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Fir tree-ring reconstruction of March – July precipitation in southern Moravia (Czech Republic), 1376 – 1996

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ABSTRACT: A ring-width chronology for fir *Abies alba* Mill. in southern Moravia (Czech Republic), compiled from historical wood and living trees, was used for the dendroclimatological reconstruction of March–July precipitation for the period 1376–1996. Based on a response function model, the precipitation series explains 38% of tree-ring width variability. In the years with thinner tree-rings, drier spring and summer seasons prevailed, whereas years with wider tree-rings indicate wetter conditions. The highest precipitation in the reconstructed series was found in the 1670s, 1710s and 1980s; the lowest in the 1380s, 1700s and, particularly, in the 1970s. Reconstruction after the 1950s is less reliable due to a weaker relationship between precipitation and fir growth. The 18th century was the driest and the 19th century the wettest in the last 600 yr. The comparison of the reconstructed March–July precipitation of southern Moravia with the Brno series (instrumental period) and with the Prague-Klementinum series (compiled from the quantitative interpretation of documentary evidence and instrumental measurements) shows a high degree of agreement, reflecting the similarities between these series over the instrumental period. During the 16th, 17th and 18th centuries the 2 proxy data sources—documentaries and tree-rings—are in satisfactory agreement with respect to those years with extremely thin or wide rings.

KEY WORDS: Fir ring-width chronology · Precipitation reconstruction · Extreme tree-rings · Documentary evidence · Southern Moravia

1. INTRODUCTION

Although the earliest known measurement of precipitation in the Czech Lands from Prague-Klementinum dates back to the year 1752, regular observations only began on 1 May 1804 (Pejml 1975). A precipitation series for Brno is preserved from the year 1803, but after 1837 the observations become less reliable due to the illness of the observer, and later they are missing altogether. As a continuous series, precipitation data are available only from 1848, after which the measurement location was changed several times (Brázdil 1979). For the period before the beginning of instrumental observations, precipitation in the Czech Lands was reconstructed on the basis of documentary evidence (Brázdil & Kotyza 1995, Brázdil 1996). For the reconstruction of precipitation, tree-ring chronologies can also be used.

Published works in dendroclimatological studies often utilise the effect of air temperature on tree growth for the purposes of reconstruction (see e.g. Briffa et al. 1988, 1992, 1995, 1996, 1999, Briffa & Schweingruber 1992, Bednarz 1996, Luckman et al. 1997, Biondi et al. 1999, Hughes et al. 1999, Briffa 2000, Xiong & Palmer 2000). In relatively warm regions the effect of precipitation can be more conspicuous, and wet and dry seasons can be distinguished by

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the width of the tree-rings (see e.g. Richter & Eckstein 1990, Till & Guiot 1990, Serre-Bachet et al. 1992, Hughes et al. 1994, Stahle & Cleaveland 1994, Villalba et al. 1998, Cook et al. 1999, Briffa 2000, Stahle et al. 2000). In some cases the numbers of precipitation days have also been interpreted (Woodhouse & Meko 1997). Tree-ring chronologies from North America and Europe have also been used for the reconstruction of the North Atlantic Oscillation (Cook et al. 1998). In the construction of long tree-ring chronologies, dendrochronologists must work with unusually long-lived trees or they must extend the records obtained from living trees by piecing together or overlapping records from sources of ancient wood, such as archaeological, historical or naturally preserved (subfossil) remnants (Briffa 2000).

In the Czech Republic dendroclimatological reconstructions have so far been paid only little attention, largely because of the absence of a suitable tree-ring series. Currently only the relationship between climatic characteristics and the radial growth of trees has been analysed (such as Sander 1991, Sander et al. 1995). The first dendroclimatological reconstruction for this area focussed on the temperature of the summer half-year for the period 1804–1989 on the basis of the chronology of maximal late-wood density of the spruce *Picea abies* (L.) Karst. from the region of the Giant Mountains (Brázdil et al. 1997). Using a combination of ancient woods and living trees, the fir ring-width chronology from southern Moravia has now been compiled for the period 1376–1996. The analysis of these dendroclimatological data forms one of the principal foci of the present paper.

2. THE DATA USED

The chronology of the fir *Abies alba* Mill. was compiled from samples taken from the roof-frames of historical buildings from 8 different places in southern Moravia, all from the period 1376–1917 (Fig. 1). In order to link this historical material with the present, cores from living trees were used from the region of the river Dyje (1825–1996). All samples were collected by researchers of the Botanical Institute, Academy of Sciences, Průhonice, between 1994 and 1998 as a part of a project to establish a standard chronology for fir in the Czech Republic (Kyncl & Kyncl 1999). Chronology replication varied between 8 and 120 samples (Fig. 2), but most replicates were based on at least 15 samples. The optimal number of samples needed for dendroclimatological studies is normally between 15 to 20 trees. In the case of a strong climatic signal as few as 7 trees might be sufficient (Cook & Kairiukstis 1990). On the basis of the chronology for the years 1850–1996 it was shown that subsample signal strength (SSS) (Wigley et al. 1984), describing agreement with theoretical population chronology, achieved a value of 0.85 with replicates from only 7 individuals. This suggests that any additional chronology error due to a decrease in chronology replication will be limited to a maximum of 15%.

The individual tree-ring series were standardised using ARSTAN (Cook & Holmes 1986) by means of a 2-step detrending procedure. The age trend was eliminated by means of the negative exponential curve. This function is the best for expression of a long-term growing trend given by increasing stem diameter. Pos-

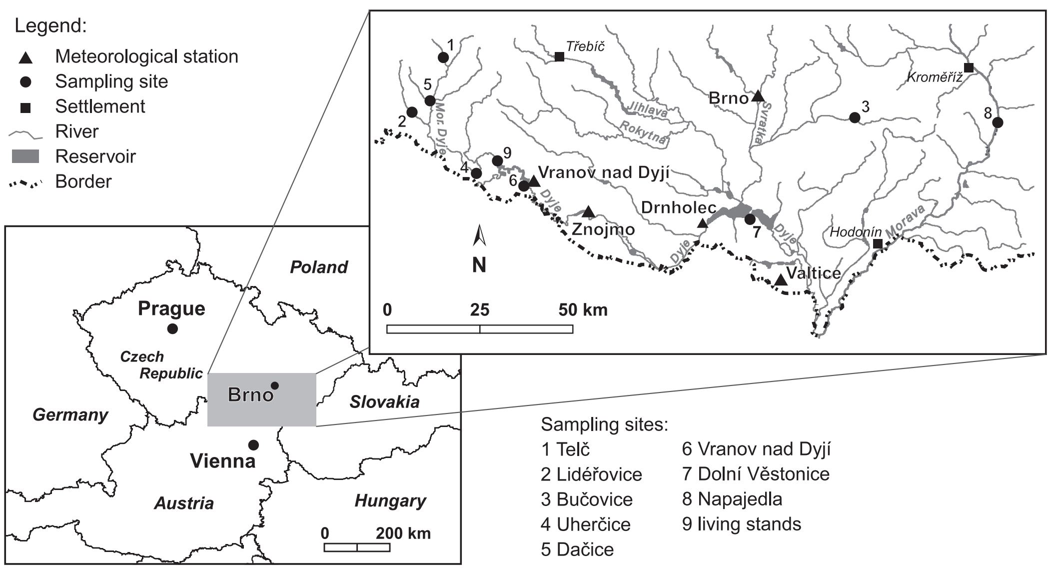

Fig. 1. Schematic map of southern Moravia showing the sampling sites and meteorological stations used

