Effect of climatic factors on the dynamics of radial increments of Norway spruce, European beech and sessile oak

R. Petráš, J. Mecko

National Forest Centre – Forest Research Institute in Zvolen, Zvolen, Slovakia

ABSTRACT: Correlations of increment indexes with average monthly temperatures and total monthly precipitation were studied on annual ring series of 455 trees of Norway spruce (*Picea abies* [L.] Karst.), sessile oak (*Quercus petrea* Liebl.) and European beech (*Fagus sylvatica* L.). Data on precipitation from the period 1901–2005 and on temperatures from the period 1931–2005 were used. Statistically significant dependences with correlation coefficients in the range of 0.2–0.5 were confirmed. All tree species react positively to precipitation mainly in June and July. An increase in precipitation by 1 mm when compared with the long-term average results in an increase in increment index of spruce almost by 0.13%. This index in oak and beech increases only by a half value of the value for spruce. Precipitation from the second half of the vegetation period of the previous year is also important. Higher temperatures during the vegetation period affect increment changes mostly negatively. With temperature increase by 1°C, when compared with the long-term average, the increment index of trees decreases by about 1–2%.

Keywords: annual ring analysis; climatic factors; radial increments; European beech; sessile oak; Norway spruce; Slovakia

Diameter and height increments are typical growth characteristics of trees and they have a seasonal character in our temperate climatic zone. Individual dispositions of tree, site and climatic conditions of each tree contribute to their formation. Possible damage to trees and change in the growth conditions are frequent reasons for increment changes. It has been confirmed by many results of research published recently, e.g. in relation with damage to forests by air pollutants and emissions as well as the results of current research on possible effects of climate change on forests. We can cite the works on dendrochronology (Fritts 1976; Schweingruber 1983) and many others that are aimed at studying the effect of climatic factors on radial increments mainly of coniferous tree species. Vita and Bitvinskas (1998) and Ots and Rauk (1999) studied annual rings of pine and spruce in Lithuania, Mäkinen (1998) studied pine in Finland and Feliksik and Wilczyński (1999a, b; 2004) studied European black pine, Weymouth pine and Douglas fir in Poland. Detailed research was conducted in spruce, larch and Swiss stone pine in the Alps, namely in the French part by Rolland et al. (1998), in the Italian part of the Alps by Anfodillo et al. (1998) and in the Austrian part by Oberhuber and Kofler (2000, 2003). In Germany Knott (2004) studied seasonal dynamics of diameter increment of fir and beech, Gruber (2002) only of beech and Röhle et al. (2010) of spruce, pine and beech. Vejpustková et al. (2004) and Novák et al. (2010) studied the effect of climatic factors on spruce and pine diameter increment in the Czech Republic. In Slovakia Ďurský and Pavlíčková (1998) dealt with the issue of climate and radial increment of pine, Šmelko and Miková (1999), Pajtík and Ištoňa (2003) investigated Turkey oak and Petráš et al. (2006, 2007) dealt with sessile oak. Recently, Kahle et al. (2008) studied the effect of precipitation on radial increments of spruce, beech and pine trees in several places in Scandinavia, Western and Central Europe. According to their results it is not probable that the higher increment of forests in Europe is a consequence of higher precipitation. In the same study Mellert et al. (2008) did not clearly confirm the

effect of precipitation even on the height growth of trees. He did not confirm the effect of precipitation even in the combination with increased content of atmospheric nitrogen.

The aim of our paper is to study by means of partial correlation dependences the effect of basic climatic factors on increment changes in the long-term growth process of spruce, oak and beech trees.

MATERIAL AND METHODS

Empirical material was collected in the central part of Slovakia. Average monthly temperatures from the years 1931–2005 and monthly precipitation totals from the years 1901–2005 were obtained from a climatic station at Sliač. Annual ring probes were taken from dominant and co-dominant trees of even-aged stands of spruce, beech and sessile oak which grow to the distance of about 20–25 km from the climatic station. At each tree only one increment bore at breast height was taken at upside of slope and other parameters such as tree diameter at breast height and height of tree, tree class, damage to the stem, crown defoliation, relative length and crown isolation were determined. Annual ring probes were taken in the period 2004–2006 from 455 trees in 18 pure stands according to tree species with the following characteristics in Table 1.

