded a (statistically) significant decrease in Prievidza (–10.2 days), Oravská Lesná (–6.2 days), Liptovský Hrádok (–7.4 days), Sliač (–11.3 days), in Poprad (–5.5 days) and in the east of the country with an average decrease of up to –14.6 days. In the warm part of the year (April to September), we observed changes in the number of frost days on Chopok –19.1 days, in Boľkovce –4 days, on Lomnický štít up to –24.7 days and in Medzilaborce –11 days.

In the cold half-year (October to March), the average decrease was –24.6 days. In the annual frequency, we recorded an average decrease from all (selected) meteorological stations –28.2 days for the period 1991 – 2020.

Table 3. Statistically significant change in the number of frost days in the period 1991 – 2020.

Ind. (short)	Name	FEB	MAR	APR	JUN	SEP	OCT	NOV	DEC	spring	summer	autumn	winter	Wp	Cp	year
805	Senica						-4.4	-7.8	-7.4			-12.1			-22.4	-23.7
816	Bratislava, airport						-4.1	-6.6	-7.7			-10.7			-20.4	-22.5
826	Piešťany	-5.3					-4.1	-5.5	-7.4			-9.6			-22.5	-23.6
835	Moravský sv. Ján											-7.6				
858	Hurbanovo						-3.5	-7.1	-6.5			-10.5			-19.5	-21.4
862	Beluša						-4.5			-8.3		-8.9				-28.0
866	Čadca															
867	Prievidza	-6.2		-3.4			-5.3		-6.4	-6.5		-9.9			-25.1	
868	Oravská Lesná						-6.9	-7.6	-4.9			-16.0	-6.2		-24.6	-26.6
872	Ružomberok											-7.9			-15.5	
874	Liptovský Hrádok	-3.2					-5.4		-5.1			-10.6	-7.4		-21.2	-25.9
880	Dudince	-5.7					-5.3	-6.9	-5.8			-12.2			-24.2	-27.7
903	Sliač	-6.1					-5.7	-7.3	-6.9			-13.1	-11.3		-29.0	-33.1
916	Chopok		-0.8	-4.4	-3.5			-5.3	-0.8	-8.8	-5.8	-12.2		-19.1		-26.3
927	Boľkovce			-3.8			-5.1			-6.7		-12.5		-4.0	-25.0	-30.7
930	Lomnický štít				-9.4	-7.7		-4.0			-13.2	-14.3		-24.7		-31.2
934	Poprad	-3.4	-3.9				-5.5		-2.7	-9.2		-11.8	-5.5		-21.4	-26.7
938	Telgárt		-3.1				-5.3	-6.9		-7.0		-12.1			-17.8	-22.2
962	Bardejov						-4.6		-7.5			-9.6			-21.2	-21.3
968	Košice, airport	-6.7	-6.5	-2.9			-5.2	-6.5	-7.6	-9.3		-11.9	-13.1		-34.5	-36.5
977	Medzilaborce	-6.0	-8.1	-7.7			-5.7	-8.2	-9.4	-17.8		-15.1	-16.9	-11.0	-40.0	-49.8
978	Milhostov	-6.9					-4.0		-7.3			-9.3	-13.8		-27.8	-29.0
979	Somotor	-7.0					-3.5		-7.6			-9.6	-14.4		-29.5	-30.5
993	Kamenica n/C	-5.1							-9.1			-6.9	-14.6		-25.4	-26.2

Table 4. Coefficient of correlation (significance) of frost days in the period 1991 – 2020.

