Ecological interpretation of climate change according to Churáňov station (NP Šumava, Czech Republic) during 60 years

Karel Matějka [1], **Roman Modlinger** [2]
[1] IDS, Na Komořsku 2175/2a, 14300 Praha 4, Czech Republic; matejka@infodatasys.cz
[2] Czech University of Life Sciences, Faculty of Forestry and Wood Sciences, 16500 Praha, Czech Republic

Abstract
Analysis of long-time climate data since 1961 from the selected meteorological station Churáňov was connected with state of Norway spruce forests in the area of spruce natural occurrence and their main pest species, *Ips typographus*, in the Šumava Mts. The current climate change was described using set of variables based on air temperature, relative air humidity and precipitations. Data were used for calculation specific indices, which are related to dynamics of *Picea abies* (growth index) and spruce bark beetle (date of first infestation and achieved bark beetle development [*G*], have been calculated by the PHENIPS model). Average air temperature increase was +0.37 °C per 10 years. Slight air humidity decrease shows a discontinuity between 1994 and 1995. Total volume of precipitation is rather constant. Increase of temperatures results in earlier onset of both vegetation growth and *I. typographus* first infestation (average shift of 1.5 days per 10 years). The modelled bark beetle's first infestation corresponds to numbers of individuals caught in the pheromone traps. The number of generations and the achieved development state of *I. typographus* was stable until 1991, from 1992 there was an increase, which was followed by past growing trend. The results from the Churáňov in mountain region of natural Norway spruce forests are compared with ones from whole area of the Czech Republic, where planted *P. abies* forests prevails.

Keywords: air temperature, relative air humidity, climatic stress, growth index, *Ips typographus*, PHENIPS model, *Picea abies*, Šumava Mts., wetness

Introduction

The meteorological station Churáňov is located in the central part of the Šumava massif (49° 04' 5.6" N, 13° 36' 53.9" E) at an altitude of 1118 m (for the location of the pressure gauge, the height is 1122 m) and is among the most important mountain meteorological stations in the Czech Republic (Jůza, Starostová et Sklenář 2011). A basic description of the station is given in the work Staněk et Bednařík (1998). The first evaluation of measurements at this station (Matějka 2014) showed some significant trends that appear both at this station and were proven on the basis of so-called territorial temperatures and precipitation for the entire Czech Republic (Matějka 2021a, Matějka et Modlinger 2023). The results of the evaluation of temperature and precipitation changes in a number of stations in the Šumava Mts. are also consistent (Bílá, Hostýnek et Kindlmann 2018). In addition to the generally known and accepted increase in average air temperatures, this is particularly the recognition of changes in the distribution of precipitation during the year, which, however, is not associated with a reduction in total precipitation totals, but in particular the recognition of a certain discontinuity in the change of some climatic characteristics, while this discontinuity can be placed between years 1994 and 1995. The observed trends are completely consistent with the results of other authors (for example, KVĚTOŇ 2001; BRÁZDIL 2022). Temperature data from this station were used for modelling historical temperatures in the Šumava Mts. back to the 18th century (Turek et al. 2014). Observations at the station were also used for modelling the occurrence of fog as an important ecological phenomenon (HŮNOVÁ ET AL. 2018).

The dominant tree species of the mountain forests in large parts of the Šumava Mts. is the Norway spruce, *Picea abies* (L.) H. Karst., especially in the 7th and 8th forest vegetation (altitudinal) zone (VIEWEGH ET AL. 2003), i.e., above approximately 1000 m above sea level, where the Norway spruce dominates the natural forests (KINDLMANN ET AL. 2012). The Churáňov station can thus well describe the climatic conditions in these forests. In lower altitudes, Norway spruce is a frequently cultivated tree species, as is the case throughout Central Europe (HLÁSNY ET AL. 2022).

The spruce bark beetle, *Ips typographus* (L.) is one of the most important economic pests of spruce-dominated forest stands in Eurasia, mainly due to its ability to increase population density exponentially in suitable conditions (WERMELINGER 2004). At endemic population phase, it mainly attacks weakened trees, whose ability to successfully resist the attack of bark beetle is reduced (NETHERER 2019). Transition to the endemic population phase is led by wind disturbance events, drought stress incidence or a combination of both (SOUKHOVOLSKY ET AL. 2022). The negative feedback, such as predators, parasitoids, diseases, interspecific competition and source depletion, mediate the return of the population to the endemic phase (KAUSRUD ET AL. 2012). For large-scale bark beetle eruption is necessary to overcome several thresholds which have a few internal and external controls and releases (RAFFA ET AL. 2008). Weather and climate, including temperature, precipitation and their interaction, govern numerous aspects of the bark beetle - spruce relationship.

Large scale disturbances were repeatedly seen in the Šumava Mts., where the highest bark beetle outbreak occurred between 1868 and 1877 (TUREK ET AL. 2014); in recent decades has been two waves of the spruce bark beetle gradation in this region were recorded after 1994 and 2003 (KINDLMANN ET AL. 2012). Since 2015, an unprecedented outbreak occurred in the most of Czech territory but the Šumava Mts., did not severely affected so far (HLÁSNY ET AL. 2021, CIENCIALA ET AL. 2017). The specific conditions of the Šumava's forests (especially the extent of the area dominated by Norway spruce, a high proportion of natural forests, the simultaneous presence of various types of protected areas, including the national park, low human population density following the existence of the former state border zone, relatively low air pollution load, etc.) make it possible to analyse the dynamics of forests in continuity with past bark beetle gradations as in the model area (ZATLOUKAL 1998; KINDLMANN ET AL. 2012). The same is true in the Tatra Mts. in Slovakia (MEZEI ET AL. 2014).

The ontogenetic development of many insect species is dependent on the course of environmental temperature (DIXON ET AL. 2009). The development from egg to imago is strongly dependent on the environmental temperature, which is why a so-called phenological model of this species (PHENIPS) could have been created (BAIER, PENNERSTORFER ET SCHOPF 2007). This model was also successfully validated in the conditions of the Šumava Mts. (BEREC, DOLEŽAL ET HAIS 2013). Fleischer et al. (2016) used this model in the Tatras. The RITY–2 model (OGRIS ET AL. 2019) is similar to the previous one and was developed in the environment of south-eastern Europe (Slovenia), so it was applied in climatically distinct conditions.

Disturbances that can take place in synchronized and large-scale events, sometimes even at the level of the entire mountain range, are of fundamental importance for the dynamics of mountain Norway spruce forests (KINDLMANN ET AL. 2012). The basic disturbance factor can be the bark beetle gradation, following the course of the weather (KREJČÍ ET AL. 2013), which causes physiological stress or directly mechanically (mainly wind) damage the stands. Through retrospective analysis (tree ring analysis), it is possible to determine the history of stands – in the Šumava Mts., for example, ČADA ET AL. (2016) proved the repeated destruction of stands, also in SVOBODA ET AL. (2010, 2012) and WILD ET AL. (2014). This fact can also be proven within the framework of the postglacial development of the Šumava's forests on the basis of the record fluctuations for Norway spruce in pollen profiles (SVOBODOVÁ, SOUKUPOVÁ ET REILLE 2002). Large-scale disturbance can affect the microclimatic characteristics of the habitat (HAIS ET AL. 2016; BEUDERT ET AL. 2018), while some authors draw attention to a significant increase in ground temperatures immediately after the collapse of the tree layer (HESSLEROVÁ ET AL. 2018), but they do not take into account the usually very fast restoration of the woody layer (KOPÁČEK ET AL. 2020).

The physiological stress of the tree manifests itself as a decrease in the tree growth. For Norway spruce, the periods of the year when the average air temperature, total precipitation and relative air humidity have the strongest influence (positive or negative) on radial growth were identified (MONDEK ET AL. 2021). It was determined at localities of the South Bohemia near to the Šumava Mts. We can assume that, based on this knowledge, the stress of spruce can be estimated with the knowledge of the relevant climatic characteristics for a specific year.

Warming has been identified as one of the indirectly indicated factors that lead to a change in the species composition of the plant communities of the Šumava's mountain forests (WILD, NEUHÄUSLOVÁ ET SOFRON 2004). The most climate-sensitive zone of the Šumava's forests is located at altitudes of 1100 to 1200 m above sea level, which correspond to the 7th forest vegetation zone (BÄSSLER, MÜLLER ET DZIOCK 2010). This is the zone in which Churáňov station is located. The change in climate is also taken into account when studying the dynamics of aquatic ecosystems. In Šumava, one can mention the glacial lakes (VRBA ET AL. 2015).

The aim of this article is to evaluate the available data on the development of the weather patterns and climate at the meteorological station Churáňov (data of the Czech Hydrometeorological Institute, www.chmi.cz) since 1961. The period 1961 to 1990 represents the climatological normal, to which the further development of the weather within the framework of the so-called climate change is related. Climate change affects the development of all ecosystems. Forests represent ecosystems with long-lived edifiers (trees), so we can consider the influence of weather (in the short term), which can be caused by, for example, short-term climatic stress (an example of climatically extreme years such as 2003; REBETEZ ET AL. 2006) or directly controls the population development of insects (a typical example is spruce bark beetle; BAIER, PENNERSTORFER ET SCHOPF 2007), as well as the long-term influence of climate on the distribution of individual forest communities in relation to forest vegetation altitudinal zones. Both short-term and long-term changes in climatic conditions cause climatic stress in individual species, which can lead to their retreat from the ecosystem, and, ultimately, to the disturbance of the ecosystem, the forest in first line (ROMEIRO ET AL. 2022). Of the climatic extremes, drought, which is a state of reduced water availability in the ecosystem, has the greatest impact (BELOIU, STAHLMANN ET BEIERKUHNLEIN 2022). This phenomenon also occurred in the past (Treml 2011), but based on observations, it seems that its occurrence has become more frequent in recent years (e.g., www.intersucho.cz).

Methods

Daily data within the period 1961 to 2021, which was published by the Czech Hydrometeorological Institute (CHMI 2021), was used for the evaluation. Since a number of averages and indices are calculated using values measured up to 365 days before the given reference day, some statistics and graphs are constructed only from 1.1.1962, i.e., for a total of 60 years.

The trend of individual variables was evaluated using linear regression, where the resulting slope of the straight line corresponds to the average change of the variable per time unit, it is usually expressed for simplicity as a change per 10 years. Pearson's correlation coefficient r, or its square r^2, is usually reported with the regression.