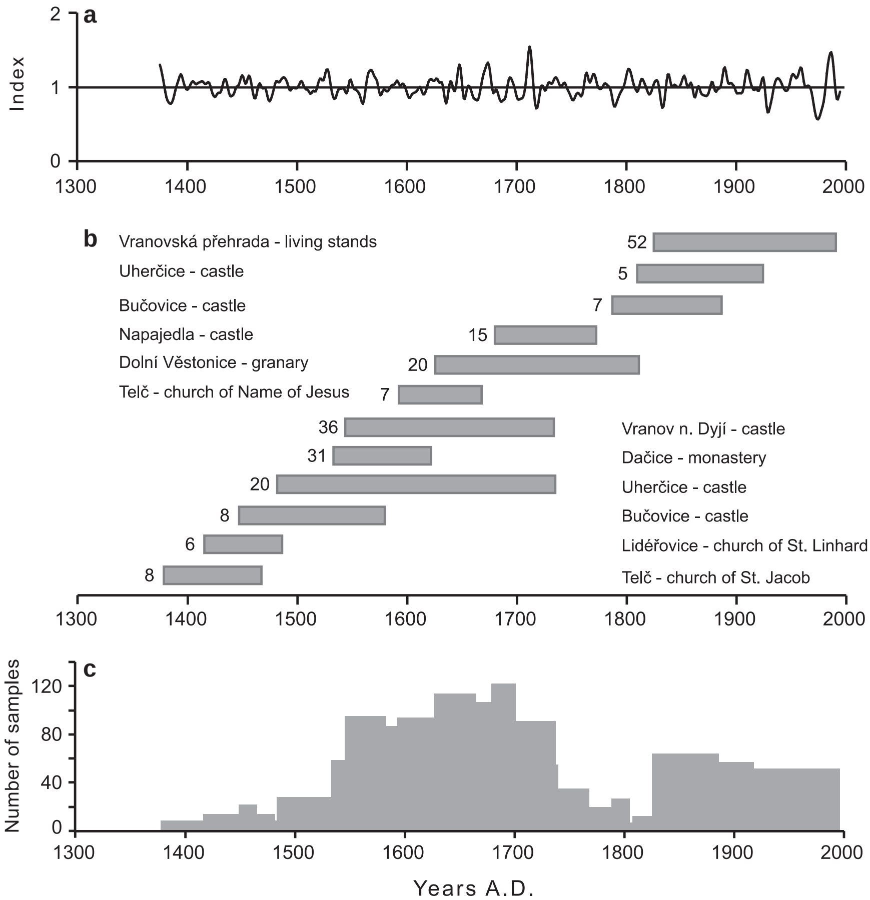

Fig. 2. Characteristics of the standardised chronology of the fir tree of southern Moravia, 1376–1996: (a) standardised chronology, (b) partial chronologies used for its compilation (numbers denote the quantity of cores used), (c) total annual number of cores used

sible non-climatic disturbances were eliminated by means of the cubic-smoothing spline curve with the 67 % criterion (Cook & Kairiukstis 1990) with the minimum 50 % frequency cut-off of 50 yr. This latter procedure was employed to ensure the preservation of a proportion of the low-frequency signal that might otherwise be lost when other filters are used (Cook & Kairiukstis 1990, Cook et al. 1995). For the same reason, the residual chronology included only those series with a minimum of 50 tree-rings (Fig. 2). Any remaining autocorrelation was removed using pooled autoregressive modelling.

The climatic data used were the homogenised temperature series for Brno for the period 1891–1996 (Brázdil & Štěpánek 1998) and the precipitation series of southern Moravia for the period 1897–1996. The latter was calculated by averaging the monthly precipitation totals for the stations at Drnholec, Valtice, Vranov nad Dyjí and Znojmo (Fig. 1). As a first step, all missing values were estimated by the method of ratios (Conrad & Pollak 1950), considering the neighbouring stations with the highest correlation. Further, by means of the Alexandersson (Alexandersson 1986) and bivariate tests (Maronna & Yohai 1978), their relative homogeneities were analysed with respect to the precipitation series, known to be homogeneous, for Vienna (Auer 1993). Any inhomogeneities were corrected by taking into consideration metadata of the individual stations, and from the corrected series the mean precipitation series of southern Moravia was calculated (Table 1). Testing against the Vienna series showed no inhomogeneities, and the correlation coefficients between these series varied between 0.630 (June) and 0.903 (November).

3. METHOD OF RECONSTRUCTION

The techniques of dendroclimatological reconstructions consist of a linear (bivariate or multivariate) regression, which is sometimes preceded by pre-selection of the variables to be used in the regression (e.g. principal component analysis — Fritts 1976) to give the best fit to the data (e.g. Woodhouse & Meko 1997). A

3-layer feed-forward neural network model used by d'Odorico et al. (2000) offers, in comparison with the regression-based model, a higher degree of accuracy for dendroclimatological reconstruction.

Table 1. Correlation coefficients of monthly precipitation totals for Drnholec (185 m above sea level; for the period 1897–1996; a distance of 72 km from Vienna), Valtice (204 m; 1897–1996; 66 km), Vranov nad Dyjí (354 m; 1914–1996; 85 km), Znojmo (325 m; 1897–1996; 75 km) and mean series for southern Moravia (SM; 1897–1996) including data for Vienna—Hohe Warte (183 m). Correlation coefficients after homogenisation are given in bold

Month	Drnholec	Valtice	Vranov n. Dyjí	Znojmo	SM
Jan	**0.627**	0.748	0.699	**0.710**	0.758
Feb	0.760	0.849	0.803	**0.717**	0.824
Mar	0.670	0.722	**0.714**	0.696	0.721
Apr	0.725	**0.804**	0.690	0.646	0.774
May	0.680	0.718	0.571	0.720	0.743
Jun	0.670	0.600	0.486	0.447	0.630
Jul	0.690	0.735	0.467	0.610	0.747
Aug	0.616	0.690	0.540	0.535	0.667
Sep	0.798	**0.838**	**0.771**	0.761	0.833
Oct	0.893	0.877	0.835	0.849	0.895
Nov	0.779	0.886	**0.824**	0.843	0.903
Dec	0.766	0.807	**0.864**	**0.721**	0.836

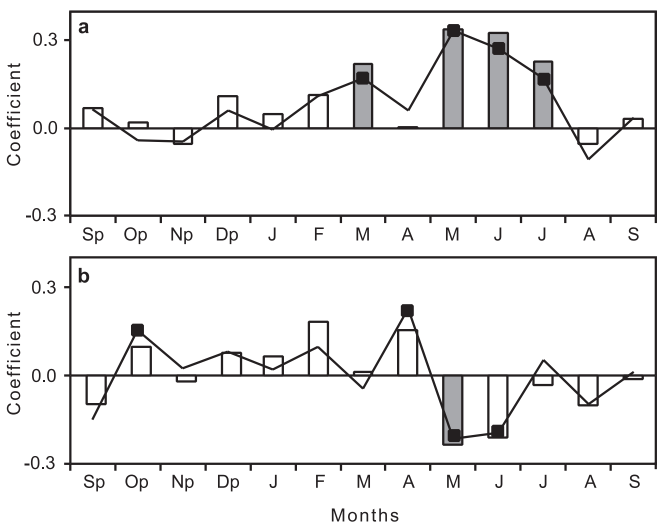

Fig. 3. Responses of tree-ring widths (a) to monthly precipitation totals for southern Moravia and (b) to mean monthly air temperatures at Brno for the period 1897–1996 expressed by correlation coefficients (columns; dark columns: values of correlation coefficients statistically significant at $\alpha = 0.05$) and coefficients of multiple regression (line; squares: statistically significant values of coefficients of multiple regression); p: months of the preceding year

In order to determine the dependence of the radial growth of the fir on climatic factors in southern Moravia, Precon software (Fritts 1994) was employed to give a response function that was here calculated for the period 1897–1996. The latter is a multiple regression analysis showing which climatic characteristics correlate most strongly with the growth of the tree-rings (Cook & Kairiukstis 1990). The calculated values of the response function of the fir tree-rings for precipitation and air temperature in the 12 months preceding September of the year of growth are shown in Fig. 3. Positive values of the regression coefficients indicate that higher numerical values of the climatic characteristic in the given month produce a positive effect on the growth of the tree, and vice versa.