Ind. (short)	Name	FEB	MAR	APR	JUN	SEP	OCT	NOV	DEC	spring	summer	autumn	winter	Wp	Cp	year
805	Senica						0.404	0.420	0.385			0.542			0.364	0.443
816	Bratislava, airport						0.438	0.365	0.387			0.496			0.346	0.389
826	Piešťany	0.304					0.374	0.304	0.368			0.435			0.380	0.430
835	Moravský sv. Ján											0.337				
858	Hurbanovo						0.351	0.394	0.314			0.482			0.335	0.371
862	Beluša						0.412			0.341		0.392				0.488
866	Čadca															
867	Prievidza	0.332		0.335			0.444		0.350	0.318		0.435			0.432	
868	Oravská Lesná						0.413	0.382	0.530			0.583	0.302		0.577	0.542
872	Ružomberok											0.356			0.304	
874	Liptovský Hrádok	0.320					0.399		0.432			0.454	0.330		0.475	0.549
880	Dudince	0.344					0.417	0.370	0.304			0.515			0.442	0.500
903	Sliač	0.411					0.466	0.374	0.387			0.553	0.332		0.517	0.595
916	Chopok		0.332	0.310	0.342			0.470		0.307	0.366	0.430		0.613		0.754
927	Boľkovce			0.322			0.425			0.305		0.530		0.324	0.447	0.539
930	Lomnický štít				0.524	0.357		0.500			0.494	0.458		0.563		0.615
934	Poprad	0.314	0.336				0.410		0.305	0.420		0.514			0.510	0.573
938	Telgárt		0.336				0.352	0.357		0.303		0.514			0.455	0.507
962	Bardejov						0.369		0.413			0.396			0.391	0.449
968	Košice, airport	0.427	0.338	0.320			0.464	0.303	0.372	0.396		0.470	0.354		0.564	0.635
977	Medzilaborce	0.392	0.435	0.474			0.393	0.398	0.507	0.577		0.564	0.437	0.552	0.600	0.714
978	Milhostov	0.406					0.349		0.354			0.373	0.339		0.459	0.566
979	Somotor	0.421					0.351		0.380			0.416	0.364		0.511	0.645
993	Kamenica n/C	0.307							0.459			0.297	0.370		0.440	0.538

Table 5. Change in the number of ice days in the period 1991 – 2020.

Ind. (short)	Name	FEB	APR	AUG	SEP	NOV	DEC	spring	autumn	winter	Wp	Cp	year
805	Senica						-4.3						
816	Bratislava, airport					-2.3	-5.0		-2.3	-11.3		-14.2	-14.4
826	Piešťany						-5.5						-9.0
835	Moravský sv. Ján					-1.6	-6.2		-1.6	-9.4		-10.4	-11.5
858	Hurbanovo					-1.1			-1.1			-8.4	-9.6
862	Beluša					-1.0	-7.0		-1.0	-9.8		-11.0	-11.5
866	Čadca					-2.9	-7.1		-2.8				-13.5
867	Prievidza						-6.3			-9.5		-10.0	-11.0
868	Oravská Lesná					-3.3	-8.9		-3.8			-16.4	-16.8
872	Ružomberok					-2.7	-5.5		-2.7				
874	Liptovský Hrádok						-7.1						-14.3
880	Dudince					-0.8			-0.8				
903	Sliač												
916	Chopok		-9.1			-10.9		-12.3	-13.2		-11.9	-15.5	-26.3
927	Boľkovce						-6.2						-9.9
930	Lomnický štít		-9.4	-1.0	-3.9	-5.7	-3.5	-11.9	-12.0		-18.0	-9.2	-27.2
934	Poprad					-4.2	-8.3		-4.7			-18.6	-17.7
938	Telgárt	-5.6					-6.4					-13.0	-13.9
962	Bardejov					-2.0	-6.6		-2.0				
968	Košice, airport						-8.0						-13.0
977	Medzilaborce					-2.4	-7.0		-2.4				-11.3
978	Milhostov	-5.1					-6.9						-12.1
979	Somotor						-8.0						-14.0
993	Kamenica n/C					-1.8	-7.7		-1.8	-13.7		-14.9	-15.8

Table 6. Coefficient of correlation (significance) of ice days in the period 1990 – 2020.