The width of annual rings was measured with a digital positiometer to the nearest ± 0.01 mm. The annual ring series were synchronized, dated and standardized. A simple method of the graphical comparison of the highest increment minimums and statistical testing of the increment trend parallelism by Schweingruber (1983) and Jačka (1989) were used. The radial increments arranged in annual ring series were synchronized in such a way that the parallelism percents of increment trends among all the individual trees from one stand were calculated. An average increment curve was calculated for the group of 4–7 trees within the same stand which had the highest percent of parallelism between each other. The increment curves of all trees in the same stand were synchronized individu-

ally according to the average increment curve. Their percent of parallelism is relatively high, for spruce it is 61–98%, on average 80%, for oak 65–96%, on average 79% and for beech 55–90%, it means on average 77%. Thus spruce and oak have only the slightly higher percent of parallelism than beech. Regarding the high percent of parallelism of all tree species we can state that their increment curves are very similar and individual trees react equally to the growth factors of a particular stand with relatively high probability of 95%. It means that individual trees in a particular year in comparison with the previous year have equally increased or decreased increment. In most cases the trees also reach increment minimums in the same calendar years. On the majority of the experimental plots it was in the years 1905, 1923, 1947, 1962, 1974, 1993, and 2000. Pine trees also reached increment minimums at the same time as reported by Petráš et al. (2000). Standardization was performed by means of the indexes of radial increments I_i, which were calculated as the ratio of real annual increments i_r and their model values i_m:

$$I_i = \frac{i_r}{i_m}$$

Model values were not derived by equalizing of age increment trends but moving averages of radial increments were calculated. Moving averages were calculated from four consecutive increments. Petráš et al. (2007) considered this procedure justified. Increment indexes were analyzed in detail and their correlation from average monthly temperatures and monthly precipitation totals was studied.

It is obvious in Fig. 1 that at the Sliač climatic station annual precipitation totals ranged from 500 to 1,000 mm for the years 1901–2005 but for the months of May–August they ranged only from 100 to 500 mm. It is similar for air temperatures. For the years 1931–2005 average annual temperatures were about 6–10°C and for the vegetation period 15–19°C. Regarding their long-term trend, it is evident that they show relatively high variability and provide good opportunities for studying their effect on tree increments.

Table 1. Stands characteristic of research plots

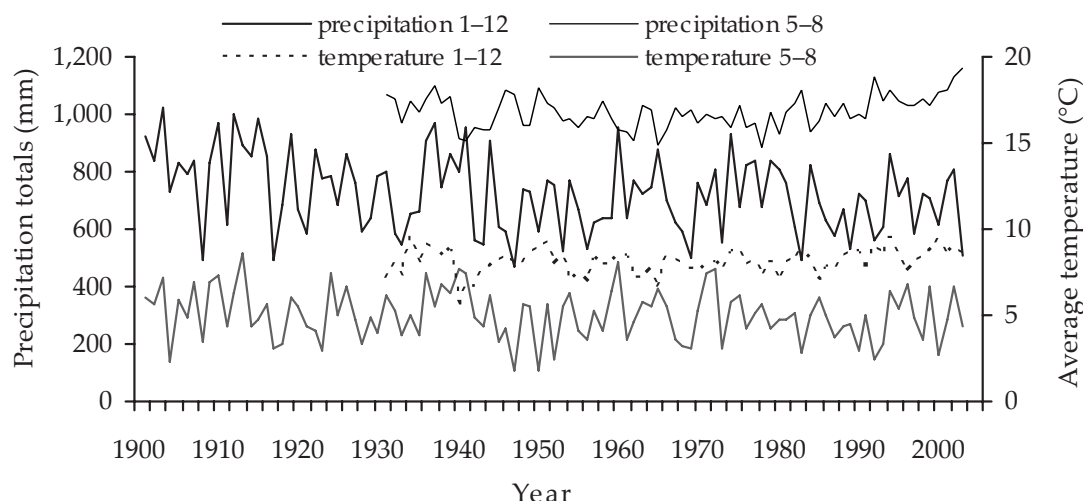| Tree species | Number of | | Age | Site index | Altitude |
	stands	trees			
Oak	8	190	70–170	22–30	400–650
Spruce	5	145	85–120	32–40	350–480
Beech	5	120	105–160	18–30	500–700

Fig. 1. Precipitation totals and average temperatures at Sliač climatic station

RESULTS AND DISCUSSION

Pairwise correlations of the effect of climatic factors on radial increments of trees

The effect of climatic factors on radial increments of trees was studied in detail by means of correlation analysis on standardized increment curves. Pair correlation coefficients were calculated for each tree which measure the linear relationship of two variables. In our case they express the intensity of the dependence of annual increment indexes on monthly precipitation totals and average monthly temperatures according to all months (January to August) of the actual calendar year, i.e. the year when the studied increment was formed as well as for the last 8 months (May–December) of a previous year. Significance of correlation coefficients was evaluated by means of statistical test at the level of significance $\alpha = 0.05$ with the number of degrees of freedom $n-2$.