Air temperatures had a statistically significant effect on the radial growth in April–June and precipitation in March and May–July. The effect of temperature was negative for May and June, whereas April temperatures had a positive effect. The positive influence of April temperatures and statistically insignificant influence of precipitation support the presumption that temperatures are a limiting climatic factor at the beginning of the growing season. From investigations of the spruce *Picea abies* available in the study region, it was found, for instance, that cambial activity of the spruce starts on the turn of April and May and is limited by a minimum temperature of 5°C (Horáček et al. 1999). Higher April temperatures have an influence on the earlier onset of the growing season when there is sufficient soil water. Precipitation had a positive effect on the radial growth of the fir for all of the significant months. This finding conforms to the known relation between these 2 climatic characteristics in which warm Mays and Junes are associated with the prevalence of drier anticyclonic weather patterns leading to spatially variable precipitation of convective origin. The overall effect of temperature explains, however, only 12% of the tree-ring variability, whereas in the case of precipitation the corresponding figure is 38%.

The objective of this dendroclimatological reconstruction was, however, not to determine the climatic characteristics of individual months, but their expression over longer time periods. With respect to the correlation coefficients themselves, those for the tree-ring response to precipitation for the March–July interval were found to be the most helpful. The period 1897–1956 was chosen for calibration as there is a notable deterioration of the correlation between the tree-ring width and precipitation in the latter half of the 20th century (Fig. 4). A similar post-1950s effect has also been observed for May precipitation for pine *Pinus nigra*, Arnold ring-widths in neighbouring Austria (Strumia et al. 1997). Increasing insensitivity of maximal wood density to temperature changes also

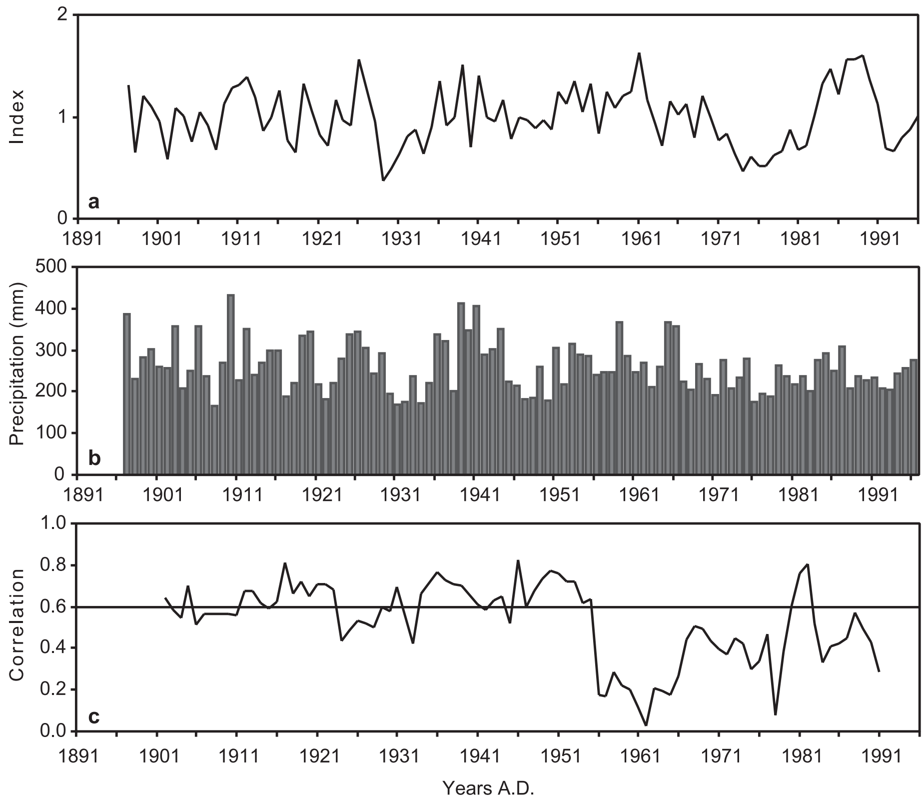

Fig. 4. Comparison of (a) fir tree-ring widths with (b) March–July precipitation totals in southern Moravia and (c) 11 yr running correlation coefficients between them in the period 1897–1996. The critical value at $\alpha = 0.05$ for $n - 2$ df ($n = 11$) is 0.60

appeared in the second half of the 20th century at high northern latitudes (Briffa et al. 1998). Thus far, no satisfactory explanation has been offered for these changes. It can be noted, however, that since the 1960s dieback symptoms such as needle yellowing and needle loss has appeared widely in the fir *Abies alba*. These effects are known to reduce the radial growth in trees (Becker 1987, Bert 1993). They are often connected with a combination of influences resulting from extremely dry years (such as 1948, 1956 and 1976) and from air pollution, mainly NO_x, SO_2 and ozone (Bert 1993). These non-climatic environmental changes will, at the very least, obscure the climatic signal in tree-rings and hamper significantly the task of reconstruction (Sander et al. 1995). Although longer continuous measurements of such pollutants for the southern Moravian region are not available, important increases in their concentrations are known to have occurred over a large part of the Czech Republic between the 1960s and 1980s (Materna 1989).

The species-specific influence of these factors on the fir growth is seen in the comparison of the fir standard chronology with that of spruce, which shows no significant dieback symptoms in this region. On the other hand, the value of 31 yr running correlation coefficient between the two is stable (above 0.6) throughout the period 1400–1950 and shows an identical growing reaction for both species of tree. After 1950 there is a marked decrease in the correlation coefficients to 0.0–0.2. This feature continues to the present. For the reliable reconstruction of the precipitation series, it is important that such different responses by the 2 species did not occur in the study period, i.e. up to 1950.

With a view to characterising the changes in the relationship between climate and fir tree growth since the 1950s, further statistical analyses were conducted using tree-ring widths, March–July precipitation for southern Moravia, and air temperatures for April and May-June from Brno. Basic statistical measures (Table 2), autocorrelations (Fig. 5), maximum entropy spectra and coherencies (Figs. 6 & 7) were calculated for these series, each of which was duplicated for 2 time periods: 1897–1956 (Period I) and 1957–1996 (Period II). All 3 series reveal different orders of change between the 2 periods. In the case of tree-ring series, the variability (expressed by the coefficient of variation) and persistency were higher in period II (Table 2, Fig. 5). At the same time, a strengthening of the low-frequency signal and a suppression of the high-frequency signal were observed (Fig. 6). As for

Table 2. Basic statistical parameters for fir tree-ring widths, March–July precipitation totals (mm) in southern Moravia, April (A) and May–June (M–J) air temperatures (°C) for Brno over the periods 1897–1956 (I) and 1957–1996 (II): *n*: length of series (yr), $\bar{x}$: arithmetic mean, *s*: standard deviation, *v*: coefficient of variation (%), *t*: linear trend for 10 yr, *cc*: correlation coefficient with tree-ring series (values statistically significant at α = 0.05 are given in bold)

Characteristic	Tree-rings		Precipitation		Temperature (A)		Temperature (M–J)	
	I	II	I	II	I	II	I	II
n	60	40	60	40	60	40	60	40
$\bar{x}$	0.999	0.991	270.4	247.7	8.3	9.0	15.1	15.6
s	0.258	0.323	67.0	45.3	1.7	1.3	1.1	1.0
v	25.8	32.6	24.8	18.3	20.0	14.5	7.1	6.1
t	0.01	−0.01	−3.9	−10.0	0.15	0.03	0.09	0.12
cc	–	–	**0.62**	**0.39**	0.09	0.27	**−0.35**	−0.25

precipitation, there is a clear decrease in its mean and variability from Period I to Period II (Table 2) when the low-frequency precipitation signal was also weaker with a lower coherency with respect to tree-ring growth (Fig. 6). In addition, the monthly distribution of March–July precipitation also underwent change. While in Period I there was a continuous increase in mean precipitation from March to July, in Period II the maximum occurred in June, and the total in July was comparable with that in May. The air temperature series also contrasts with that for precipitation in demonstrating an increased linear trend and a decrease in variability (Table 2). Coherency of tree-rings with temperatures is more or less reversed between the 2 periods (Fig. 7). These results suggest that suppression of the high-frequency signal in fir tree-rings occurs as a result of increasing temperatures and decreasing precipitation. In summary, these finding highlight the contrasting response functions over the 2 periods (Fig. 8). It seems that fir growth after the 1950s is a reflection of complex influences, including changes in climatic factors (warming, drying, increase in weather extremes), atmospheric pollution and other non-climatic factors. In particular, the tree-rings for the most recent 50 yr of the chronology differ in being taken from trees of greater age than those for earlier periods.