The discontinuity in the development of the weather between 1994 and 1995 has been already pointed out (MATĚJKA 2014, 2021a). The change in the development of the monitored characteristics was evaluated both for this divide, and another break point at which a change could have occurred was sought. For this purpose, a procedure was developed for calculating the so-called broken line regression and optimizing the location of the broken point, where difference between directions of two regression lines is statistically significant, or the RMSD (root-mean-square deviation) ratio for simple linear regression and broken-line regression reaches a local extremum. Difference of two regression coefficients consists in the transformation

$$Z = 1/2\ log((1+r)/(1-r))$$

Difference of coefficients r_1 and r_2 transformed into Z_1 and Z_2, respectively, was calculated as

$$U = (Z_1 - Z_2) / \sqrt{(1/(n_1-3) + 1/(n_2-3))}$$

where n_1 and n_2 are point counts in first and second subset, respectively. The U variable has normal distribution.

This procedure was implemented in the IDSDataView software (MATĚJKA 2022a). Due to the earlier division of the period between 1994 and 1995, regressions were also calculated separately for the period 1961 (1962) to 1994 and 1995 to 2021, in the event that such a division turns out to be statistically significant for the given characteristic. Arithmetic averages were also calculated for these periods, the difference of which in both periods was evaluated with a t–test. Since the difference in the standard deviations of the respective samples was minimal and the t–test is not very sensitive to violations of the condition of equality of standard deviations, a version of the test with equal standard deviations was used (LEPŠ ET ŠMILAUER 2016).

As in the previous evaluation (Matějka 2014), the analysis is based on the moving averages with three basic window lengths – one month, three months and one year. Moving averages represent a simple low-pass filter from the viewpoint of time series analysis. The basic variables monitored are the air temperature at 2 m above the surface, the sum of precipitation, and relative air humidity. Based on these data, the following indices were calculated. All methods including calculated indices are comparable with they in data processing from whole Czech Republic (MATĚJKA ET MODLINGER 2023).

Sum of active daily temperatures

As air temperatures increase throughout the year, some seasons start earlier, typically the end of winter with deep freezes and the start of spring (the growing season). For the development of vegetation and the development of a number of organisms, such a characteristic as the sum of active (also effective in the literature) daily temperatures (SAT, the unit is day.°C [d.°C]) above a certain limit, often calculated for 0, 5 or 10 °C, is decisive. Average daily temperatures were used for the calculation. The calculation was performed in accordance with the work of HEIKINHEIMO ET LAPPALAINEN (1997). Given that higher air temperatures can also occur to a limited extent in winter, the end of winter with deep frosts can be considered the day when the sum of active temperatures above 0 °C (SAT_0) exceeds 10 d.°C. The day when SAT_5

exceeds 10 d.°C is considered the beginning of growth. The period of full vegetation occurs on the day when SAT_{10} exceeds 10 d.°C. A linear regression was calculated for each of these characteristics (first day of the year when SAT exceeds the limit), which determines how the onset of the given season changes.

Wetness index

For each day of the year, the wetness index W was calculated according to MATĚJKA (2014). This calculation was based on rainfall data for the 150 days preceding the given date. Furthermore, the standardized value of this index was calculated

$$W_{rel} = (W-W_{avg}[d])/W_{std}[d]$$

relatively to the average $W_{avg}[d]$ and standard deviation $W_{std}[d]$ for the relevant day d of the year, where the average and standard deviation were calculated for the period 1961 to 1990. The index W has a significant periodicity in the year corresponding to the annual precipitation course. W_{rel} is independent of the day and, moreover, a normal distribution can be assumed for it, so that the limit values can be easily derived. For both indices a connection with the drought stress of the spruce trees as well as with the susceptibility to bark beetle infestation is assumed.

Potential evaporation

Evaporation from a free shaded water surface is referred as potential evaporation. The calculation method was derived in the work of MATĚJKA (2022b) based on measurements at the Rudolfov station in South Bohemia. Based on relative air humidity and temperature, the saturation supplement (D) is calculated. The evaporation index (I) is calculated by multiplying the saturation complement and the square root of the air velocity (w)

$$I = D \sqrt{w}$$

The evaporation index was calculated for three variants (I_0, I_1 and I_2) using the daily average, maximum and minimum of air temperature, combined with the daily average of relative air humidity and the daily average wind speed. A relationship for calculating daily evaporation (ε) was found by non-linear regression analysis in the form

$$\varepsilon = a + b_0 I_0^{c0} + b_1 I_1^{c1} + b_2 I_2^{c2}$$

with regression coefficients a, b_0, b_1, b_2, c_0, c_1 and c_2. The regression was statistically strongly significant. This relationship was used to calculate evaporation at the Churáňov station for every day since 1961.

Growth index for *Picea abies*

The further index combines climate parameters with biological features of Norway spruce. The stress of Norway spruce as a result of the weather conditions in individual years was calculated on the basis of the annual radial increments determined by tree ring analysis. The tree ring index data from the work of MONDEK ET AL. (2021) were used. From this published analysis (121 individuals of *Picea abies* from research plots around Písek in South Bohemia, these plots are in distance of approximately 35–50 km from Churáňov that climate trend would be very similar in both areas; tree-ring indices from 1962 to 2019, used meteorological data from the CHMI Vráž station) it follows that the radial growth of spruce is most influenced by the average air temperature $T_{avg}(225;30)$, average of daily maximum air temperature $T_{max}(20;345)$, average of daily minimum air temperature $T_{min}(20;335)$ and average relative air humidity $H_{avg}(230;60)$. Each of these variables $Var(D,P)$ was calculated for an interval of P days in length ending on the D-th day of year. Correlations between tree ring indices and these variables were significant (error probability $\alpha < 0.05$). Therefore, a multiple regression was calculated in the form

$$GI = a + b_{t\text{-}avg} T_{avg}(225;30) + b_{t\text{-}max} T_{max}(20;345) + b_{t\text{-}min} T_{min}(20;335) + b_{h\text{-}avg} H_{avg}(230;60)$$

The regression coefficients a, $b_{t\text{-}avg}$, $b_{t\text{-}max}$, $b_{t\text{-}min}$ and $b_{h\text{-}avg}$ were used to calculate the spruce growth index *GI* at the Churáňov station for the period 1962 to 2021.

Phenological model of *Ips typographus* (PHENIPS)

The daily sum of global radiation is needed as input data for modelling the phenology and development of spruce bark beetle (BAIER, PENNERSTORFER ET SCHOPF 2007). Global radiation is not available for the station in Churáňov. Instead, daily sunshine duration is used to estimate the daily global radiation according to the work of MATĚJKA (2021b):

$$E = \alpha\, e_T^{\varepsilon} (s_0 + s^{\sigma})$$

where e_T is the theoretical radiation at the atmospheric boundary (MJ.m^{-2}.d^{-1}), s is the sunshine time (h.d^{-1}) and E is the global radiation (MJ.m^{-2}.d^{-1}). Based on non-linear regression analysis, parameters α, ε and s_0 were estimated for Mrzky station ($r^2 = 0.938$).

Realization of the PHENIPS model (MATĚJKA 2021c) calculates infestation date as term when the temperature sum according to equation A.8 in BAIER, PENNERSTORFER ET SCHOPF (2007) exceeds the limit. For each day after infestation, sums of effective bark temperatures according to equations A.10 – A.12 (BAIER, PENNERSTORFER ET SCHOPF 2007) are divided by the sum temperature constant which is necessary for total development of parental generation. This ration is labelled as *G* value. Final dimensionless *G* value in the year corresponds to number of finalized bark beetle generations (integer part of *G*) and stage of development of the last incomplete generation. The PHENIPS model was processed with parameters

Start day = 80 (day of year for calculation begin)

K = 557 (sum temperature limit)

Day length = 14.5 (day length conditioning the transition to diapause)

Glag = 0 (coefficient for delaying the begin of infestation)

Compared to the original proposal of the model (Start day = 92; BAIER, PENNERSTORFER ET SCHOPF 2007), the first value was adjusted for the reason that the growing season starts significantly earlier, especially in recent years, and as a result spring bark beetle infestation was observed several times earlier. Moreover, if there is a cold onset of spring, the values of the additive model increase only slowly, if at all, in the first few days, and the final modelled results are only slightly affected.

The PHENIPS model was calculated for each year – the values of the day of infestation (ordinal day of the year when first infestation probably occurs) and the maximum value of *G* (at the time of the end of the bark beetle development in autumn) were entered in the database. The resulting values of the first infestation were compared with the number of individuals of *I. typographus* captured in pheromone traps in nearby forest stands on the territory of Šumava National Park in the years 2011 to 2021. According to the year, 1 to 5 traps were used. Traps were managed by administration of NP Šumava, which was a data provider. The distance of the traps from the meteorological station was 2 to 7 km, the average altitude (1121 m) fully corresponded to the altitude of the meteorological station (1118 m). The number of trapped beetles was usually checked at weekly intervals from the 110th day of the year (April 20th). Since 2016, the traps have been checked until the second half of September.

Results and discussion

Air temperature

The monthly moving average of air temperatures (Figure 1) exceeds 18 °C only exceptionally (1994, 2003 and 2015). The minimum below -12 °C was reached at the beginning of the evaluated series (in the winter of 1962/3). A similar picture is presented by the 90-day moving average of temperatures (Figure 2), from the perspective of which the highest average summer temperature was reached in 2003, which was a climatically extreme year across Europe (REBETEZ ET AL. 2006).

The average air temperature in the warmest 90-day (summer) period grew by an average of 0.43 °C per 10 years ($r = 0.671$). The average air temperature in the coldest 90-day (winter) period increased by an average of 0.41 °C per 10 years ($r = 0.423$). The average temperature change in summer and winter was thus comparable, the interannual variability was higher in winter temperatures (Figure 4).

The annual moving average of air temperature (Figure 3) shows an uneven rise in temperature. The regression line corresponds to an average temperature change of +0.370 °C per 10 years ($r^2 = 0.5255$) for the entire period 1961–2021, +0.276 °C per 10 years ($r^2 = 0.1597$) for the period up to 1994 and +0.515 °C per 10 years ($r^2 = 0.3102$) for the period since 1995. Break-point regression suggests the possibility of dividing the entire period in 1981, while in the first subset the temperature increased by only 0.135 °C per 10 years ($r = 0.1367$), from 1981 it accelerated to an average of 0.462 °C per 10 years ($r = 0.6579$), while the difference is strongly significant ($U = 16.02$; $p > 0.999$). The highest positive deviation was reached in the first half of 2007. Negative deviations were related to the cold winters and subsequent spring of 1962/1963, 1980/1981, 1996/1997, and 2010/2011.