Significance of correlations for oak

The proportion of trees with statistically significant correlation was different according to stands. The lowest one was in stand No. 8, where only about 5% and 25% of trees had a statistically significant positive correlation of annual increments and monthly precipitation in December and January. For 10% and 45% of trees the correlation of precipitation in September and August of the actual year was also significant. The correlation between annual increments and average monthly temperatures was negligible. The highest correlations were found out in stand No. 6, where precipitation in June and July of the actual year and in September of the previous year affected the increment of about 65–85% of trees statistically significantly and positively. The intensity of their correlation is not high as correlation coefficients range only from 0.28 to 0.51. The negative effect of precipitation and temperature is small and illogical similarly like in the previous stand.
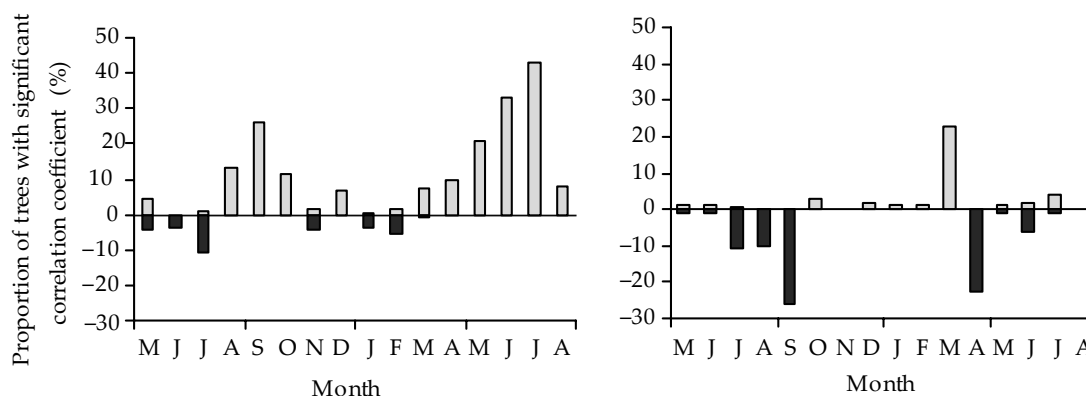

Fig. 2. Proportions of oak trees with significant effects of precipitation (left) and temperature (right) on increment on all plots. Single letters mean particular months continually in the previous year and in the actual year

After summarizing the significant correlation coefficients from all 8 stands and 190 trees according to Fig. 2 (left) we can state that precipitation in the spring and summer season of the actual calendar year affects annual increments significantly and positively. In the period of March–July the proportion of trees for which the precipitation is significant increases by about 10–45%. Another important period regarding precipitation is August–October of a previous year. The proportion of trees which are significantly influenced by precipitation is about 10–25%. The temperature affects radial increments mostly negatively (Fig. 2, right). About 10–25% of trees react negatively to average temperatures in the period of July–September of the previous year and in April of the actual year. March air temperatures affect only 20% of trees positively.

Significance of correlations for spruce

Spruce stands have a different proportion of trees with statistically significant correlation coefficients. The lowest proportion of trees with the statistically significant effect of precipitation on annual ring indexes was found on plot No. 1. On this plot the June and July precipitation of the actual year, i.e. the year when the annual ring was formed, was most significant for 80% and 70% of trees, whereas for 20% or almost 40% of trees precipitation from the period of August–September of the previous year was also significant. The negative effect of higher temperatures in September of the previous year on almost 90% of trees is unusual. The highest proportion of trees with the statistically significant effect of precipitation on annual ring indexes was recorded in stand No. 5. The June and July precipitation of the actual year is most significant for 100% of trees and for almost 80% of trees in this stand, and only for 10% or 5% of trees the precipitation in September

and October of the previous year is also significant. Similarly to the previous stand, higher temperatures in September of the previous year had a negative effect almost on 80% of trees.

Based on the proportion of the trees with significant correlation coefficient (Fig. 3) in all 145 trees in 5 stands together we may state with 95% probability that:
– About 85–90% of trees react positively to precipitation in June and July,
– Only about 10% of trees react positively to precipitation in April, May or August,
– Only about 20% of trees react positively to precipitation in August and September of the previous year,
– Influence of monthly temperatures on diameter increments of spruce is mostly negative,
– About 30% of trees react negatively to higher temperatures in August of the actual year,
– About 40% of trees react negatively to high temperatures in June, and almost 65% of trees to high temperatures in September of the previous year,
– Only 30% of trees react positively to higher monthly temperatures but only in March of the actual year.

We can state from the obtained results that summer precipitation is very important for spruce stands. Even very high supplies of winter and/or of spring moisture are insufficient to cover the high consumption of water during summer months. We also confirmed a more significant but negative effect of monthly temperatures on radial increments. Anfodillo et al. (1998), Mäkinen (1998), Kahle et al. (2008) and Mellert et al. (2008) attributed higher but positive significance to temperatures only in cold climatic zones or in high mountainous locations, where it is relatively cold, with permanent excess of precipitation and soil moisture during the vegetation period.
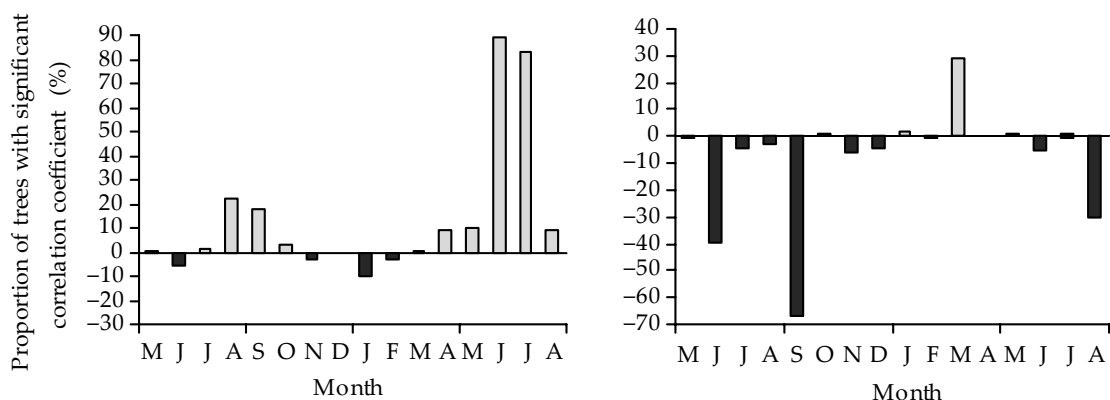