Ind. (short)	Name	FEB	APR	AUG	SEP	NOV	DEC	spring	autumn	winter	Wp	Cp	year
805	Senica						0.297						
816	Bratislava, airport					0.342	0.342		0.342	0.338		0.395	0.453
826	Piešťany						0.343						0.296
835	Moravský sv. Ján					0.343	0.394		0.343	0.300		0.320	0.424
858	Hurbanovo					0.277			0.277			0.280	0.368
862	Beluša					0.272	0.399		0.272	0.281		0.292	0.352
866	Čadca					0.313	0.336		0.312				0.299
867	Prievidza						0.367			0.323		0.330	0.405
868	Oravská Lesná					0.275	0.425		0.340			0.287	0.337
872	Ružomberok					0.413	0.289		0.413				0.366
874	Liptovský Hrádok						0.342						
880	Dudince					0.336			0.336				
903	Sliač												
916	Chopok		0.549			0.593		0.581	0.531		0.597	0.345	0.543
927	Boľkovce						0.298						0.304
930	Lomnický štít		0.532	0.454	0.269	0.369	0.336	0.430	0.396		0.544	0.269	0.595
934	Poprad					0.382	0.393		0.429			0.345	0.399
938	Telgárt	0.275					0.340					0.274	0.318
962	Bardejov					0.287	0.319		0.287				
968	Košice, airport						0.370						0.378
977	Medzilaborce					0.371	0.310		0.371				0.334
978	Milhostov	0.282					0.325						0.352
979	Somotor						0.407						0.396
993	Kamenica n/C					0.415	0.359		0.415	0.320		0.340	0.456

Evaluation of the change in the number of ice days in the period 1991 – 2020

We observed statistically significant changes (decrease) in the number of ice days especially in November and December (Tab. 5 and Tab. 6). In high mountain locations, significant changes also occurred in April and in August or September. Average decrease in November –3.1 days, in December –6.6 days. In the summer months, the decrease at the highest altitudes (Chopok –9.1 days and Lomnický štít – 9.4 days). In the spring, the decrease in the mountains (Chopok –12.3 days and Lomnický štít –11.9 days). Average fall in autumn –3.7 days at most selected meteorological stations. In winter, the frequency of statistically significant changes is lower (average decrease –10.7 days). In the warm half-year, changes only in the mountains (Chopok –11.9 days and Lomnický štít –18 days). In the cold half of the year, the frequency is higher (average decrease –12.9 days. Significant change in annual frequency at most stations (average decrease in the number of ice days –14.3)

Evaluation of the change in the number of summer days in the period 1991 – 2020

The occurrence of summer days we connect to the warm part of the year, although their occurrence in March or October we cannot exclude. Statistically significant increase (Tab. 7 and Tab. 8) in the number of summer days was in **June** at almost all meteorological stations meeting the assumption of this characteristic, by an average of +7.3 days, with a maximum of +9.1 days in Prievidza with a correlation coefficient of 0.545. Statistically significant increase in the number of summer days in **July**, especially in the colder (mostly in north part) locations of Slovakia (Čadca, Oravská Lesná, Sliač, Poprad), with the exception of Somotor (south of eastern Slovakia), with an average increase of +5.4 to 5.7 days. In **August**, similar to July, statistically significant increase in the number of summer days in the colder locations of our country (Čadca, Oravská Lesná, Liptovský Hrádok) and also in the east of Slovakia (Milhostov, Somotor and Kamenica nad Cirochou) with an average increase of 6.6 days respectively in the east 5.6 days was recorded. In **September** (similarly to June), statistically significant increase in the number of summer days at most weather stations, on average by +6.5 days with a maximum of +10.1 days in the east of the country in Somotor was recoded. Changes in the frequency of occurrence of summer days in the period 1991 – 2020 during the **summer** were significant at practically all meteorological stations (except Senica and Telgárt) with an average increase in the period of +15.5 summer days. In **autumn**, the situation repeated, but the changes in the number of summer days were smaller, an increase of +6.5 days on average. In the **warm half-year** (also considering the length of the period), the frequency of increase was even

Table 7. Change in the number of summer days in the period 1991 – 2020.