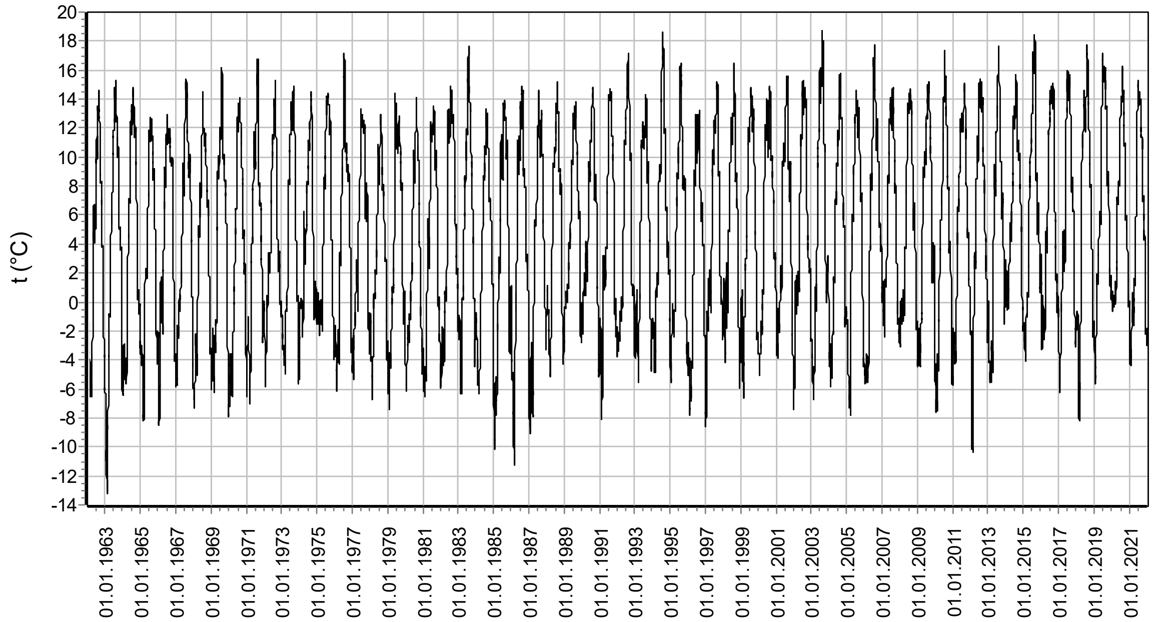


Figure 1. 30-day running average of air temperature at the Churáňov station.

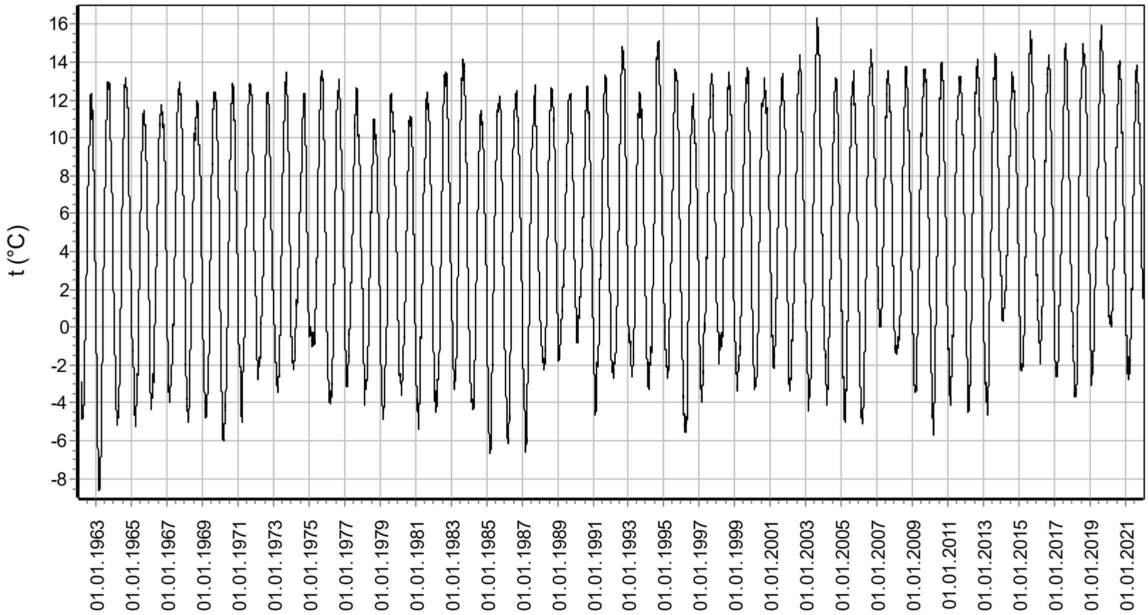


Figure 2. 90-day running average of air temperature at the Churáňov station.

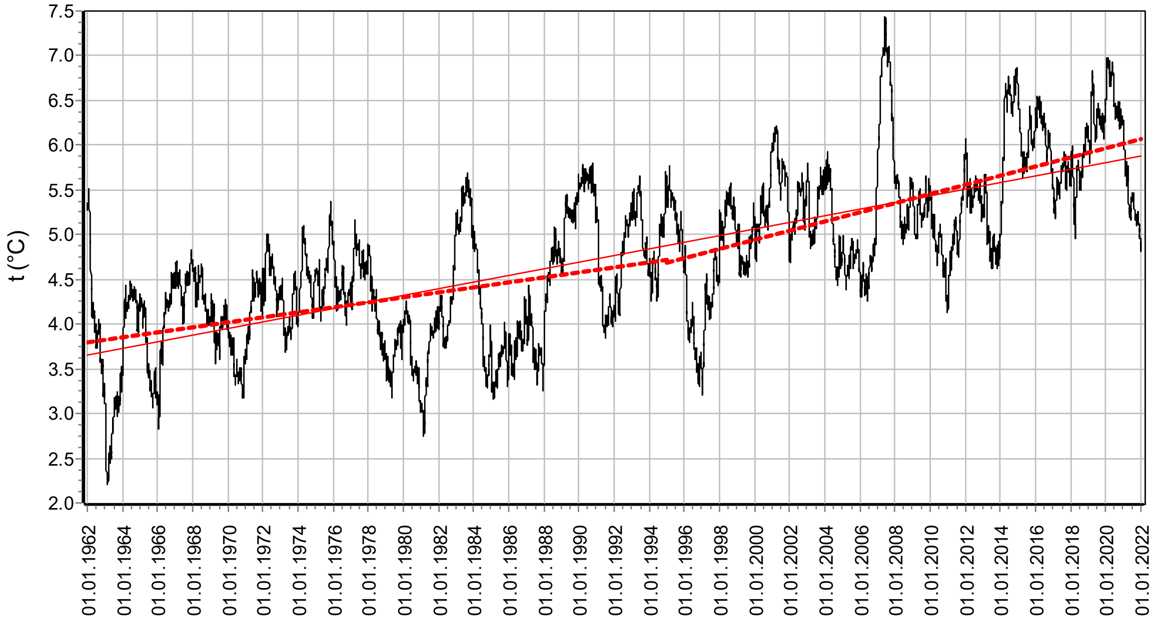


Figure 3. 365-day running average of air temperature at the Churáňov station.

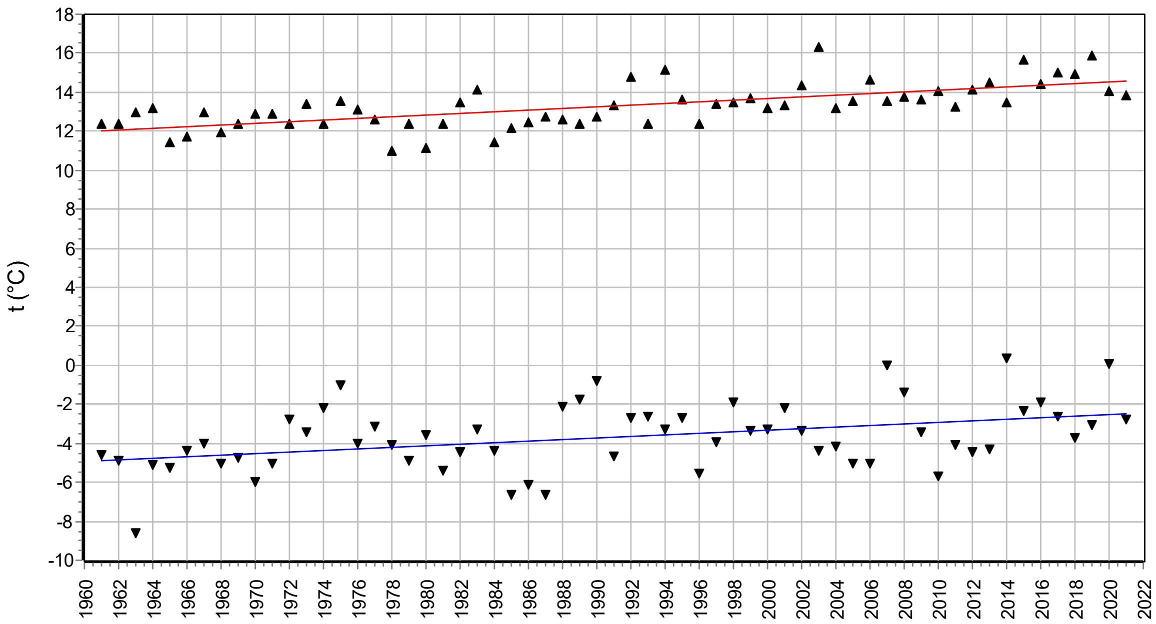


Figure 4. Average air temperature in summer and winter at the station Churáňov. Values calculated as extremes of 90-day running averages.

Average air temperature increase at Churáňov is equal to temperature in the whole region of the Czech Republic (MATĚJKA ET MODLINGER 2023). Temperature increase was accelerated since 1995 at Churáňov (Figure 3) comparing to the linear increase without any breakpoint in whole Czech Republic.

The temperature change did not occur uniformly in all months of the year (Table 1). The greatest warming was observed in June (+1.7 °C). Statistically significant warming ($\alpha < 0.05$) occurred in the months of April to August (i.e., throughout the growing season) and at the beginning of winter (November and December), when a later onset of winter weather was observed.

Table 1. Comparison of the average air temperature at the Churáňov station in the period up to 1994 and since 1995. STD - standard deviation, *t* - T-test of the difference of averages, α - probability of the test error.

	1961-1994		1995-2021			
Month	Average	STD	Average	STD	*t*	α
1	-3.88	2.68	-3.23	1.99	1.0836	0.1415
2	-3.74	2.90	-2.60	2.79	1.5575	0.0624
3	-0.89	2.40	-0.17	1.94	1.2873	0.1015
4	2.97	1.63	4.76	2.08	3.6552	0.0003
5	7.89	1.66	9.15	1.52	3.0999	0.0015
6	11.12	1.23	12.84	1.65	4.5210	0.0000
7	13.07	1.72	14.21	1.55	2.7354	0.0041
8	12.69	1.33	14.04	1.68	3.4190	0.0006
9	9.52	1.58	9.68	1.81	0.3760	0.3541
10	5.16	1.80	5.89	1.90	1.5272	0.0660
11	0.11	1.72	1.36	1.96	2.6146	0.0057
12	-2.95	1.98	-1.98	2.17	1.8036	0.0382
Year	4.30	0.70	5.37	0.75	5.7016	0.0000

Precipitations

When comparing the five-day precipitation totals, no trend is evident (Figure 5). The highest values were found in 2002, when large floods were recorded in Central Europe (REZACOVA ET AL. 2005).