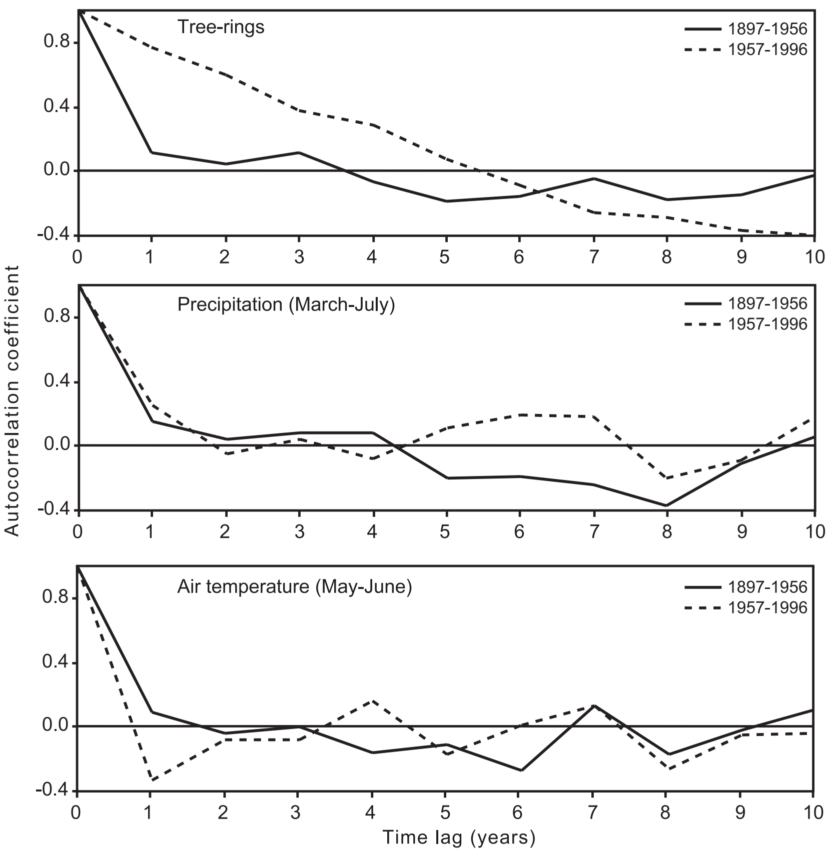

Fig. 5. Autocorrelation coefficients for the series of fir tree-ring widths in southern Moravia, for March–July precipitation totals in southern Moravia and May–June temperatures at Brno in the periods 1897–1956 and 1957–1996

For the calibration and verification of the transfer function, the so-called cross-calibration-verification scheme was used (Briffa et al. 1988, 1992). The period 1897–1926 was chosen for this calibration, and the period 1927–1956 for its verification; subsequently the 2 periods were reversed. The verification statistics of the dendroclimatological reconstruction of March–July precipitation are shown in Table 3. The nature of these statistics can be briefly explained but see Gordon & LeDuc (1981) and Cook et al. (1994) for a fuller account:

- *Correlation.* The correlation coefficient is a measure of the linear relation between measured x_i and reconstructed $\hat{x}_i$ values ($i = 1, \ldots, n$, where n is the number of pairs of observations).

Table 3. Verification statistics of the dendroclimatological reconstruction of the March–July precipitation totals for southern Moravia on the basis of the fir tree-ring chronology (values statistically significant at α = 0.05 are given in bold)

Characteristic Period	Calibration 1897–1926	Verification 1927–1956	Calibration 1927–1956	Verification 1897–1926
Correlation	**0.623**	**0.602**	**0.602**	**0.623**
Sign-test	**7**	**6**	**7**	**7**
Negative first difference	**9**	**8**	**8**	**9**
t-value	**2.672**	**1.801**	1.587	**2.922**
Reduction of error	**0.389**	**0.389**	**0.362**	**0.405**
RISK	–0.389	–0.388	–0.362	–0.346
BIAS	0.000	0.046	0.000	0.049
COVAR	0.778	0.721	0.724	0.701

- *The sign test.* The sign test is a simple non-parametric test of the similarity between 2 series based on a count of the number of agreements and disagreements in sign. If the number of agreements exceeds the number of disagreements by more than that expected from chance alone, the reconstruction passes the test. The sign test can be applied either to the departures from the mean of the measured and reconstructed data or to the sign changes associated with the first differences of each series. The first differences are computed simply as $\Delta x_i = x_i - x_{i-1}$.
- *Product means test.* The product means test takes into account the signs and the magnitudes of the changes when testing for any agreement between the 2 series. It is calculated from the cross-products of the measured and reconstructed annual departures from their respective mean values. If the signs of departures are the same, the cross-products are positive. If the signs of the departures are different, the cross products are negative. The difference between the mean positive cross-products and the mean negative cross-products is tested using a standard *t*-test (see *t*-value in Table 3). If the mean positive cross-product is significantly greater than the mean negative cross-product based on the *t*-test, the reconstruction passes this verification test.
- *Reduction of error (RE).* The reduction of error provides a sensitive measure of reliability of any reconstruction, i.e. does the selected model give a better reconstruction than that based on climate given by the mean of measured values in the calibration period? It is calculated from

$$RE = 1 - \frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x}_c)^2}$$

where $\hat{x}_i$ are reconstructed data and $\bar{x}_c$ is the mean of the measured data in the calibration period. If RE = 0, the model is no better than climatology. For RE > 0, the reconstruction is better than the calibration period mean.

The RE can be partitioned into 3 component parts that can be used to analyse sources of error affecting a particular climatic reconstruction:

$$RE = RISK + BIAS + COVAR$$

- *RISK.* The RISK term is always negative, and its absolute magnitude is a comparative measure of the variability of the reconstructed and measured values used in testing. Models with a small explained variance usually have –0.5 < RISK < 0.0. If RISK = –1.0,

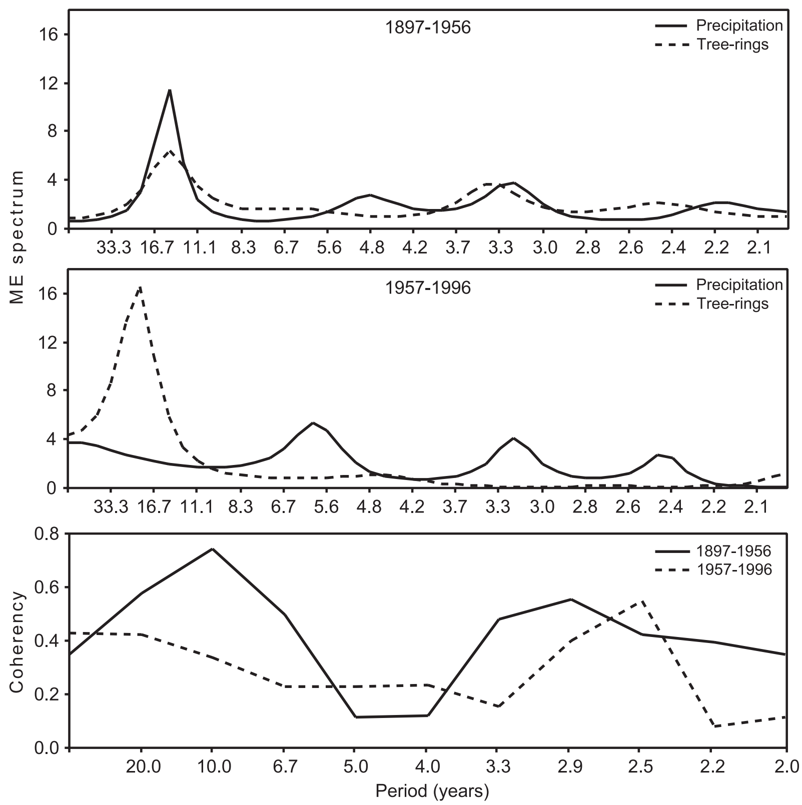

Fig. 6. Maximum entropy spectral analysis and coherency analysis for the series of fir tree-ring widths and March–July precipitation totals in southern Moravia in the periods 1897–1956 and 1957–1996

then a model should produce as much variance in $\hat{x}_i$ as in x_i.