Ind. (short)	Name	JUN	JUL	AUG	SEP	summer	autumn	Wp	year
805	Senica	6.5						13.3	13.4
816	Bratislava, airport	7.8				13.2	5.4	19.7	20.3
826	Piešťany	8.7			5.4	13.1	5.6	17.0	17.2
835	Moravský sv. Ján	8.4				14.5		20.4	20.5
858	Hurbanovo	7.4			7.0	12.6	8.0	21.0	21.9
862	Beluša	8.9			6.4	15.5	6.7	24.6	24.9
866	Čadca	7.4	5.9	6.2	6.4	19.5	6.2	26.3	26.1
867	Prievidza	9.1			7.8	14.2	8.9	26.4	27.5
868	Oravská Lesná	4.4	5.5	7.1	3.4	17.1	3.3	21.1	21.1
872	Ružomberok								
874	Liptovský Hrádok	6.4	6.3	5.7	5.6	18.4	5.9	25.9	26.3
880	Dudince	8.9			7.3	15.2	7.4	23.9	24.0
903	Sliač	8.1	4.8		8.2	16.5	8.5	27.5	27.8
916	Chopok								
927	Boľkovce	8.8			8.0	16.2	8.1	27.2	27.3
930	Lomnický štít								
934	Poprad	4.4	6.0	7.3	3.3	17.7	3.4	21.5	21.6
938	Telgárt				1.2		1.2	8.4	8.4
962	Bardejov	7.7			6.3	16.6		24.2	24.1
968	Košice, airport	6.5			7.6	14.7	7.4	22.4	22.2
977	Medzilaborce	4.7			6.4	10.5	6.1	17.5	17.1
978	Milhostov	5.1		5.0	7.7	13.8	7.4	20.5	20.2
979	Somotor	8.9	4.1	6.5	10.1	19.4	10.0	33.2	33.2
993	Kamenica n/C	6.9		5.4	8.5	15.3	7.9	24.3	23.7

Table 8. Coefficient of correlation (significance) of summer days in the period 1991 – 2020.

Ind. (short)	Name	JUN	JUL	AUG	SEP	summer	autumn	Wp	year
805	Senica	0.376						0.300	0.302
816	Bratislava, airport	0.459				0.425	0.305	0.417	0.426
826	Piešťany	0.523			0.321	0.435	0.317	0.366	0.368
835	Moravský sv. Ján	0.503				0.516		0.437	0.435
858	Hurbanovo	0.494			0.343	0.502	0.353	0.464	0.457
862	Beluša	0.512			0.371	0.485	0.368	0.479	0.477
866	Čadca	0.448	0.310	0.328	0.563	0.532	0.554	0.551	0.548
867	Prievidza	0.545			0.434	0.501	0.455	0.530	0.533
868	Oravská Lesná	0.341	0.337	0.435	0.541	0.543	0.534	0.592	0.589
872	Ružomberok								
874	Liptovský Hrádok	0.423	0.318	0.297	0.533	0.499	0.563	0.596	0.598
880	Dudince	0.593			0.347	0.546	0.320	0.483	0.468
903	Sliač	0.519	0.296		0.466	0.531	0.454	0.548	0.548
916	Chopok								
927	Boľkovce	0.568			0.416	0.514	0.395	0.500	0.495
930	Lomnický štít								
934	Poprad	0.361	0.386	0.392	0.410	0.529	0.428	0.542	0.543
938	Telgárt				0.494		0.494	0.308	0.308
962	Bardejov	0.484			0.540	0.450		0.516	0.513
968	Košice, airport	0.431			0.459	0.444	0.433	0.446	0.436
977	Medzilaborce	0.320			0.456	0.362	0.440	0.413	0.404
978	Milhostov	0.375		0.324	0.437	0.458	0.412	0.443	0.434
979	Somotor	0.582	0.273	0.412	0.490	0.604	0.468	0.604	0.592
993	Kamenica n/C	0.440		0.318	0.505	0.486	0.484	0.503	0.493

Table 9. Change in the number of tropical days in the period 1991 – 2020.