In individual months, the difference in rainfall totals up to 1994 and since 1995 is highly variable, it is not possible to determine the months when there would be an increase or decrease in precipitation totals (table 2). The annual total of precipitation increased by an average of 38 mm, which is, however, not statistically significant. In the whole Czech Republic, yearly precipitation totals were without any significant change (MATĚJKA ET MODLINGER 2023).

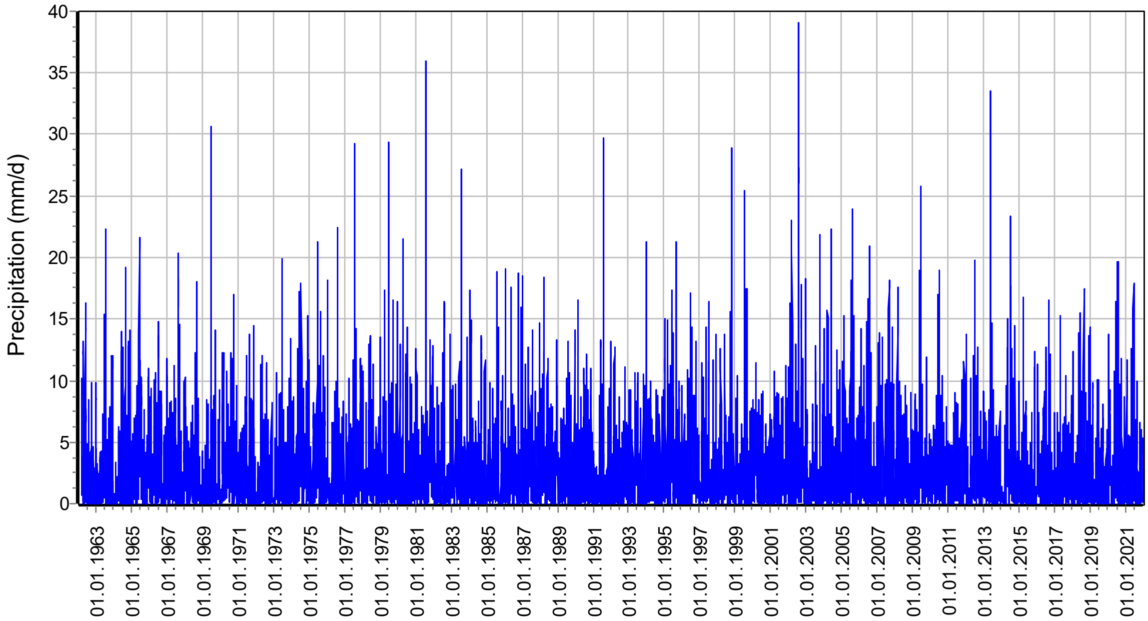


Figure 5. 5-day running sum of precipitations at the Churáňov station.

Table 2. Comparison of the precipitation sums at the Churáňov station in the period up to 1994 and since 1995. STD - standard deviation, *t* - T-test of the difference of averages, α - probability of the test error.

	1961-1994		1995-2021			
Month	Average	STD	Average	STD	*t*	α
1	76.5	54.1	92.6	50.1	1.2085	0.1158
2	64.7	43.2	78.4	49.0	1.1427	0.1289
3	80.9	38.4	91.5	45.7	0.9641	0.1695
4	82.5	37.3	66.3	33.5	-1.7889	0.9606
5	99.3	54.4	107.5	39.5	0.6807	0.2494
6	125.2	52.7	119.2	54.8	-0.4304	0.6658
7	114.0	50.8	130.5	60.5	1.1393	0.1296
8	111.6	43.8	115.5	73.7	0.2442	0.4039
9	75.7	36.1	80.2	41.0	0.4513	0.3267
10	64.1	41.5	77.9	46.2	1.2126	0.1151
11	82.1	35.7	69.2	37.2	-1.3634	0.9110
12	98.5	61.2	84.1	41.3	-1.0942	0.8608
Year	1075.0	151.0	1113.1	174.0	0.8982	0.1864

Relative air humidity

The moving 30-day (i.e., short-term) average of relative air humidity is highly variable (Figure 6). Its lowest value was found in 1976 (approximately July). Other minima were found in the winter of 1972/1973, 1988/1989, and in the spring of 2020 (April). There were also summer lows in 1983 and 2003.

The moving 90-day average of relative air humidity indicates a trend of increasing variability of this statistic in the second half of the evaluated period (Figure 7). While minimums below 70% (characteristic for summer or spring) have been similar since at least 1976, maximum average values above 90% (typical for winter) have only been occurring since 1999 (1998).

The lowest values of the annual moving average of air humidity were found in 1990, while the highest average values were in 2010.

The annual moving average (Figure 8) reveals a decreasing trend in relative humidity (-1.02% per 10 years) in the period 1962 to 1994, followed by a sudden increase in the air humidity. In the period from 1995 to 2019, higher fluctuations of this parameter were observed, while the overall tendency was also a decrease of this parameter (-0.50% per 10 years). Both linear regressions are strongly significant. Since 2019 (really since 2018, because these are annual averages), there has been a significant decrease in air humidity. However, it is not yet possible to conclude whether this is a long-term trend or an episodic fluctuation. Wetness index (Figure 9) mainly indicates the time points with extreme high precipitation sums. The observed trends of relative humidity correspond to the trends for the relative wetness (W_{rel}) calculated on the basis of precipitation (Figure 10). Relative wetness break point position is approximately the same as for relative air humidity (1994/1995).

For both relative air humidity and relative wetness index, discontinuity near 1994 / 1995 was detected at Churáňov, but similar one was not visible in whole Czech Republic, where small decrease of relative air humidity (-0.55 % per 10 years) was observed (MATĚJKA ET MODLINGER 2023).

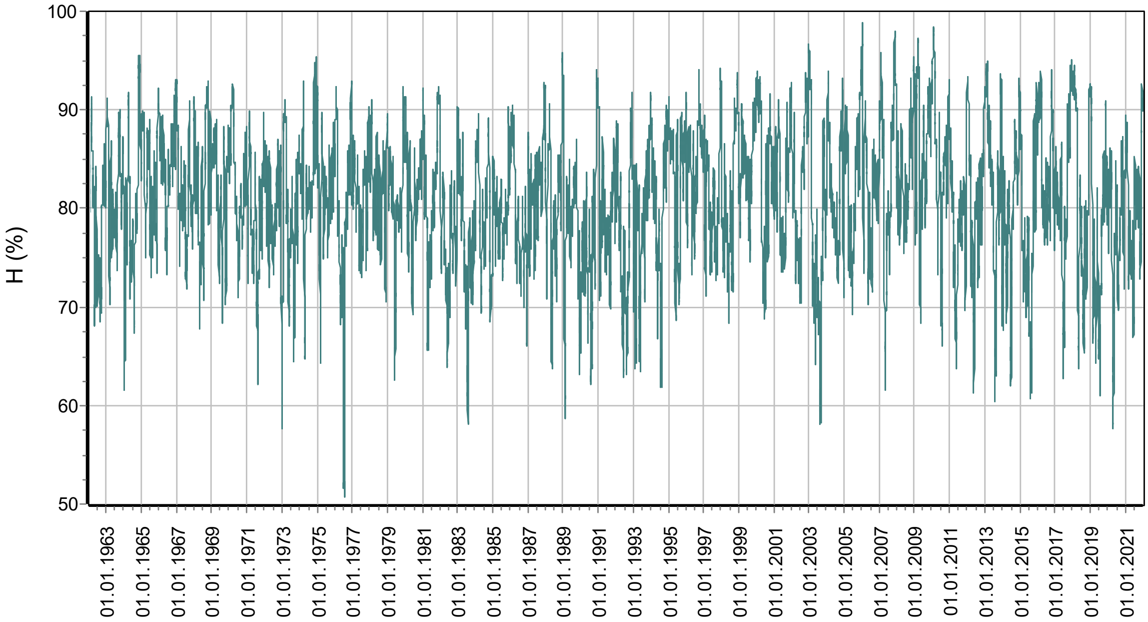


Figure 6. 30-day running average of relative air humidity at the Churáňov station.

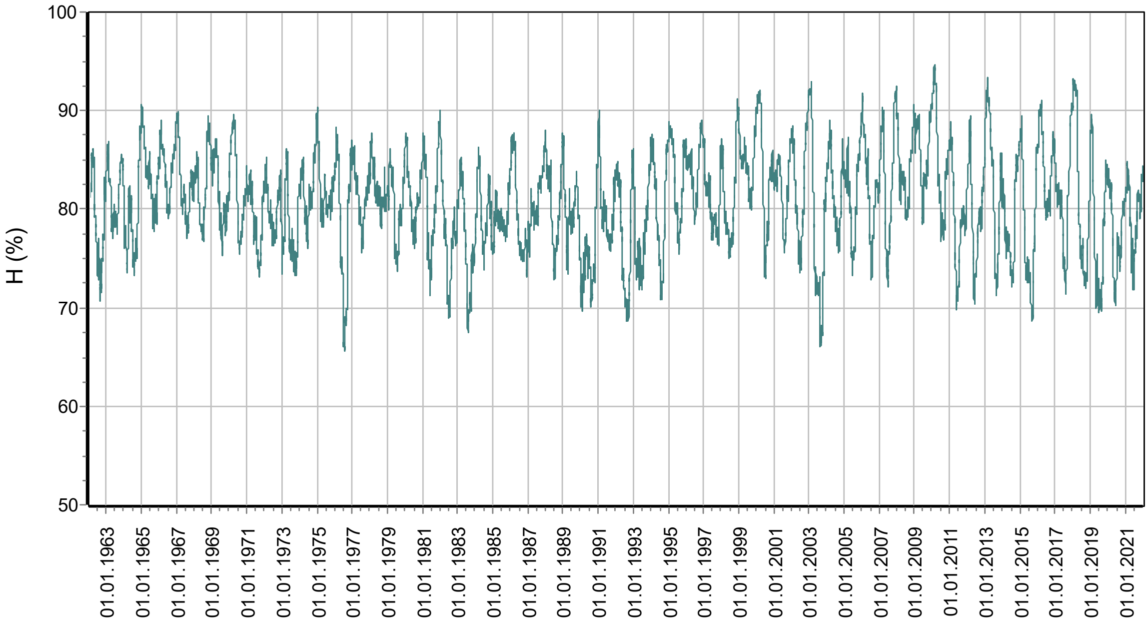


Figure 7. 90-day running average of relative air humidity at the Churáňov station.