- *BIAS*, *COVAR.* BIAS and COVAR represent the accuracy of the model. The BIAS is positive when the mean of the reconstructed values is on the same side of the calibration mean as the measured data used for verification testing. It is negative when the mean of reconstruction is on the opposite side of the calibration mean compared to the mean of the measured data. COVAR reflects the strength of the correlation between $\hat{x}_i$ and x_i, and it measures the similarity between the reconstructed and measured temporal patterns.

It follows from Table 3 that all verification criteria are statistically significant for the significance level α = 0.05, i.e. the chosen models are confirmed as being correct. An exception occurs for the calibration period 1927–1956, when the *t*-value of the product mean test is not significant. Otherwise RISK has values between –0.5 and 0.0 for all periods. This implies that the model expresses the variability in a less satisfactory way. For the reconstruction of the March–July precipitation (PS_{M-J}) in southern Moravia for the period 1897–1956 a regression equation was used, having the form

$$PS_{M-J} = 110.4 + 160.0 \, RW$$

where RW is the ring-width index of the fir standard chronology.

4. RESULTS AND DISCUSSION

The reconstructed precipitation totals of March–July from southern Moravia for the period 1376–1996, expressed in the form of anomalies from the mean of the period 1901–1990 and smoothed by a 10-yr Gaussian filter, are shown in Fig. 9. The 1670s, 1710s and 1980s (112 to 113% of the mean of the period 1901–1990) emerge as being particularly wet in the reconstructed series, whilst the 1380s, 1700s (90 to 91%) and, above all, the 1970s (80%) were notably dry. In the case of values for the 1970s and 1980s, it is necessary to take into account the fact that after 1956 the reconstruction loses some of its reliability due to a weakening of the relationship between precipitation and fir tree growth. Decades with relatively low (below 95% of a long-term mean) and high (above 105% of a long-term mean) precipitation were concentrated in the 17th, 18th and 20th centuries (6 decades in each), the longest continuous extreme periods occupied the 1700s–1730s and the 1950s–1980s. In the 16th century only the 1520s were relatively wet. The 15th and 19th centuries were characterised by having 2 relatively wet or dry decades. From a century-scale perspective, the driest was the 18th century and the wettest the 19th century, but differences from the long-term mean were negligible (only up to ±1%).

The quality of the reconstruction of the March–July precipitation series in southern Moravia can be verified by comparing it with the observed precipitation series for Brno between 1848 and 1996 (Fig. 10). In the 1860s and again from the mid-1870s to the 1940s the 2 series show relatively good agreement (e.g. over the period 1891–1949 the correlation coefficient is 0.66), but the reconstructed and the measured values then diverge conspicuously. Taking into consideration the fact that in the period

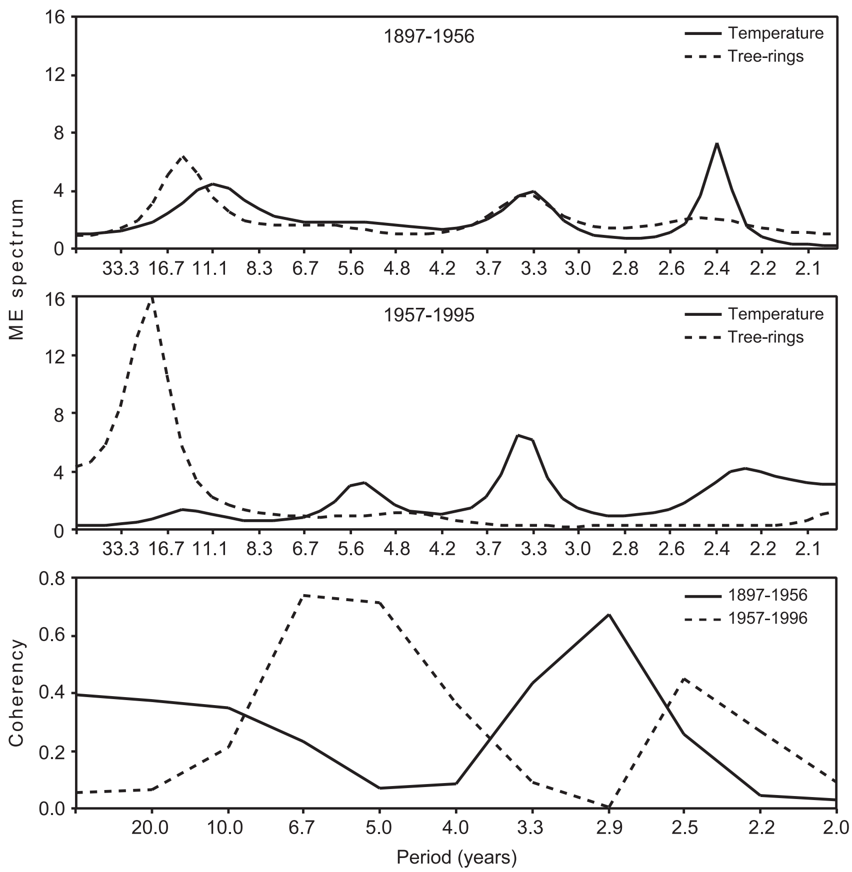

Fig. 7. Maximum entropy spectral analysis and coherency analysis for the series of fir tree-ring widths in southern Moravia and May–June temperatures at Brno for the periods 1897–1956 and 1957–1996

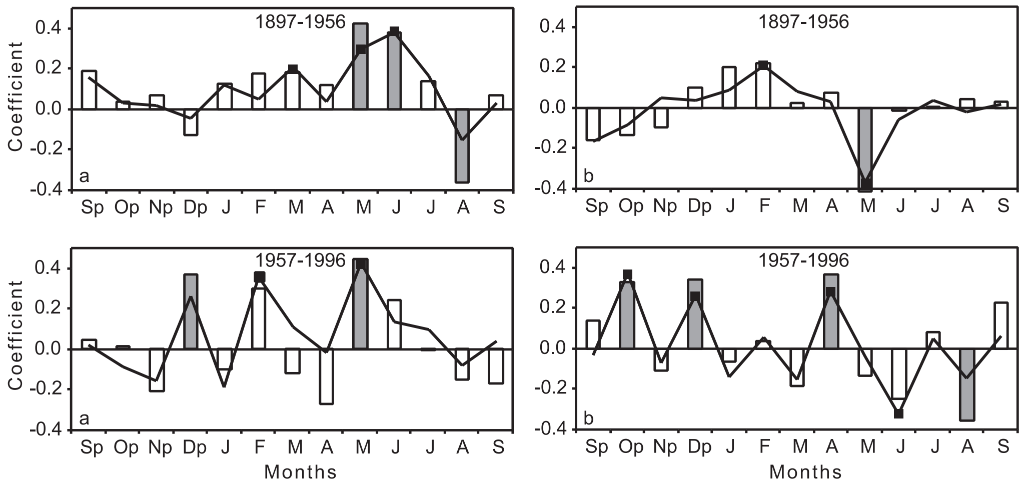

Fig. 8. Responses of tree-ring widths to monthly precipitation totals in southern Moravia (a) and to mean monthly air temperatures in Brno (b) for the periods 1897–1956 and 1957–1996 expressed by correlation coefficients (columns; dark columns: values of correlation coefficients statistically significant at $\alpha = 0.05$) and coefficients of multiple regression (line; squares: statistically significant values of coefficients of multiple regression); p: months of the preceding year

1897–1996 the correlation between the measured March–July precipitation totals of the Brno series and that of southern Moravia was 0.74, the results of the reconstruction up to the 1950s can be considered satisfactory.