Fig. 3. Proportions of spruce trees with significant effects of precipitation (left) and temperature (right) on increment on all plots. Single letters mean particular months continually in the previous year and in the actual year
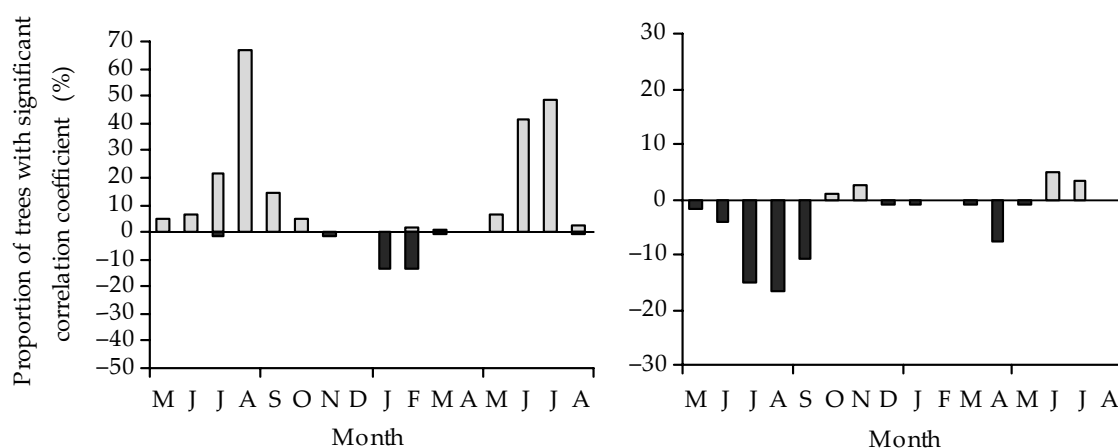
Fig. 4. Proportions of beech trees with significant effects of precipitation (left) and temperature (right) on increment on all plots. Single letters mean particular months continually in the previous year and in the actual year

Significance of correlations for beech

Similarly like for oak and spruce, the significance of correlation coefficients for beech in the particular stands was considerably different. The lowest proportion of trees with the statistically significant effect of precipitation on increment indexes was recorded in stand No. 3. In this stand June and July precipitation of the actual year was most significant only for 20% of trees but precipitation in August of the previous year was significant almost for 90% of trees. We recorded the highest proportion of trees with the statistically significant effect of precipitation on increment indexes in stand No. 4. The June and July precipitation of the actual year is most significant almost for 100% of trees, and precipitation in August and September of the previous year is significant only for 30–60% of trees.

Based on the proportion of trees with statistically significant correlation coefficient together for all 120 trees in 5 stands, which are illustrated in Fig. 4, we can state with 95% probability that:
– About 40–50% of trees react positively to precipitation in June and July,
– About 20% and 70% of trees react positively to precipitation in July and August of the previous year, effect of monthly temperatures on diameter increment of beech trees is mostly negative,
– Only about 10–15% of trees react negatively to higher temperatures in July until September of the previous year.

Multiple correlation models of the effect of climatic factors on radial increments of trees

After performing the detailed analysis of pair correlation coefficients sets of monthly precipitation

amounts and average monthly air temperatures were chosen which formed significant pair correlations with increment indexes of a larger number of trees on each research plot. A different set of monthly precipitation amounts and temperatures was chosen for each tree species:

Oak - - , *P8ly, P9ly, P10ly, P5ay, P6ay, P7ay, T7ly, T8ly, T9ly, T3ay, T4ay,* - ,

Spruce - - , *P8ly, P9ly,* - , - , *P6ay, P7ay,* - , - , *T9ly, T3ay,* - , *T8ay,*

Beech - *P7ly, P8ly,* - , - , - , *P6ay, P7ay, T7ly, T8ly, T9ly,* - , - , - ,

Abbreviations: *P* – precipitation, *T* – temperature, number – calendar month, *ly* – previous year, *ay* – actual year. For example the abbreviation *P8ly* means precipitation for August of the previous year, it means in the previous year when increment was formed. As it obvious from the list of climatic factors for the three tree species, precipitation in August of the previous year and precipitation in June and July of the actual year are significant. Regarding monthly temperatures, only the temperature in September of the previous year is significant for each tree species. The method of multiple correlations was used for the derivation of the models of dependence of increment indexes on selected climatic factors together for all trees in each stand and together for every tree species. Tables 2–4 present statistically significant parameters and multiple correlation coefficients according to tree species. The multicollinearity was tested by Scott's criterion (Kupka 2002) and it was not supported in any occasion.