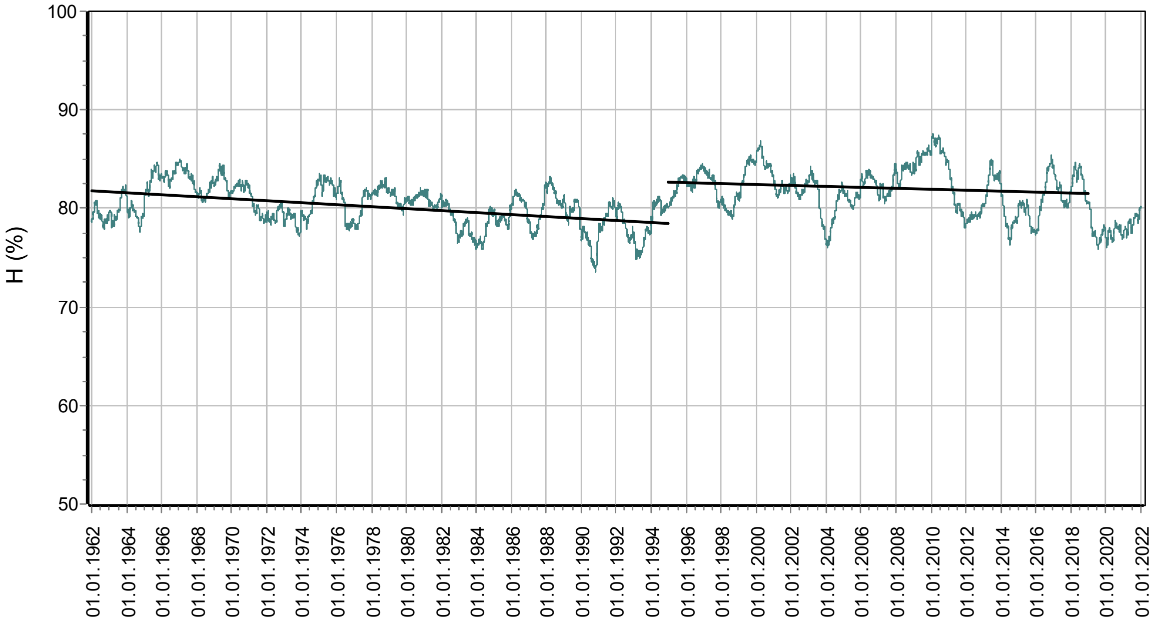


Figure 8. 365-day running average of relative air humidity at the Churáňov station.

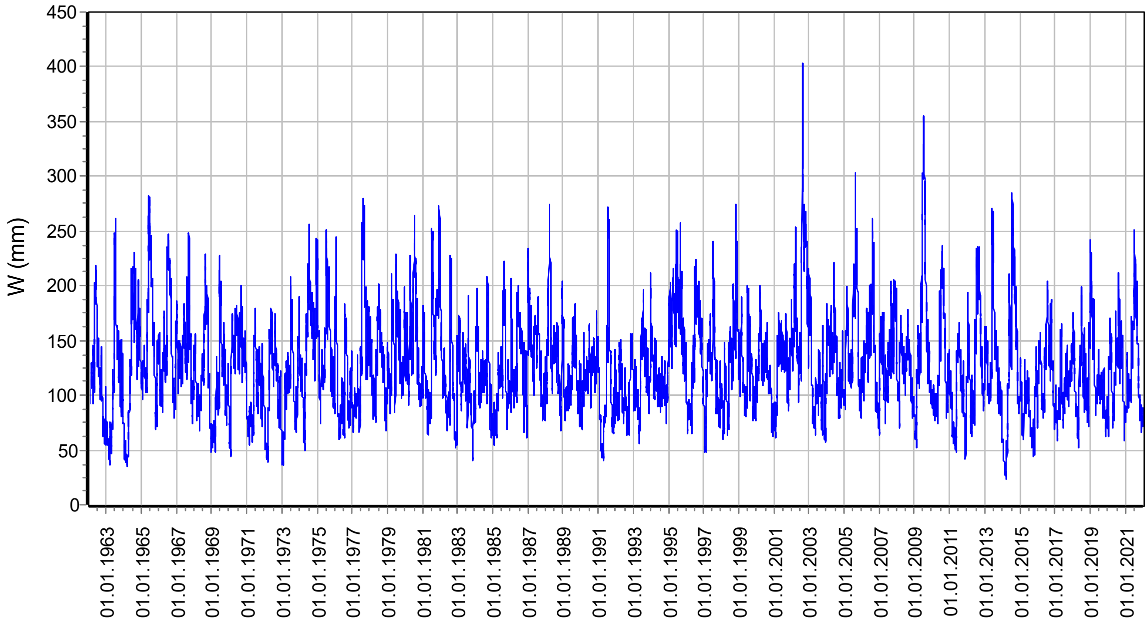


Figure 9. Wetness index *W* at the station Churáňov since January 1st, 1962.

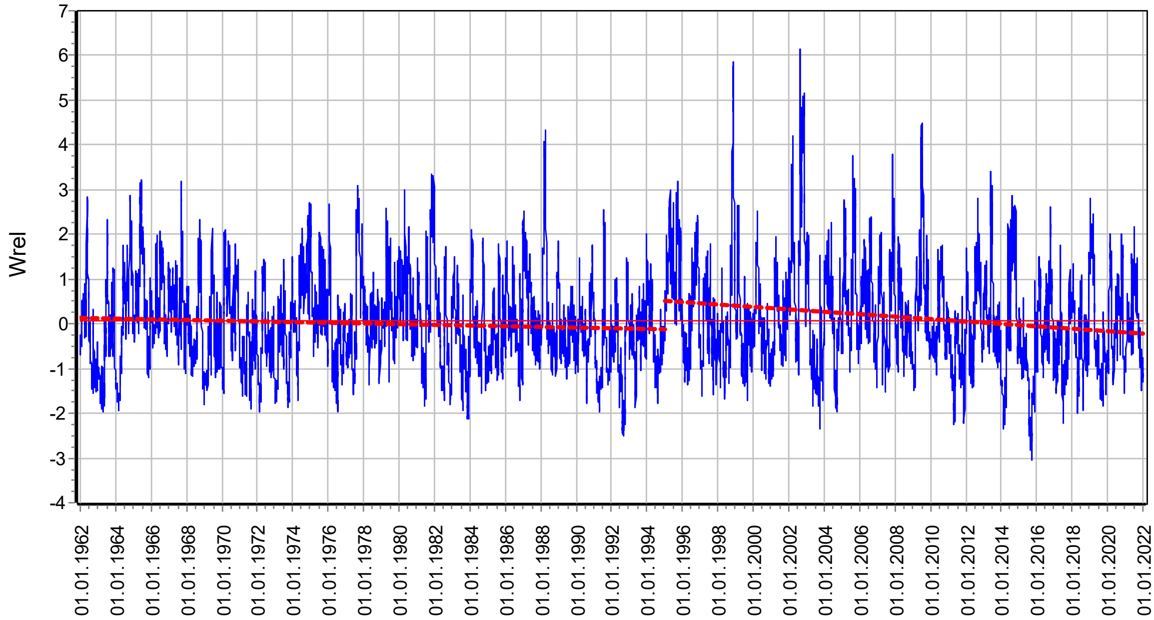


Figure 10. Relative wetness index W_{rel} at the station Churáňov since January 1st, 1962.

Phenology of *Ips typographus*

The PHENIPS model reveals clear trends in the change in phenology and annual generation development of this species. The day of first infestation (Figure 11) varies greatly from year to year, but there is a significant trend toward earlier onset of infestation ($r = -0.2324$; $p = 0.0358$). On average, infestation in spring occurs 1.5 days earlier every 10 years. The last snowmelt date, defined as the last day with at least 5 cm of snow cover, shows similar trend ($r = -0.3996$; $p = 0.0007$; accelerated by 2.5 days every 10 years). Modelled data for the end of winter, onset of vegetation growth, and onset of full vegetation showed a more pronounced trend toward earlier onset than the modelled timing of bark beetle infestation in spring (Table 3).

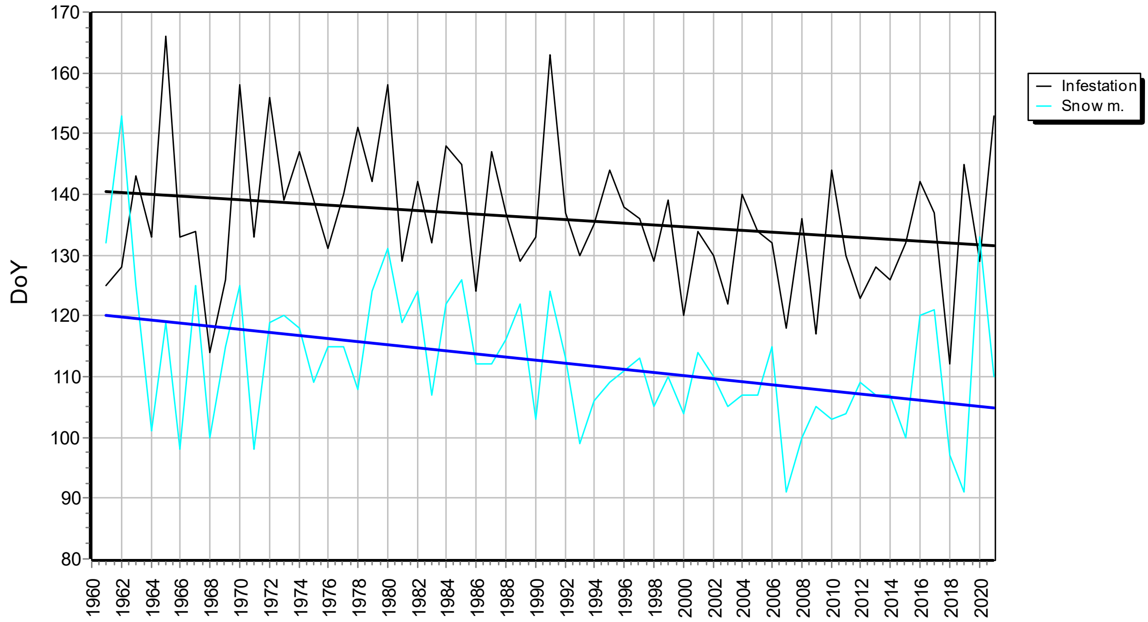
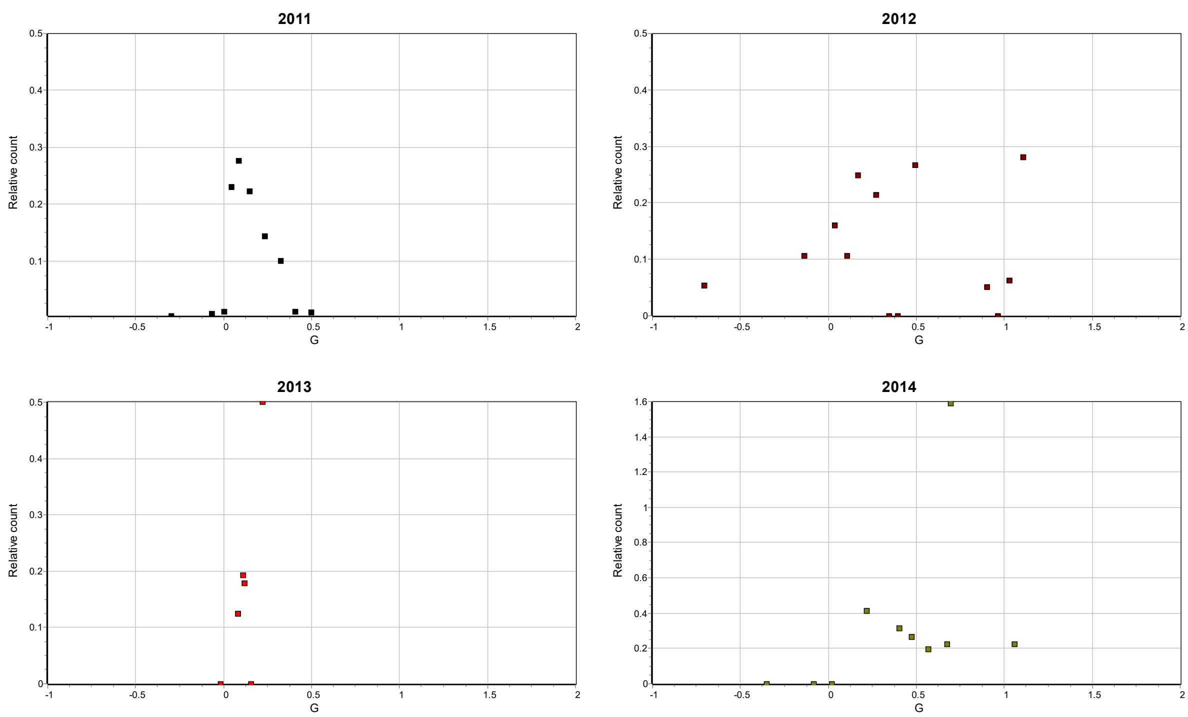