Using the Prague-Klementinum series a reconstruction of decadal precipitation totals was carried out for seasonal and for annual periods from the 13th century on the basis of documentary evidence combined, from 1804, with measured precipitation totals (Brázdil 1996). This series can also be used for the comparison with the reconstructed series for southern Moravia. Unfortunately the monthly values from this reconstruction for Prague are not available and a series including the spring-summer period (March–August) only was compiled. A low level of agreement was found between the Prague and southern Moravian series (Fig. 11) for much of the study period, during which the correlation coefficient was as low as 0.37. This correlation is, however, comparable to that for the measured decadal precipitations for March–July between the same 2 series over the period 1900–1989 (0.42). The differences are no doubt connected to the distance between the 2 areas (around 200 km) and the spatial variability of precipitation and synoptic processes affecting them. Some of the differences can be attrib-

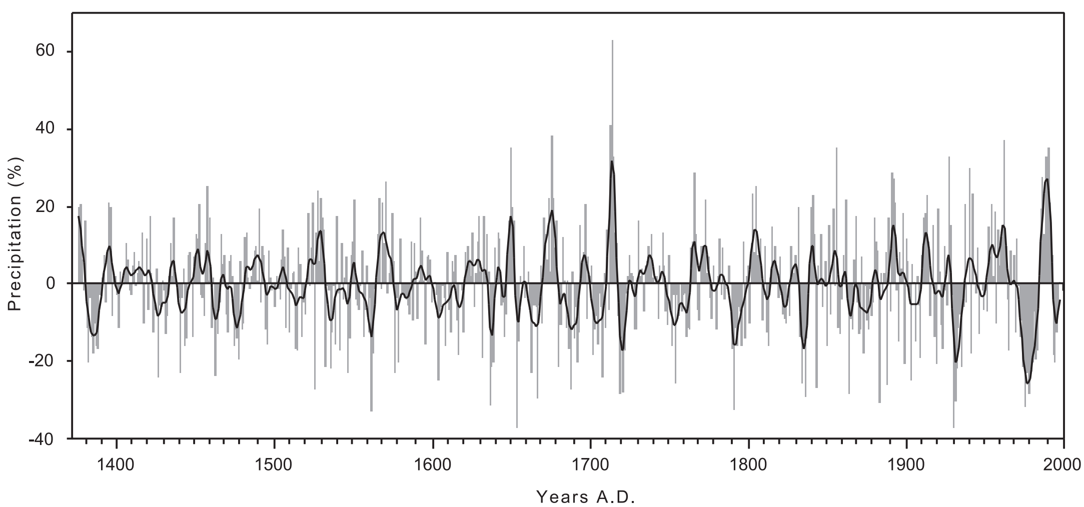

Fig. 9. Reconstructed precipitation anomalies (columns) for March–July in southern Moravia in the period 1376–1996 smoothed by a Gaussian 10-yr filter (reference period 1901–1990)

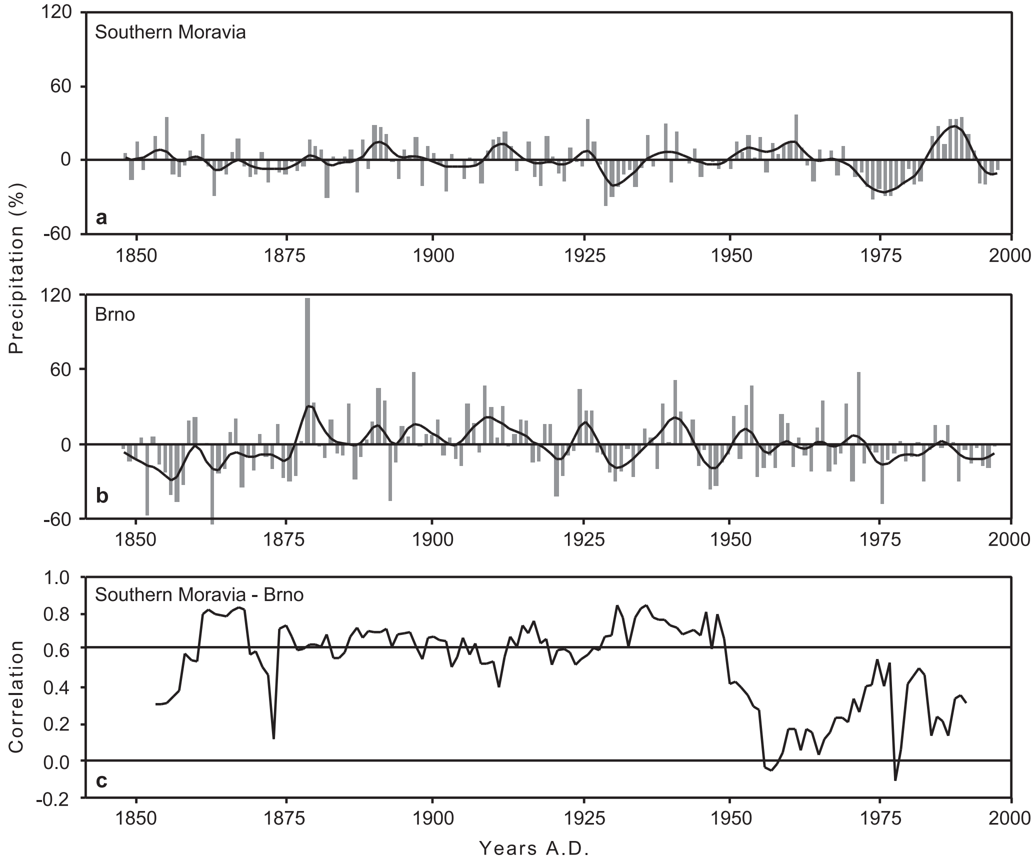

Fig. 10. Comparison of (a) the reconstructed March–July precipitation anomalies (columns) of southern Moravia with (b) the measured anomalies of Brno (smoothed by a Gaussian 10 yr filter) and (c) 11 yr running correlation coefficients between them in the period 1848–1996. The critical value at $\alpha = 0.05$ with $n - 2$ df ($n = 11$) is 0.60

uted to the lower quality of the reconstructed Prague precipitation series before 1500, itself a result of the paucity of documentary evidence. There is also a possible problem with the homogeneity of this series in the 19th century. Although the precipitation totals of Prague-Klementinum were corrected according to the recommendation of Křivský (1957), the relative homogeneity of the Prague series cannot, because of the absence of any sufficiently lengthy and nearby reference station, be confidently judged. As a result of the decreasing precipitation correlation with the increasing distance, practically no concordance can be expected between the March–July precipitation series and those from Switzerland (Pfister 1988a) or Germany (Glaser 2001); these being derived from documentary evidence since the 16th century. In the latter studies, the monthly precipitation was expressed differently: for Switzerland in a 3-step scale (–1: dry month; 0: average month; +1: wet month), and for Germany in a 7-step scale (–3: extremely dry; –2: very dry; –1: dry; 0: average; +1: wet; +2: very wet; +3: extremely wet). For each decade the sums of differences of positive and negative indices were plotted, so that positive and negative differences correspond respectively to wetter and drier periods. The correlation coefficient between the Swiss and German series is +0.5. In contrast, their correlations with the Moravian series fall to +0.2. This poor correlation also reflects the fact that reconstructed precipitation totals were compared with a series based on precipitation indices.

The available documentary evidence from the Czech Lands permits a more detailed characterisation of precipitation patterns of years with exceptionally thin or wide ring-widths. In the case of air temperatures in Switzerland, such a comparison with extreme tree-rings of Alpine conifers was carried out by Pfister (1988b). Becker et al. (1995a) used documentary evidence to characterise signatures in a spruce chronology in the Franconian area of Germany. Manrique & Fernandez-Cancio (2000) selected outstanding tree-rings (mostly between about 1400 and 1600) when studying extreme climatic events in Spain.