Ind. (short)	Name	JUN	JUL	AUG	SEP	summer	autumn	Wp	year
805	Senica	4.3			2.0	11.2	2.0	13.6	13.6
816	Bratislava, airport	3.7			1.9	10.7	1.9	12.6	12.6
826	Piešťany	4.2			1.8	12.1	1.8	14.6	14.6
835	Moravský sv. Ján	3.8			1.9	9.4	1.9	11.4	11.4
858	Hurbanovo	4.1	6.5		3.2	12.6	3.2	15.9	15.9
862	Beluša	3.9	6.1		2.2	14.9	2.2	17.5	17.5
866	Čadca	2.1			0.6	8.8	0.6	9.6	9.6
867	Prievidza	4.9	6.5		2.2	17.0	2.2	20.2	20.2
868	Oravská Lesná	1.2				4.3		4.4	4.4
872	Ružomberok								
874	Liptovský Hrádok	3.2				9.5		9.6	9.6
880	Dudince	5.3	7.3		3.1	16.4	3.1	19.7	19.7
903	Sliač	5.8	6.1	5.6	1.8	0.2	1.8	20.3	20.3
916	Chopok								
927	Boľkovce	4.6	6.5		2.0	16.5	2.0	18.8	18.8
930	Lomnický štít								
934	Poprad								
938	Telgárt								
962	Bardejov	3.1				7.8		8.1	8.1
968	Košice, airport	3.5			1.8	9.4	1.8	11.4	11.4
977	Medzilaborce								
978	Milhostov	3.2		5.3	1.4	11.5	1.4	13.0	13.0
979	Somotor	5.7	4.8	8.1	2.5	18.5	2.5	22.2	22.2
993	Kamenica n/C	3.3			1.2	9.3	1.2	11.0	11.0

Table 10. Coefficient of correlation (significance) of tropical days in the period 1991 – 2020.

Ind. (short)	Name	JUN	JUL	AUG	SEP	summer	autumn	Wp	year
805	Senica	0.375			0.442	0.346	0.442	0.402	0.402
816	Bratislava, airport	0.336			0.420	0.298	0.420	0.336	0.336
826	Piešťany	0.397			0.429	0.359	0.429	0.409	0.409
835	Moravský sv. Ján	0.341			0.325	0.296	0.325	0.344	0.344
858	Hurbanovo	0.309	0.380		0.475	0.368	0.475	0.414	0.414
862	Beluša	0.353	0.338		0.489	0.439	0.489	0.488	0.488
866	Čadca	0.301			0.420	0.362	0.420	0.386	0.386
867	Prievidza	0.467	0.404		0.501	0.516	0.501	0.573	0.573
868	Oravská Lesná	0.324				0.312	0.311		0.311
872	Ružomberok								
874	Liptovský Hrádok	0.412				0.404		0.405	0.405
880	Dudince	0.381	0.398		0.475	0.436	0.475	0.479	0.479
903	Sliač	0.458	0.366	0.279	0.421	0.489	0.421	0.527	0.527
916	Chopok								
927	Boľkovce	0.390	0.391		0.441	0.479	0.441	0.498	0.498
930	Lomnický štít								
934	Poprad								
938	Telgárt								
962	Bardejov	0.372				0.333		0.335	0.335
968	Košice, airport	0.370			0.514	0.317	0.514	0.354	0.354
977	Medzilaborce								
978	Milhostov	0.329		0.275	0.309	0.382	0.309	0.381	0.381
979	Somotor	0.455	0.299	0.391	0.439	0.499	0.439	0.497	0.497
993	Kamenica n/C	0.375			0.359	0.324	0.359	0.346	0.346