Figure 11. The PHENIPS model of spruce bark beetle *Ips typographus*: day of infestation. Second curve shows observed day of the last snow melting. DoY: day of year.

Table 3. Regression analysis for the first day of year when sum of effective temperatures (SAT) exceeded the limit value (0, 5 and 10 °C) with the comparison of day of melting of last snow and day of infestation of *Ips typographus*. *r* - regression coefficient; *p* - probability; *b* - slope of the regression line (days per year); AVG - average (day of year).

Begining of the period	*r*	*p*	*b*	AVG
$SAT_0 > 10$	-0.3157	0.0066	-0.4144	33.7
$SAT_5 > 10$	-0.3422	0.0035	-0.3248	96.0
$SAT_{10} > 10$	-0.2665	0.0189	-0.2239	130.8
Snow melting	-0.3996	0.0007	-0.2521	112.4
PHENIPS: infestation	-0.2324	0.0358	-0.1492	136.0

The onset of infestation indicated by the PHENIPS model with the parameters that were used corresponds to the actual numbers of *I. typographus* individuals captured by nearby pheromone traps (Figure 12). The population density of *I. typographus* varies greatly from year to year. Therefore, the number of trap catches was related to the sum of trap catches during the period when trap control was conducted on days where modelled *G* was in the interval between 0 and 0.5. This ratio is mentioned as relative count, which is dimensionless. Very good agreement with the start of infestation occurred, for example, in 2011, 2013, 2016, 2018, and 2021. The most captures before modelled infestation were in 2012 (12%), and 2019 (10%), in the other years they ranged between 0 and 2%. There was only an important delay in modelled infestation compared to recorded captures in some years (2013 12 days, 2014 17 days, and 2015 22 days, the number of days being only an estimate that is influenced by the dates of inspections), otherwise such a delay was 0 to 5 days. The model was also good at predicting the end of first-generation development, as shown by reascending trap catches (particularly in 2012, 2019, and 2021). The start of sister broods is also indicated by increased numbers of captures at G values close to 0.5. In the extremely warm year 2018, the end of the development of the second sister generation can be seen at *G* = 1.5.



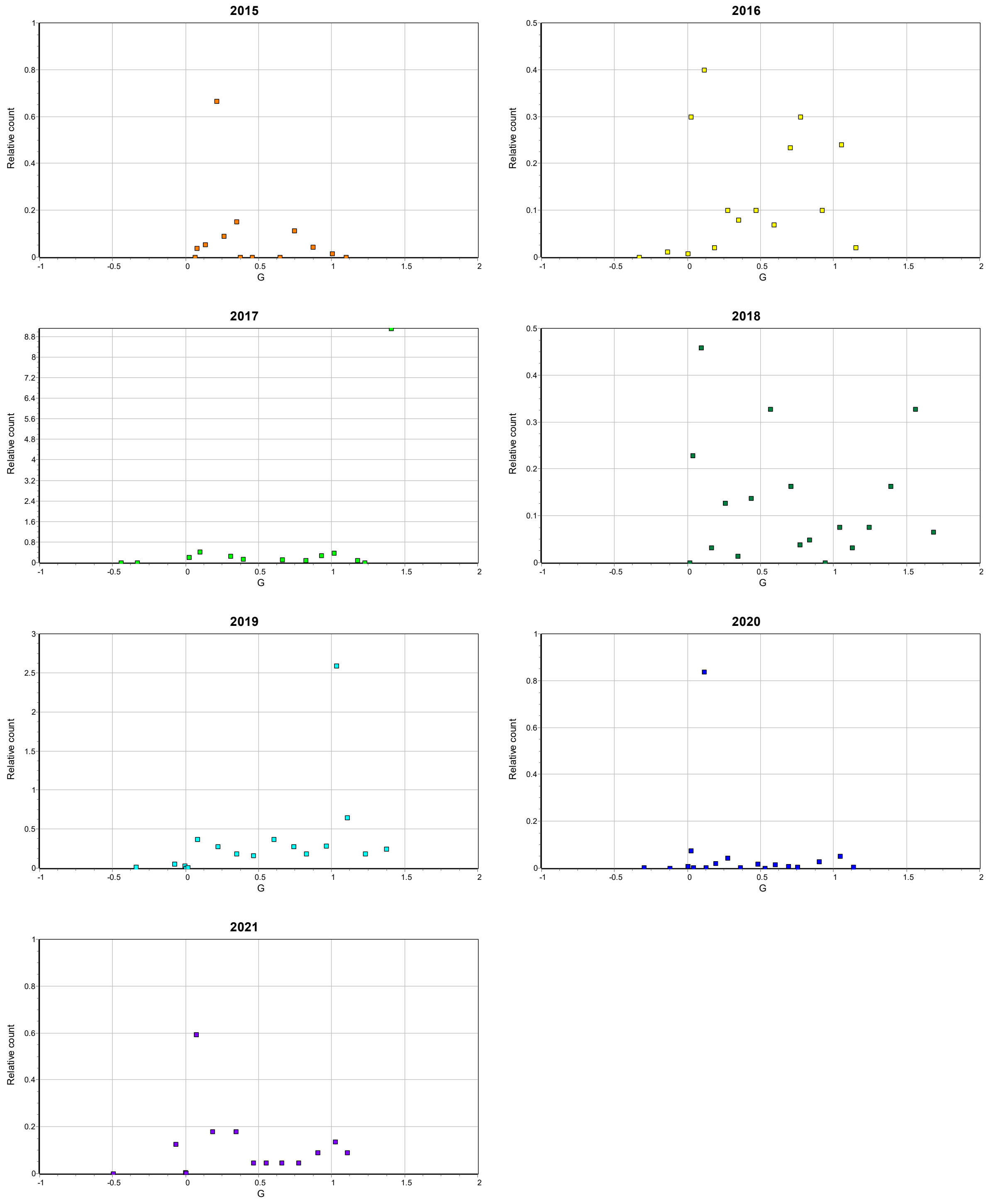


Figure 12. The relative counts of *Ips typographus* captured in pheromone traps compared to the *G* values of the PHENIPS model achieved on the day of the trap checking for individual years 2011 to 2021. Post-development checks (usually after 13 August) are not shown in the graphs.

The total number of generations per year and the achieved development degree are described by the index *G* (Figure 13). While the *G* values do not change until 1991, from 1992 there is a sudden rise, and in addition, the linear regression shows an increasing trend of the achieved values (+0.048 per 10 years). Extremely high values were achieved in 2003 and 2018. A shortening of the day length below 14.5 hours (in the conditions of Churáňov, this is usually August 13th) indicates the end of the bark beetle development, yet in some years catches were recorded until the second half of September. If the number of captures is standardized again to the interval *G* (0; 0.5]), 55 and 50% of individuals were captured after the end of the *I. typographus* development in 2016 and 2019, respectively. The extreme situation was recorded in 2017, when 691% of individuals were recorded in this period, i.e., the *I. typographus* population has increased extremely during the year, which is also indicated by the very high abundance during the check, which was carried out before the swarming of the second sisterbrood (at *G* = 1.4).

Under comparison with whole Czech Republic (MATĚJKA ET MODLINGER 2023), the onset of infestation was changed slowly at Churáňov (1.49 days per 10 years comparing 1.62 days per 10 years) but the index G was rather equal or higher (increase 0.070 comparing 0.068 each 10 years).

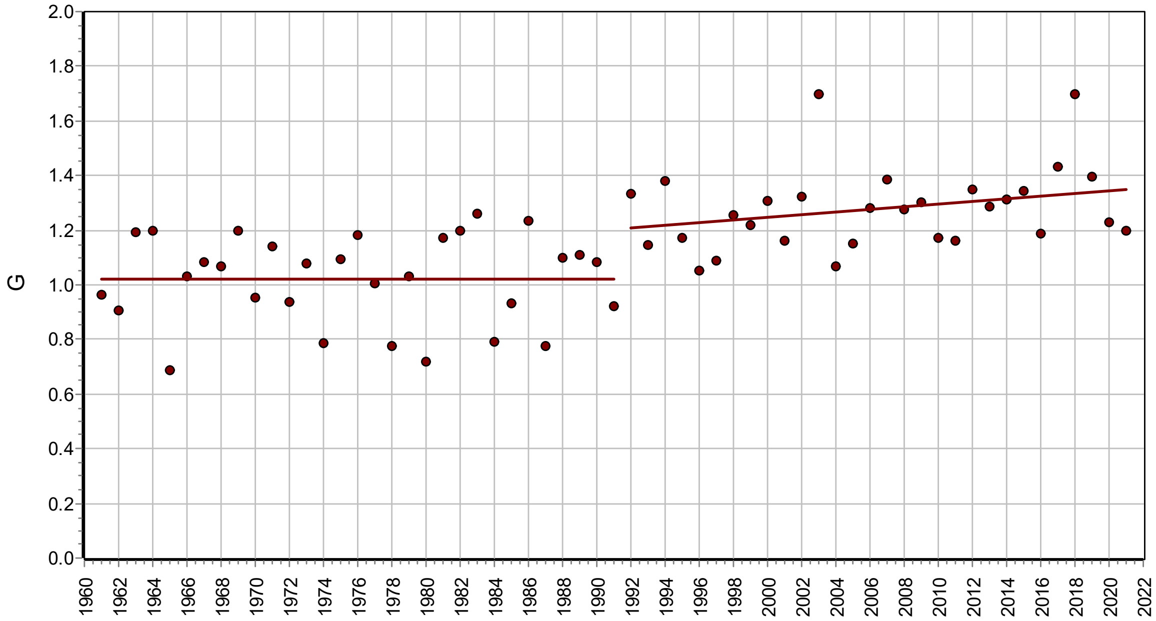


Figure 13. The PHENIPS model of spruce bark beetle *Ips typographus*: maximal values of the G index since 1961.