From the fir standard chronology of southern Moravia, years were selected in which the ring-width index exceeded the mean index in the standardised chronology by more than 1 standard deviation

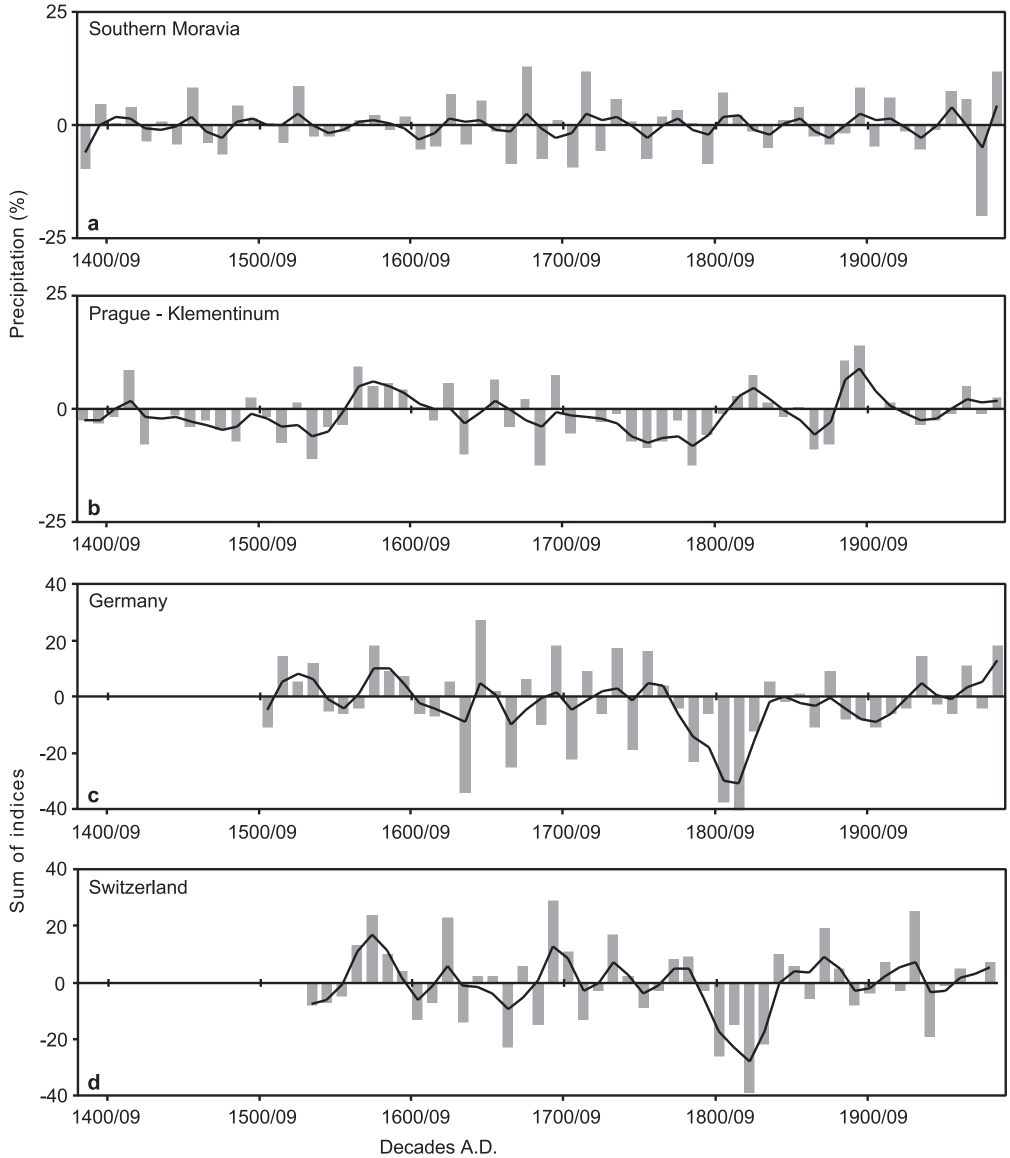

Fig. 11. Selected decadal precipitation series (columns) of March–July in central Europe in the 14th–20th centuries (smoothed by a Gaussian filter of 5 items): (a) southern Moravia, (b) Prague-Klementinum (March–August), (c) Germany and (d) Switzerland (data for b–d from Brázdil 1996, Glaser 2001 and Pfister 1988a, respectively; reference period for a and b is 1901–1990)

(Fig. 12). Extremely thin fir tree-rings were most frequent in the 20th century (24 cases, of which 8 were from the 1970s), followed by the 17th, 16th and 19th centuries. The same holds for extremely wide tree-rings, which were most often found in the 20th century (20 cases), followed by the 19th, 16th and 17th centuries. The extreme ring-widths of the 20th century are the outstanding feature of the 620-yr fir tree-ring chronology.

Those years during the 16th to 18th centuries displaying extreme ring-widths are given in Table 4, and may be associated with anomalous periods of the March–July precipitation patterns in the Czech Lands already identified from documentary evidence (Brázdil & Kotyza 2000b). If, in any given year, the documentary evidence is partly or completely missing, it need not imply that precipitation in March–July was normal, as is sometimes assumed in historical-climatological studies. Prior to 1500, the documentary evidence for the Czech Lands is very scant, and 1476 was the only year with a thin tree-ring that was associated with a dry spring (Brázdil & Kotyza 1995). Since the 19th century those springs and summers interpreted from the tree-ring series as having experienced extreme precipitation are also identified as such from the instrumental observations from Brno.

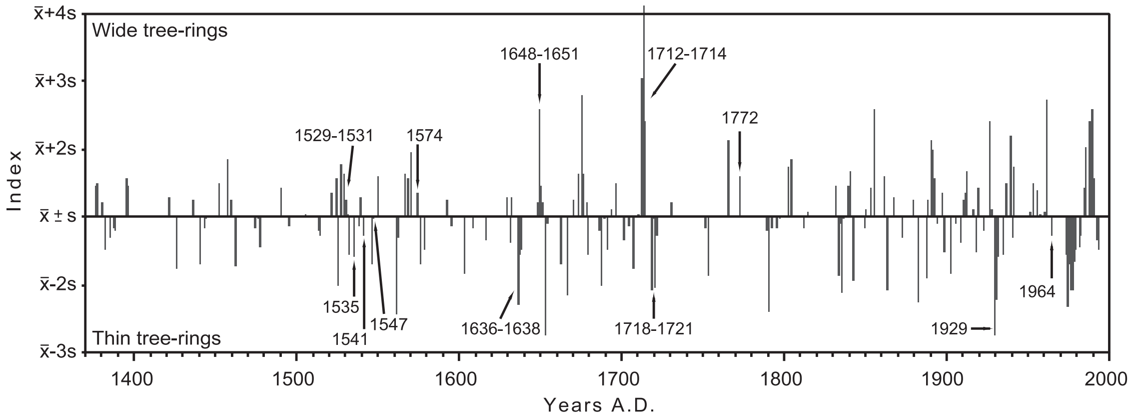

Fig. 12. Occurrence of years with extremely wide and thin fir tree-rings in southern Moravia over the period 1376–1996 (for the method of their selection see text). Corresponding ring-width indices are expressed as deviations from the value $\bar{x} + s$ (wide tree-rings) and $\bar{x} - s$ (thin tree-rings), respectively ($\bar{x}$: long-term mean, s: standard deviation)

Those years (Table 4) with extremely thin tree-rings are associated with dry periods, whereas in the years of extremely wide tree-rings the opposite was the case. This relation is more stable and consistent with respect to low precipitation than is the case for wet conditions. Fir growth can also, however, be influenced by other climatic factors. Above all the effect of extremely low air temperatures in the winter season is significant, mainly in years with limited snow cover (Lenz et al. 1987, Desplanque et al. 1999). This effect is particularly conspicuous at dry sites (Bert 1993). Typical examples were the severe winters of 1928/29 and 1962/63, when the fir was significantly damaged. This consequence was particularly marked in trees growing at elevations up to 600 m. The effect of frost damage on radial growth can persist for a further 3 to 4 yr (Schweingruber & Müller 1992). The resulting climatic reconstruction can also be made more questionable by the persistent reduction in tree growth that results from several dry years (Becker et al. 1995b). This factor is usually quoted as the reason for the depressed growth of trees in the 1970s that also appeared in the firs used in the current reconstruction (Fig. 2). It can be suggested in the light of these facts that extreme ring-widths might tend to cluster in the series or follow each other at short intervals. In the case of extremely thin tree-rings the years 1636–1638 and 1718–1721 might fall into this category. For extremely wide tree-rings, the years 1529–1531, 1648–1651 and 1712–1714 might do likewise. In some of the extreme tree-rings there is a discernible effect from exceptional weather of the preceding year. A good example can be seen in the thin tree-rings in the years 1535, 1541 and 1547, which followed very dry years (Brázdil & Kotyza 2000a). The summer half-year of 1540, for example, is considered to be the driest and warmest such period in the whole period of documentary data for Central Europe (Glaser et al. 1999). Similarly, the period of extremely wide radial growth in the years 1529–1531 was probably initiated by the exceptionally wet conditions of 1529 that are documented in central Europe by daily weather records, when, for example, Kilian Leib in Eichstätt, Germany, recorded 45 precipitation days in May and June and another 16 in July (Pfister et al. 1999). The increased growth in fir trees also followed after a very cold and wet year in 1573 (Glaser et al. 1999) as well as after the wet years 1770 and 1771 (Brázdil et al. 2001).