higher (compared to summer or autumn) and statistically significant at all (relevant) meteorological stations with an average increase of +22.2 during the period 1991 – 2020. Changes (increase) in the **annual** frequency of occurrence of summer days, which primarily linked to the warm part of the year, and the results are similar to the summer half-year. However, even the rare frequency of occurrence outside the summer half-year caused the result to be different. The average change (increase) in the annual number of summer days was +22.3.

Evaluation of the change in the number of tropical days in the period 1991 – 2020

The occurrence of tropical days is associated with the warmest part of the year. We recorded a statistically significant increase in the number of tropical days in **June** (Tab. 9 and Tab. 10) at almost all meteorological stations meeting the assumption of this characteristic, by an average of +3.9 days, with a maximum of +5.8 days at Sliač with a correlation coefficient of 0.458. We observed a statistically significant increase in the number of summer days in **July** at a smaller number of locations in Slovakia (Hurbanovo, Beluša, Prievidza, Dudince, Sliač, Boľkovce and Somotor) with an average increase of +6.2 and a maximum of +7.3 days in Dudince. In **August**, we recorded a statistically significant increase in the number of tropical days at Sliač and in the east of Slovakia. In **September** (similarly to June), we observed a statistically significant increase in the number of tropical days at most weather stations, on average by +2.0 days with a maximum of +3.2 days in the southwest of the country in Hurbanovo. Changes in the frequency of occurrence of summer days in the period 1991 – 2020 during the **summer** were significant at practically all meteorological stations (except higher meteorological stations) with an average increase in the period of +11.1 tropical days. In **autumn**, the situation repeated, but the changes in the number of summer days were smaller, an increase of +2.0 days on average. In the **warm half-year** (also considering the length of the period), the frequency of increase was even higher (compared to summer or autumn) and statistically significant at all (relevant) meteorological stations with an average increase of +14.1 days during the period 1991 – 2020. Changes (increase) in the **annual** frequency of occurrence of tropical days corresponded to the warm half-year.

CONCLUSION

Decadal processing as well as processing according to altitude showed us the need to restore long-term averages of various characteristics (here air temperature) for the various needs of the national economy, tourism, etc. We pointed out the fact of almost an increase in air temperature in recent decades as well as significant differences corresponding altitudes in different normal periods.

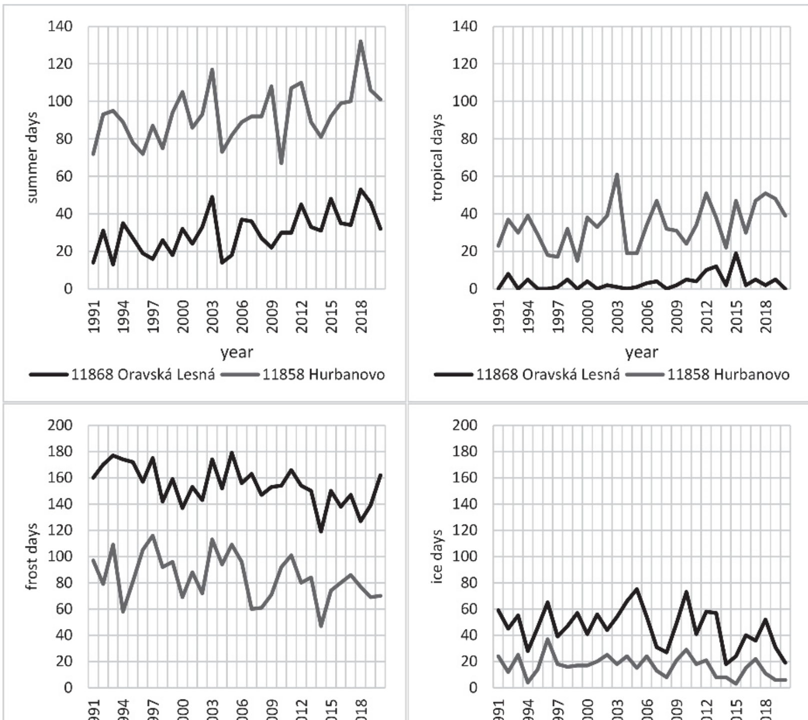
The above results have shown that the analyzed temperature characteristics of the Slovak Republic have changed positively during the observed period 1991 – 2020 compared to the periods 1981 – 2010 or 1961 – 1990. If we take into account the average monthly air temperatures, then the most significant increases in the **average monthly air temperature** we see in the summer months.