Effective temperature sums and begin of vegetation period

All three characteristics, or rather the beginnings of the periods defined by them, have fluctuated since 1961, but they are also shifting systematically (Table 3, Figure 14).

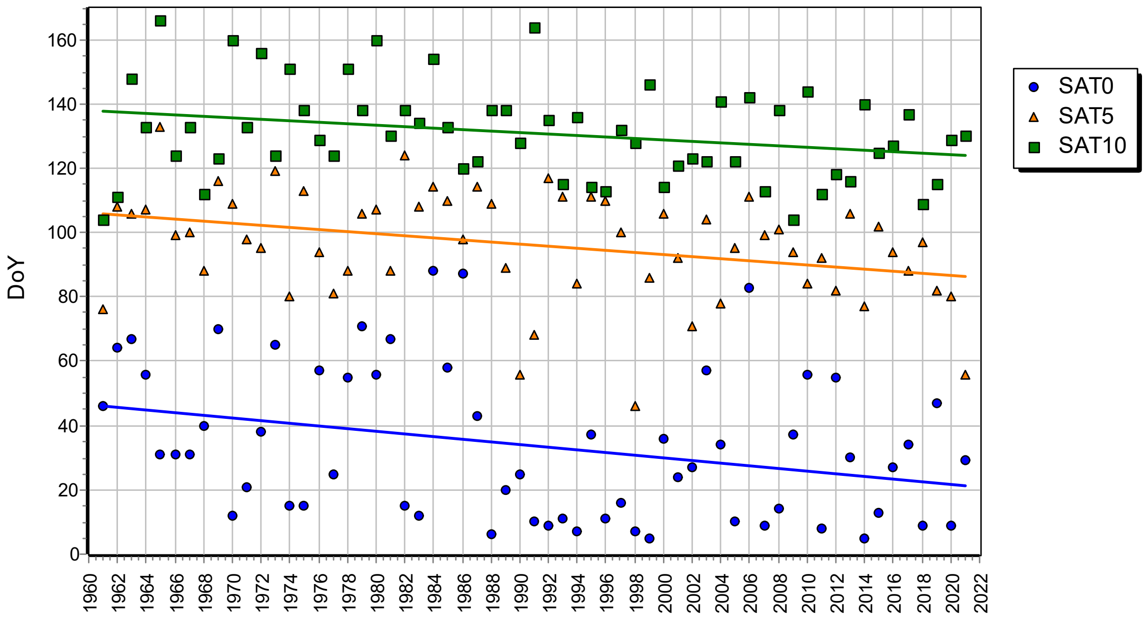


Figure 14. The first day of the year when the sum of active temperatures (SAT_0, SAT_5 or SAT_{10}) exceeded 10 d.°C.

The end of winter with a deep frost occurred at the latest in 1984 (March 28), 1986 (March 28) and 2006 (March 24), while the earliest occurred in 1999 (January 5), 2014 (January 5), and 1988 (January 6), when the deep winter did not actually occur. There is a significant shift in the end of winter over the years.

The onset of physiological vegetation activity characterized by the first day when $SAT_5 > 10$ was recorded in 1965 (May 13), 1982 (May 4), and 1973 (April 29) at the latest. However, in some years the corresponding day was already during the winter (February 15, 1998, February 25, 2021 and 1990). In such years, especially evergreen species can constantly transpire and thus lose not only water, but also sugars. The importance of the variable SAT_5 is also shown by its connection with the beginning of the sprouting of Norway spruce (BEDNÁŘOVÁ ET MERKLOVÁ 2011). The onset of days with $SAT_5 > 10$ precedes the melting of the last snow by an average of 16 days.

The onset of full vegetation characterized by the first day when $SAT_{10} > 10$ was recorded at the latest in 1965 (June 15), 1991 (June 13), and 1980 (June 8), on the contrary, it was first recorded in 1961 (April 14), 2009 (April 14), and 2018 (April 19). The systematic change in the onset of full vegetation is less significant than it was in the two previous parameters, but it is still statistically significant. The onset of vegetation characterized in this way is preceded by an average of 5 days before the *I. typographus* infestation.

However, days with average temperature below 0 °C were also recorded after the onset of full vegetation – such situation occurred in 1962 (April 28 to May 2 and June 1), 1987 (May 22), 1995 (May 14), 2011 (May 3–4), and 2019 (May 5 and 15). In such situations, there is a risk of frost damage to plants. This was observed in the past in the Šumava Mts., for example, with *Vaccinium myrtillus*.

Wetness index

The wetness index W (Figure 9) was around 127.1 ± 43.8 mm (mean ± standard deviation) within the entire evaluated period. The individual values are dependent on the season. Therefore, it is more appropriate to use the relative index W_{rel} (Figure 10), whose values oscillate with a long-term average equal to zero (0.07 ± 1.07), as follows from the definition of this index. Until 1994, the average *W* was 125.5 ± 42.7, which shows that the humidity conditions (really precipitation totals) did not change in the following years. Only after 1995 can be observed three years when *W* > 300 mm (2002, 2005, and 2009). Since 2015, mean *W* and W_{rel} (115.7 ± 36.4 mm and -0.25 ± 0.96, respectively) were particularly low compared to previous years, indicating dry conditions in recent years.

The break point regression for the relative humidity index W_{rel} (Figure 10) shows a sudden change when comparing the periods 1962–1994 and 1995–2021.

Figure 15 shows examples of the course of the wetness index in climatically extreme years. The first was the year 1983, when there was a frequent alternation of deep drought and, conversely, sudden heavy rains, the drought occurring mainly during the longer period of the main growing season (July) and then in autumn. In 1994, the drought was not as deep, but it occurred practically continuously from the end of April. The year 2003 was characterized by a significant drought that started already in March and was only broken by rainfall in October. The deepest drought in the growing season was recorded in 2015, yet the effect on vegetation was probably not that significant, as the driest part of the year was August to November. Year 2018 was even drier in most of the Czech Republic, but this is not matched at Churáňov, where above-average precipitation was even recorded in July.

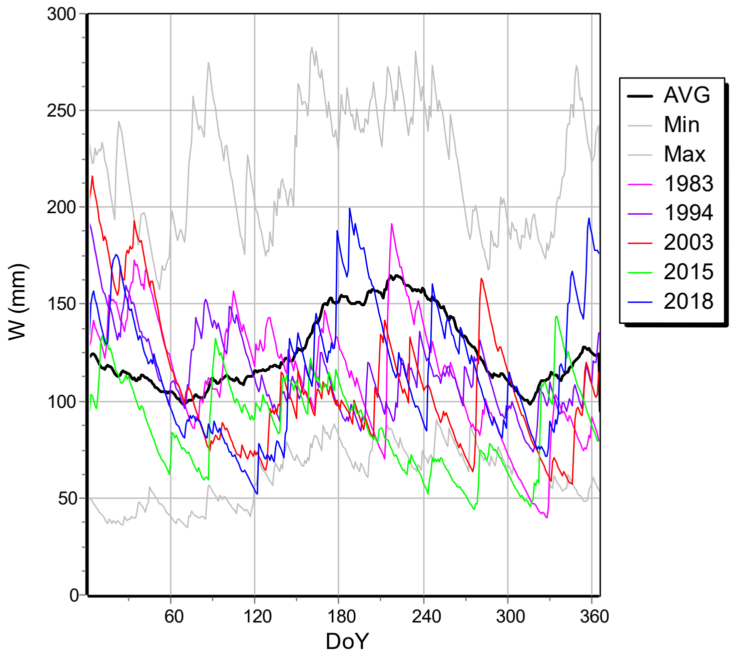


Figure 15. The course of the wetness index W at the Churáňov station in selected climatically extreme years in comparison with the average and extremes over the period 1962-1994.

Potential evaporation

Potential evaporation varied between 360 and 660 mm per year with a mean of 490 mm per year, standard deviation 65.3 mm. The ratio of precipitation to potential evaporation averaged 2.29 with a range of 1.20 and 3.55, while this ratio decreased insignificantly over time (r = -0.036). While until 1994 quite regular oscillations of values around the average occurred, positive deviations dominated in the period 1995 to 2010 with the exception of the extremely dry year 2003. From 2011, a series of significantly dry years with low values of the ratio follows. The lowest value of the ratio was recorded in 2015. Thus, the most pronounced drought stress was recorded in 1983, 1992, 2003, 2011, 2015, and 2019 (Figure 16).

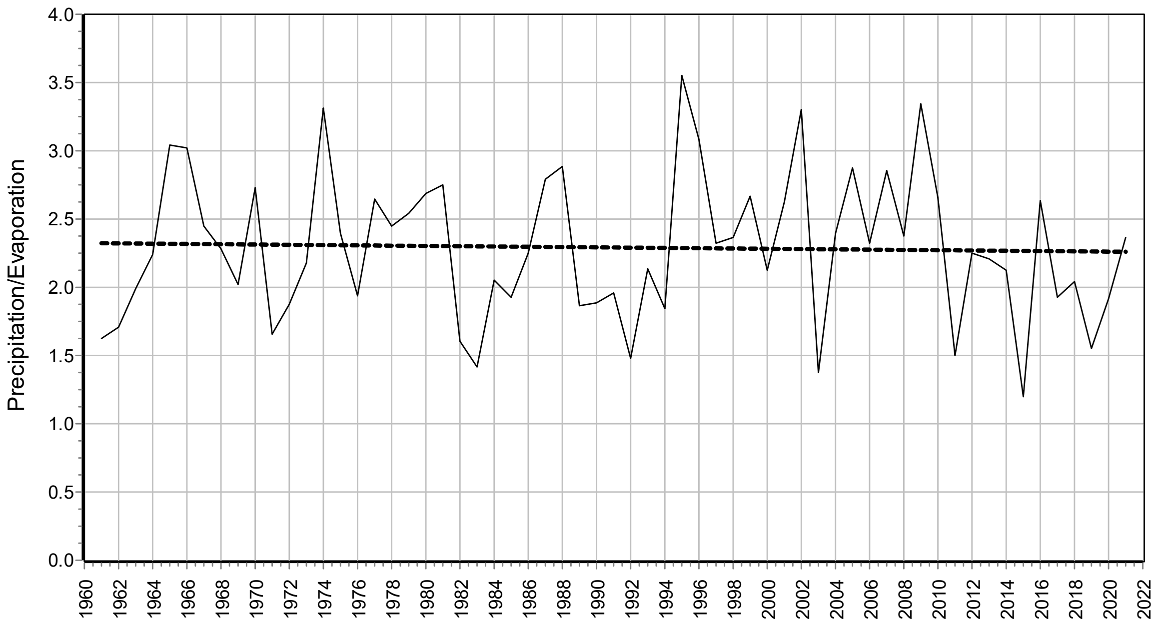


Figure 16. The precipitation / potential evaporation ratio at the Churáňov station during 1961-2021.