Model for oak

According to the parameters of the model in Table 2 it is obvious that a different combination

Table 2. Oak – correlation coefficients and parameters of a regression model of the dependence of increment indexes on significant climatic factors

| Plot | Number | | Correlation coefficient | Model parameters for variable | | | | | | | | | | | |
	trees	annual rings		absolute	P8ly	P9ly	P10ly	P5ay	P6ay	P7ay	T7ly	T8ly	T9ly	T3ay	T4ay
P01	25	1,773	0.298	1.004896				0.000638	0.000656	0.000243			-0.010894	0.007195	
P02	24	1,726	0.429	1.914429	-0.000277	0.000558		0.000634	-0.000267	0.000495	-0.017220	-0.017445	-0.015837	0.006610	-0.018868
P03	23	1,656	0.492	1.657849		0.000968	0.000253	0.000683		0.000783	-0.011827	-0.021317	-0.016016	0.015628	-0.007234
P04	24	1,728	0.424	1.481642	0.000404	0.000707	0.000277	0.001102		0.000647	-0.016279	-0.016705	-0.014291	0.008094	-0.013275
P05	25	1,800	0.406	1.634443		0.000769		0.000523		0.000427	-0.010820	-0.012375		0.008638	-0.018124
P06	26	1,380	0.526	0.893821	0.000378	0.000907	0.000447	0.000625	0.001303	0.001075	-0.012275	-0.008693	0.009056	0.009358	
P07	24	1,728	0.419	1.514752	-0.000278	0.000567	0.000465	0.000820	0.000560	0.000803	-0.011139	-0.024825	-0.006930	0.007451	
P08	19	1,368	0.203	0.659786			-0.000371				0.016938		0.006922	0.008818	
Together	190	13,159	0.363	1.392695		0.000596	0.000098	0.000672	0.000260	0.000576	-0.008487	-0.012873	-0.007211	0.009092	-0.010206

of climatic factors is significant for each stand. For most stands the precipitation in September and October of the previous year and especially in May and July of the actual year is significant. According to negative parameters mainly in July and August of the previous year we can state that the effect of their average monthly temperatures is mostly negative. A positive effect on all plots was confirmed only for March temperature in the actual year. Based on the parameters of the model for 190 trees of eight research plots we can state that only precipitation in August of the previous year was insignificant. Although all dependences are statistically significant, they are not very close. Multiple correlation coefficients on 8 plots range from 0.203 to 0.526 and the whole set of oak trees has the value 0.363 only. Determination coefficient, which is its square, has the value 0.132. It means that it is possible to explain only 13.2% of the total variability of increment indexes by means of the model. The other reasons are currently unknown.

Model for spruce

Spruce has a lower number of significant climatic factors in the model. According to their list given in Table 3 it is obvious that only precipitation and temperature in September of the previous year are not significant for all stands. In other cases precipitation in August of the previous year and in the period of June–July of the actual year have a positive effect on increments as well as temperatures in March of the actual year. Regarding negative parameters of the temperature in September of the previous year and August of the actual year we can state that their effect is negative. The model for 145 trees from five research plots has all significant factors. Correlation dependences are not very close even for spruce. They range from 0.402 to 0.517 for individual stands, and for the whole set of all spruce trees the value is 0.465. Coefficient of determination has the value 0.216.

Model for beech

Beech has the same number of significant climatic factors in the model as spruce. It is obvious from Table 4 that only precipitation in August of the previous year and July of the actual year is significant for all stands. In other cases precipitation in July of the previous year and June of the actual year as well as temperatures influence increments posi-

Table 3. Spruce – correlation coefficients and parameters of a regression model of the dependence of increment indexes on significant climatic factors

Plot	Number		Correlation coefficient	Model parameters for variable								
	trees	annual rings		absolute	*P8ly*	*P9ly*	*P6ay*	*P7ay*	*T9ly*	*T3ay*	*T8ay*
P01	25	1,821	0.484	1.664746	0.000496	0.000560	0.000938	0.000662	–0.043009	0.019164	–0.018901
P02	30	2,133	0.402	1.119192	0.000457		0.001320	0.000840		0.013136	–0.020775
P03	29	2,117	0.491	1.264223	0.000792		0.001627	0.001219	–0.021325	0.016136	–0.017332
P04	31	2,291	0.463	1.249972	0.000302		0.001486	0.000946	–0.022995	0.011584	–0.010935
P05	30	2,220	0.517	1.365978	0.000443	0.000543	0.001320	0.001175	–0.025552	0.025557	–0.020064
Together	145	10,567	0.465	1.333279	0.000478	0.000291	0.001329	0.000965	–0.022961	0.016812	–0.017370

tively in September of the previous year. Regarding negative parameters in July–August of the previous year we can state that the effect of their average monthly temperatures is negative. The model for all 120 trees from all 5 stands has all significant factors. Correlation dependences are not very close for beech as well. They range from 0.216 to 0.422 in the particular stands, and for the whole set of all trees the value is 0.341. Coefficient of determination has the value 0.116.