An increase in air temperature is evident in every month of the year except January and May in the period 1991 – 2020. On average for Slovakia, the highest air temperature increases are observed in February (+2.3 °C), April (+2.5 °C), June (+2.3 °C), November (+2.7 °C) and in December (+3.1 °C). In seasonal values, there is an increase everywhere (spring +1.5 °C, summer +1.7 °C, autumn +2.0 °C (maximum) and winter +1.5 °C). The cold half-year warms up more significantly than the warm half-year. The warming of the annual air temperature for Slovakia represents a value of +1.8 °C. As such, the good news in the adverse development of air temperatures is that in the highest locations of the Tatras in the winter months (December, January, February), the changes are the lowest (even negative in January). At the same time, however, the correlation coefficients in the winter months for these locations (as well as many others especially in January and February) are statistically below the threshold of significance. Peculiarities in the variability as well as in the explicitness of the trend or the differences of locations in the south and north of Slovakia see in Fig. 15.

We observed a statistically significant change in the number of **frost days** in the period 1991 – 2020 in February to April, in more remote locations also in June and July and then in September. October to December turned out to be the most numerous (also statistically significant). In the seasonal evaluation, autumn occurred the most, but in some localities also winter (more significant in the east of Slovakia). In the warm half-year, especially the mountainous and cold regions of Slovakia. In the cold half-year, there was a (statistically significant) decrease in the number of frost days in almost all locations in Slovakia. In the annual frequency, we recorded a decrease in the number of frosty days by an average of 27 days.

The most significant decrease in the number of **ice** days in the period 1991 – 2020 is observed mainly at the end of autumn (November, decrease of –3.1 days) and even more significantly at the beginning of winter (December, decrease of –6.6 days). In the highest mountain locations, we note

Figure 15. Number of summer, tropical, frost and ice days in different locations in the period 1991 – 2020.



a decrease even earlier (in April –9.4 days, in August –1 day, in September –3.9 days). In the annual frequency, the changes are the biggest, namely a decrease (decrease) of ice days up to –14.3 days on average. We recorded the highest decrease in ice days up to –27.2 at Lomnický štít.

We expected that with the increase in air temperature, the number of summer days would also increase. However, it was not clear where the number of days statistically significantly increase the most, i.e. how the significant changes in the warm part of the year are distributed. Statistical evaluation confirmed that despite the fact that we observe an increase in the number in almost all months (April – September in the period 1991 – 2020) we observe a statistically significant increase precisely at the beginning and end of the warm part of the year.

Changes (increase) in the number of **tropical** days are mainly concentrated in the beginning of summer (June) and then in the beginning of spring (September) in the period 1991 – 2020. We also observe changes in some stations (especially those located further south (except for stations that may have slightly changed their position to a warmer position) in July. In the seasons, the biggest changes are quite logically recorded in summer (11.1 days on average) and smaller in autumn (2 days on average). Due to the fact, that tropical days occur mainly in the warm half of the year, changes in frequency for the period 1991 – 2020 are identical to changes in annual frequency and reach an increase of 14 days on average.

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