Picea abies growth index

The *GI* growth index in the period 1962 to 2021 has an average of 1.42, a standard deviation of 0.15 and a slightly increasing tendency (+0.018 in 10 years; $r = 0.2085$; $p = 0.945$). The lowest value (that corresponds the highest predicted climatic stress) was found in the climatically extreme year 2003, and also in 1983. Other years were more favourable for the growth of Norway spruce at the Churáňov station, including the years 2015 to 2020 (Figure 17). In the mountainous conditions of the Šumava Mts., we do not observe an increase in the climatic stress of *P. abies*, as is the case in the rest of the Czech Republic (MATĚJKA ET MODLINGER 2023).

This approach is only an approximation, as the plots in Písek are located at 500–600 m a.s.l. (submontane sites) and the climatic and growing conditions for spruce in Churáňov (with distance only 35 to 50 km) may be different, but trends in main features is the same.

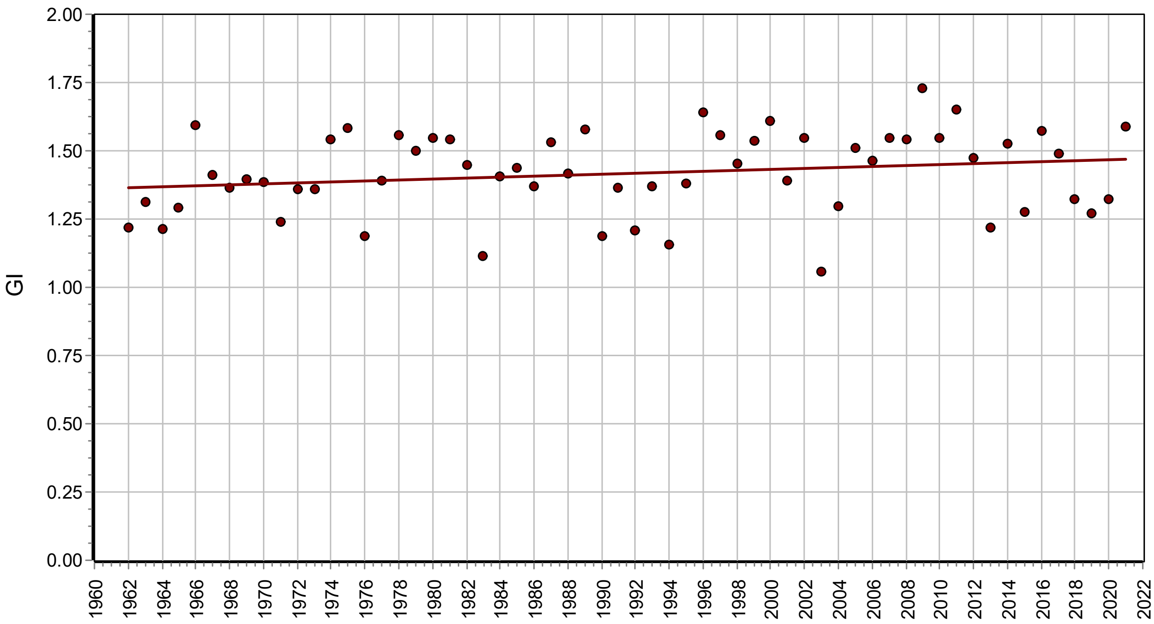


Figure 17. The *Picea abies* growth index (*GI*) according to the Churáňov station.

Potential for forest disturbance by wind

The forest stands are disturbed mainly by extremely strong wind, therefore the value of the recorded maximum wind speed in individual years of the monitored period is compared (Figure 18). Contrary to the commonly assumed hypothesis of increasing wind speed during climate change, the maximum wind speeds at the Churáňov station had a demonstrably decreasing tendency. The highest wind gusts were recorded on (descending by speed ≥ 35 $m.s^{-1}$) 12.2.1962, 1.3.1990, 24.11.1984, 1.8.1983, 17.1.1965, 18.1.2007 [windstorm Kyrill, 38 $m.s^{-1}$], 20.1.1986, 23.1.1995, 13.12.1989, and 15.1.1968, mostly winter storms. The aforementioned windstorm Kyrill led to the destruction of a number of stands in the Šumava Mts.

Wind damage of stands not only depends on maximum wind speed. Data and analysis concerning changes of frequency of strong winds or seasonal changes of wind speed were not presented. Therefore, more cautious conclusions would be drawn concerning changes of disturbance by wind in future.

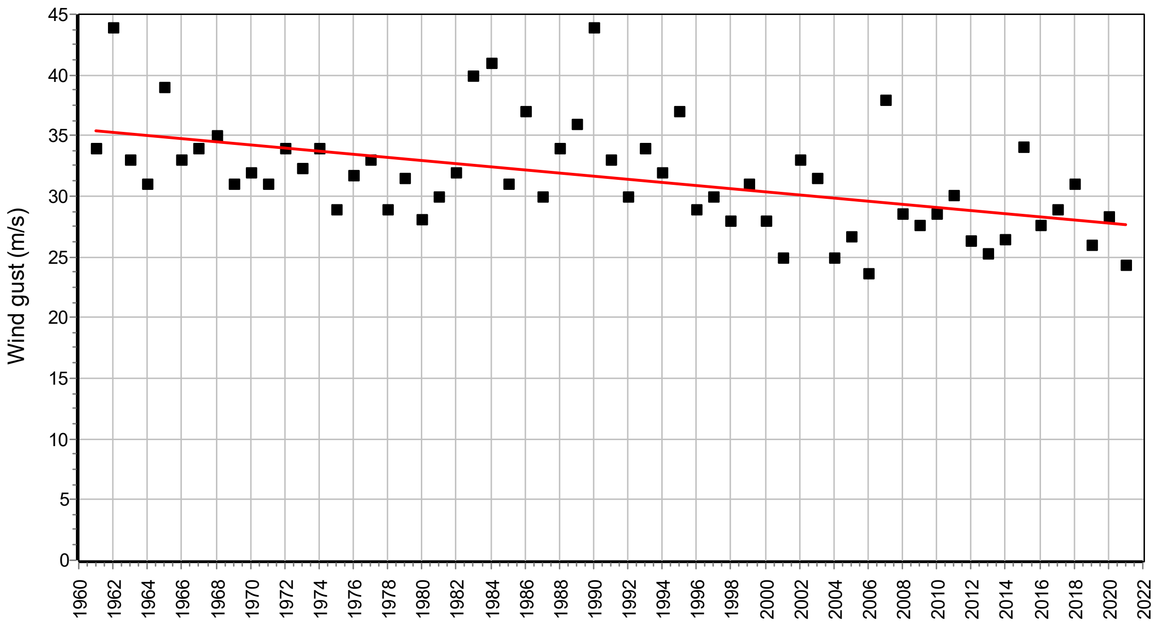


Figure 18. The maximum wind gusts recorded in individual years at the Churáňov station. Linear regression (decrease -1.41 $m.s^{-1}$ in 10 years) is statistically significant ($r^2 = 0.2937$; $p < 0.0001$).

Conclusions

The mountain meteorological station Churáňov (1118 m above sea level) provides long-term data on the development of the weather in the central part of the Šumava Mts. Since 1961, there has been a significant increase in average air temperatures (+0.37 °C per 10 years), while the increase in temperatures was most noticeable from April to August, i.e., during the growing season. Precipitation was highly variable from year to year and there was no evidence of a trend of change in their totals. The relative air humidity is apparently stable, but when the period is divided into two intervals with the border between the years 1994 / 1995, a slight decrease in the relative air humidity appears in both intervals and a significant jump in humidity at the border of mentioned years.

The earlier onset of vegetation is associated with the increase in average temperatures, by an average of 2 to 4 days per 10 years, which also corresponds to the shift in the melting of the last snow. The shift in the onset of *I. typographus* infestation was not as pronounced (an average of 1.5 days per 10 years), but it was still demonstrable. The infestation occurs on average 20 to 25 days after the last snow melts. The first *I. typographus* infestation indicated by the PHENIPS model was confirmed on the basis of captures in pheromone traps near the meteorological station.

The number of generations and the achieved development state of *I. typographus* was stable until 1991 (index *G* around 1), from 1992 there was a sharp increase, which was followed by another growing trend. Extreme values with *G* around 1.7 were recorded in 2003 and 2018.

The climatic stress of *Picea abies* is essential for the development of gradations of spruce bark beetle. This stress is highly variable from year to year, yet its increase is noticeable especially in the last decade. The basis of climate stress is the lack of precipitation, which was most noticeable using the W_{rel} moisture index in the years 1992, 2003, 2012, 2014–2015, and 2017. A comprehensive indicator for the occurrence of drought is the ratio of the volume of precipitation to potential evaporation, which points to the critical years 1983, 1992, 2003, 2011, 2015, and 2019.

The growth index of *Picea abies* (*GI*) shows a slightly increasing trend in mountain locations, which indicates an increase in the average annual increments given by the apparently increasing average temperature, but we can clearly identify years with deteriorated growth conditions, i.e., with high climatic stress. From this point of view, the most problematic years were 1983 and 2003. In both of these years, there were massive gradations of *I. typographus* in Šumava.

In contrast to the commonly considered increase in the forest disturbance risk caused by wind, it has been proven that this risk rather decreases, because the maximum value of wind gusts decreases. Although it is known that wind damage to stands can accelerate the population gradation of bark beetle, in general, the maximum wind speed data failed to identify such situations associated with any gradation wave. The only exception is perhaps the disruption of stands by windstorm Kyrill at the beginning of 2007, when the destruction of some stands in the Šumava Mts. accelerated the bark beetle gradation initiated by the climatically extreme year 2003.

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