Intensity of the effect of climatic factors on trees increments

Based on the values of model parameters in Tables 2–4 we can evaluate and quantify also the intensity of the effect of significant climatic factors on the increment of trees of the studied tree species. Figs. 5 and 6 illustrate changes of increment indexes in percent in dependence on the unit change of a particular climatic factor. Regarding Fig. 5 (left) we can state that an increase of precipitation in the period of July–October of the previous year by 1 mm will result in an increase of increment

indexes differently according to the respective tree species within 0.01–0.11%. Precipitation in August affects spruce and beech to the largest extent, while precipitation in September affects oak to the greatest extent. The effect of the previous year's precipitation on oak is only a half of the effect on beech.

The effect of precipitation on increment formed in the same year is slightly higher. June and July precipitation has the greatest effect (Fig. 5, right). With its increase by 1 mm increment indexes also increase by about 0.03–0.13%. Precipitation in June has a greater effect on spruce and July precipitation has a greater effect on beech and oak. Spruce reacts to precipitation in both months by about one half more intensively than beech and especially oak. It is interesting that precipitation in May has about the same effect on oak as precipitation in July.

The effect of temperatures of the previous year is negative with one exception. Fig. 6 (left) illustrates that with an increase of average monthly temperatures by 1°C the increments will decrease by about 2.2%. This is most marked for spruce and September temperatures. Higher July and August temperatures have a higher negative effect on oak and beech.
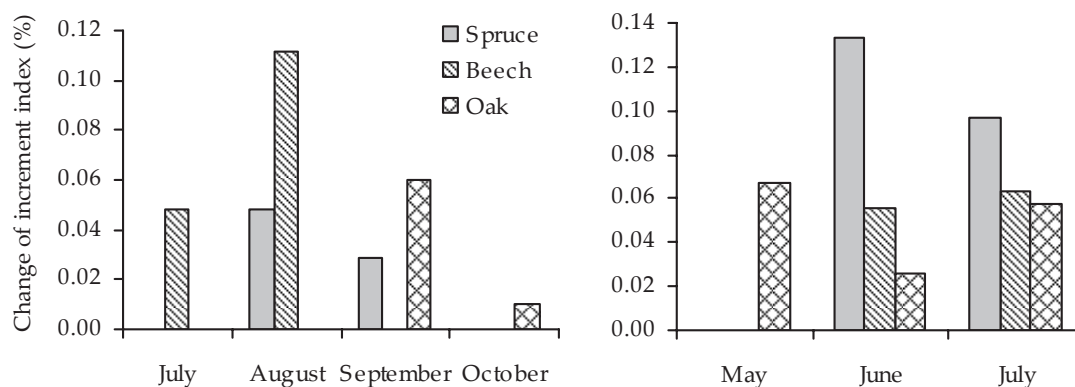

Fig. 5. The intensity of the effect of monthly precipitation during the vegetation period of the previous year (left) and of the actual year (right) on increment indexes of tree species
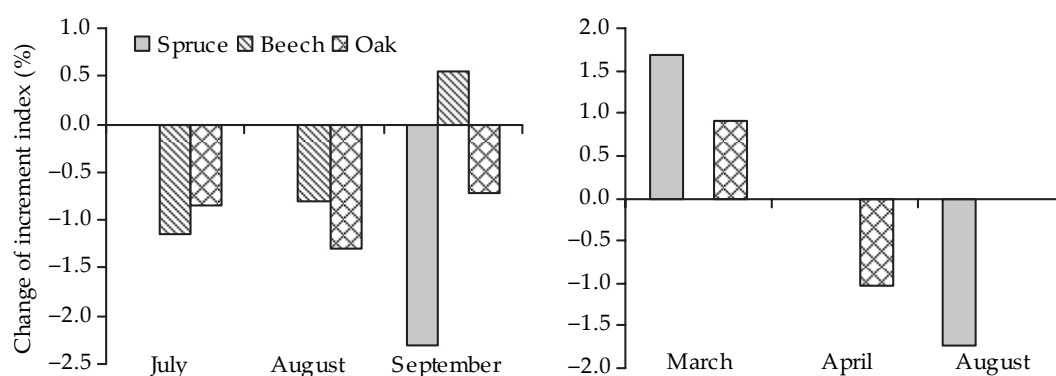
Fig. 6. The intensity of the effect of average monthly temperature during the vegetation period of the previous year (left) and of the actual year (right) on increment indexes of tree species

Table 4. Beech – correlation coefficients and parameters of a regression model of the dependence of increment indexes on significant climatic factors

Plot	Number		Correlation coefficient	Model parameters for variable							
	trees	annual rings		absolute	P7ly	P8ly	P6ay	P7ay	T7ly	T8ly	T9ly
P01	25	1,825	0.387	1.053807	0.000776	0.001384		0.000530	−0.013553		
P02	22	1,628	0.216	1.138951		0.000511	0.000220	0.000398	−0.012698		
P03	24	1,776	0.393	1.056726	0.000653	0.001376		0.000375	−0.012991	−0.006338	0.008768
P04	26	1,924	0.420	1.105563		0.000578	0.001432	0.001309	−0.020709		
P05	23	1,702	0.422	1.091096	0.000798	0.001617	0.000665	0.000464	−0.024951		0.007815
Together	120	8,855	0.341	1.071975	0.000478	0.001115	0.000554	0.000629	−0.011522	−0.008050	0.005463

We can see (Fig. 6, right) that in the actual year August temperatures have a negative effect on spruce and April temperatures on oak. On the contrary, March temperatures have a positive effect on the same tree species. Their change by 1°C will increase the increment index by 0.9–1.7%.

CONCLUSIONS

After summarizing all obtained knowledge we can state that statistically significant dependences, though not very close, were confirmed between basic climatic factors and increment changes. Their correlation coefficients are only 0.2–0.5. The intensity of their effect on increment change is not high either. All tree species react positively mainly to precipitation during the vegetation period. Mainly precipitation in June and July, known in Central Europe as summer monsoons, is significant for increment changes. With the increase of precipitation by 1 mm, when compared with the long-term average, the increment index of spruce increases the most, almost by 0.13%. It is only a half of this value for oak and beech. Precipitation from the second half of the vegetation period of the previous year is also significant. The effect of higher temperatures during the vegetation period on increment changes is mostly negative. With their increase by 1°C, when compared with the long-term average, the trees have mostly lower increment indexes by about 1–2%. Higher temperatures in March affect increment changes positively only in spruce and oak. The increment increases by about 0.9–1.7% with the temperature higher by 1°C.

The knowledge we have obtained is not surprising as many other authors attribute a greater significance to higher precipitation under our climatic conditions than to air temperature (Anfodillo et al. 1998; Mäkinen et al. 1998; Kahle et al. 2008; Mellert et al. 2008; Novák et al. 2010; Röhle et al. 2010). Higher precipitation is very important mainly in lower and middle locations, where the consumption of soil moisture, needed for evapo-

transpiration, is high during the vegetation period. Even very high supplies of water in the soil from winter and/or spring precipitation are insufficient to cover water consumption during summer months. Although the reaction of the studied tree species to climatic factors is different, we can state that spruce reacts in the best way and it is followed by beech and oak. The main reason for this fact may be anatomical dispositions of the spruce tree. Its shallow root system is capable of absorbing even a small amount of precipitation that penetrates only to the surface of the soil profile. The assimilatory apparatus of spruce is productive both in early spring and in autumn, when broadleaved tree species only start to form own leaves or the leaves start to fall. Beech and mainly oak have deeper root systems and water penetrates to these root systems only from heavy precipitation. The finding that mainly broadleaved tree species react positively to precipitation in August and September of the previous year is also noteworthy. This reaction of broadleaved tree species is probably connected with greater supply of substances for the more intensive formation of assimilatory organs in the next year.

References

ANFODILLO T., CARRER M., RENTO S., URBINATI C. (1998): Long and short growth dynamics of *Picea abies* (L.) and climatic factors: first results of an integrated study at the timberline in eastern Italian Alps. Écologie, *29*: 253–259.

ĎURSKÝ J., PAVLÍČKOVÁ A. (1998): Dendroclimatic model of Scotch pine in Záhorska lowland. Acta Facultatis Forestalis Zvolen-Slovakia, *XL*: 85–97. (in Slovak)

FELIKSIK E., WILCZYŃSKI S. (1999a): Influence of thermal and pluvial conditions on the radial increment of the Austrian pine (*Pinus nigra* Arnold). Acta Agraria et Silvestria, Silvestris, *37*: 3–10. (in Polish)

FELIKSIK E., WILCZYŃSKI S. (1999b): Influence of climatic conditions on the annual ring increment of the Weymouth pine (*Pinus strobus* L.). Zeszyty Naukowe Akademii Rolniczej, Krakow 362, Leśnictwo, *28*: 17–25.

FELIKSIK E., WILCZYŃSKI S. (2004): Dendroclimatological regions of Douglas fir (*Pseudotsuga menziesii* Franco) in western Poland. European Journal of Forest Research, *123*: 39–43.

FRITTS H.C. (1976): Tree rings and climate. London, New York, San Francisco, Academic Press.

GRUBER F. (2002): Wachstum von Altbuchen (*Fagus sylvatica* L.) auf einem Kalkstandort (Götingen/Sodderich) in Abhängigkeit von der Witterung. III. Bohrkernanalysen. Allgemeine Forst-und Jagdzeitung, *173*: 117–122.

JAČKA J. (1989): Parallelism, testing its significance and utilization in discipline annual ring analysis. Zprávy lesnického výzkumu, *34*: 42–45. (in Czech)

KAHLE H.P., SPIECKER H., UNSELD R., PÉREZ-MARTÍNEZ P.J., PRITZEL J., MELLERT K.H., STRAUSSBERGER R., REHFUESS K.E. (2008): Short-, medium-, and long-term variation in radial growth, and the role of changes in the climatic water balance for the growth of three tree species in Europe. In: KAHLE H.P., KARJALAINEN SCHUCK A. (eds): Causes and Consequences of Forest Growth Trends in Europe – Results of the Recognition Project. EFI Research Report 21. Brill, Leiden, Boston: 169–182.

KNOTT R. (2004): Seasonal dynamics of the diameter increment of fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) in a mixed stand. Journal of Forest Science, *50*: 149–160.

KUPKA K. (2002): QC. Expert 3.1, User's manual. TryloByte, Ltd., Pardubice.

MÄKINEN H. (1998): The suitability of height and radial increment variation in *Pinus sylvestris* (L.) for expressing environmental signals. Forest Ecology and Management, *112*: 191–197.

MELLERT K.H., PRITZEL J., STRAUSSBERGER R., DORSCH B., KAHLE H.P., PÉREZ-MARTÍNEZ P.J., REHFUESS K.E., SPIECKER H. (2008): Historical development of nutrition and climate and their relationships with tree growth for three European tree species. In: KAHLE H.P., KARJALAINEN SCHUCK A. (eds): Causes and Consequences of Forest Growth Trends in Europe – Results of the Recognition Project. EFI Research Report 21. Brill, Leiden, Boston: 83–125.

NOVÁK J., SLODIČÁK D., KACÁLEK D., DUŠEK D. (2010): The effect of different stand density on diameter growth response in Scots pine stands in relation to climate situations. Journal of Forest Science, *56*: 461–473.

OBERHUBER W., KOFLER W. (2000): Topographic influences on radial growth of Scots pine (*Pinus sylvestris* L.) at small spatial scales. Plant Ecology, *146*: 231–240.

OBERHUBER W., KOFLER W. (2003): Einflus des Klimas und der Hangexposition auf das Dickenwachstum der Zirbe (*Pinus cembra* L.) im alpinen Waldgrenzökoton am Patscherkofel (Tirol, Österreich). Centralblatt für das gesamte Forstwesen, *120*: 39–50.

OTS K., RAUK J. (1999): Influence of climatic factors on annual rings of conifers. Zeitschrift für Naturforschung, *54*: 526–533.

PAJTÍK J., IŠTOŇA J. (2003): Dynamics of diameter growth of Turkey oak on loess loam in the dependence on climatic factors. Lesnícky časopis – Forestry Journal, *49*: 39–48.

PETRÁŠ R., NOCIAR V., MECKO J. (2000): Diameter and height increments of Scots pine trees damaged by crown. Journal of Forest Science, *46*: 515–525. (in Slovak)

PETRÁŠ R., MECKO J., NOCIAR V. (2006): Some comments on the study of the effect of climatic factors on radial increments of oak trees. In: Climate Change – Forest Ecosystems & Landscape. Zvolen, National Forest Centre: 49–54.

Petráš R., Brezina L., Mecko J. (2007): Dynamics of radial increments of oak due to climatic factors effect. Ekológia, *26*: 295–304.

Rolland Ch., Petitcolas V., Michalet R. (1998): Changes in radial tree growth for *Picea abies*, *Larix decidua*, *Pinus cembra* and *Pinus uncinata* near the alpine timberline since 1750. Trees, *13*: 40–53.

Röhle H., Gerold D., Gemballa R. (2010): Beziehungen zwischen Klima und Zuwachs, dargestellt am Beispiel von Fichte, Kiefer und Buche in Sachsen. Allggemeine Forst- und Jagdzeitung, *181*: 21–35.

Schweingruber F.H. (1983): Der Jahrring-Standort, Methodik, Zeit und Klima in der Dendrochronologie. Bern, Stuttgart, Verlag Paul Haupt.

Šmelko Š., Miková A. (1999): Dendrochronological analysis of diameter growth and increment of Turkey oak (*Quercus cerris* L.) in Danube floodplain forests. Folia Oecologica, *25*: 101–119.

Vejpustková M., Zahradník D., Šrámek V., Fadrhonosová V. (2004): Growth trends of spruce in the Orlické hory Mts. Journal of Forest Science, *50*: 67–77.

Vita A., Bitvinskas T. (1998): Dendroclimatological similarities of *Picea abies* (L.) Karsten and *Pinus sylvestris* (L.). Baltic Forestry, *1*: 24–28.

Corresponding author:

Ing. Julian Mecko, CSc., National Forest Centre – Forest Research Institute in Zvolen, T. G. Masaryka 22, 960 92 Zvolen, Slovakia

e-mail: mecko@nlcsk.org