Similar relationships to those found for the 16th to the 18th centuries were encountered in the March–July precipitation patterns when set against Brno records from 1803 onwards. In 85 % of years with extremely thin tree-rings there were dry periods. In 60 % of such years the precipitation was below 90 % of the 1901–1990 average, whilst in 29 % of the years precipitation was less than 80 % of the normal. The corresponding figure for wet years was lower at 72 % overall, but with 64 % of them falling in years with precipitation in excess of 110 % of the average and 42 % of years with precipitation greater than 120 % of the average. Interestingly, more than 50 % of the dry periods occurred in the second half of the 20th century.

Some dendroclimatological relationships for the early growing season were studied using data from Austrian pine from the Viennese Basin in Austria (Strumia et al. 1997, Wimmer et al. 2000); this region is at no great distance from the southern Moravia. But the reaction of both groups of trees to precipitation was in contrast to that observed for the later period of May–July (when expressed in the form of running regression coefficients as in Fig. 13). While for Austrian pine the growth effect of precipitation increased slowly for July, decreased for May and was stable for June for the period 1890–1990, in the Moravian chronology it was more or less stable in July, decreased in June and,

Table 4. Years with extreme fir tree-rings in southern Moravia in the 16th, 17th and 18th centuries including the March–July precipitation patterns in the Czech Lands according to documentary evidence (Brázdil & Kotyza 2000b)

Year	Short description of weather and related events
Extremely thin tree-rings (dry patterns)	
1513	Drought from May to July
1514	Frosts up to April (dry autumn 1513; severe winter 1513/14)
1525	Hot and dry summer
1532	Drought from March to June
1535	Hot and dry summer (dry summer 1534)
1538	Hot and dry summer
1541	Dry May, wet summer (very dry summer and autumn 1540)
1546	Hot and dry summer
1547	No interpretable report in terms of precipitation patterns
1561	Very dry summer (severe winter 1560/61)
1562	No interpretable report in terms of precipitation patterns
1576	Early spring warm, then frosts
1578	No interpretable report in terms of precipitation patterns
1595	Bad harvest due to heat and drought (dry summer 1594; severe winter 1594/95)
1603	Great drought, from spring to harvest no rains
1608	Very dry summer (severe winter 1607/08)
1616	Drought from April to August
1631	Drought from April to summer (dry summer and autumn 1630)
1636	Moderately dry year (dry September and October 1635)
1637	Dry spring and very dry summer
1638	Dry spring and summer
1653	Dry April and May, dry year (dry autumn 1652)
1654	No interpretable report in terms of precipitation patterns
1662	Hot and dry April, frosts in May
1666	Hot and dry summer
1679	Drought before and after 6 May (severe winter 1678/79)
1686	Drought before harvest, grain perished; dry year
1687	Drought in spring and summer
1689	Drought in May and in summer
1691	Great drought (without exact dating)
1701	No interpretable report in terms of precipitation patterns (severe winter 1700/01)
1704	No interpretable report in terms of precipitation patterns
1707	Dry year (very low level of water in the Vltava in August) (severe winter 1706/07)
1718	Great drought before 24 June, dry summer (severe winter 1717/18)
1719	Dry summer
1720	Great drought (on 8 May a beseeching procession for water)
1721	Great drought (without exact dating)
1751	Drought from May to July
1753	Great drought in summer
1789	Snow and frost in March, drought in May, rains in the harvest time
1790	Drought from February to June (on 13 June a beseeching procession for water)
1792	Dry summer (dry autumn 1791)
1795	Drought in April and May, wet July
1797	Dry February and March
Extremely wide tree-rings (wet patterns)	
1505	Floods in July, grain rotted due to wet patterns (mild winter 1504/05)
1521	Warm February and April, wet May (wet autumn 1520)
1524	Wet year, flood of the Elbe in summer (wet autumn 1523)
1527	No interpretable report in terms of precipitation patterns
1529	Wet summer and wet year (wet August and autumn 1528)
1530	Dry summer
1531	Wet spring, frequent land-slides
1539	No interpretable report in terms of precipitation patterns
1550	Sulphur rained on 10 June (volcanic eruption?)
1566	No interpretable report in terms of precipitation patterns
1568	Much snow lying up to the end of April, wet June
1570	Frequent floods (wet autumn 1569)
1574	Drought in summer
1592	Wet July; late harvest

Table 4 (continued)

Year	Short description of weather and related events
1629	No interpretable report in terms of precipitation patterns
1632	Frosts and snow in April; cold summer
1648	Cold and wet summer
1649	No interpretable report in terms of precipitation patterns (wet autumn 1648)
1650	Wet year, the Kobylí lake filled (it dried up in 1640)
1651	Dry summer
1670	Drought in summer, but floods too (severe winter 1669/70)
1673	Wet summer
1675	Wet summer, floods
1676	No interpretable report in terms of precipitation patterns (mild winter 1675/76)
1678	Wet April, then drought
1693	Wet summer
1696	Wet year, frequent rains in summer
1710	No interpretable report in terms of precipitation patterns
1712	Wet April, dry June
1713	Wet year, frequent rains
1714	Wet June and July, bad wine due to wet patterns
1730	Very wet summer
1765	No interpretable report in terms of precipitation patterns (wet November and December 1764)
1772	No interpretable report in terms of precipitation patterns (wet year 1771; mild winter 1771/72)

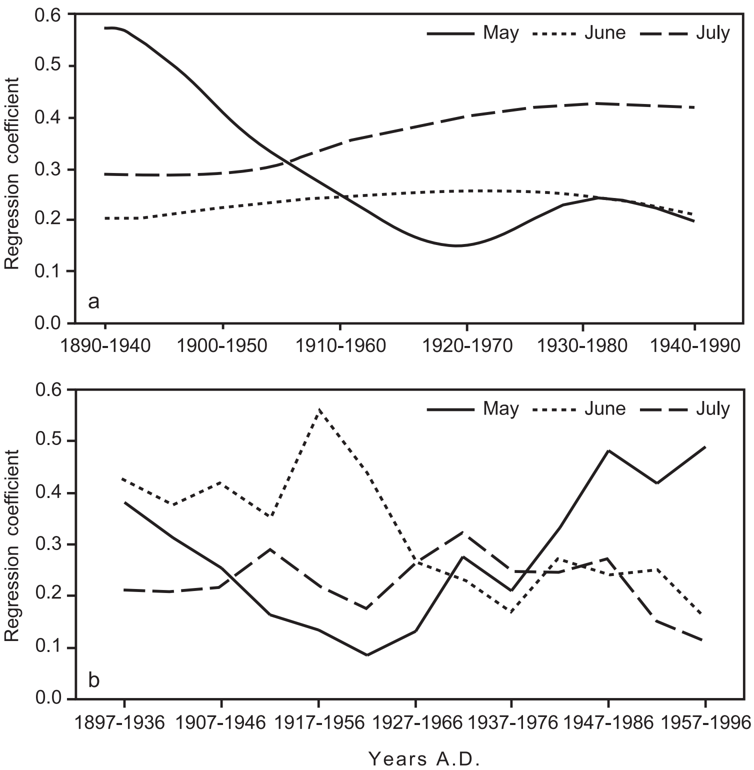

Fig. 13. Partial regression coefficients calculated (a) for Austrian pine from the Viennese Basin, Austria and (b) for the fir from southern Moravia, the Czech Republic for May–July. A 50-yr window moved with 10-yr step between 1890 and 1990 was used in case (a) (modified according to Strumia et al. 1997), a 40-yr window moved with 5-yr step between 1897 and 1996 in case (b)

approximately from the 1940s increased for May, before which a decrease was evident beginning in 1897. Wimmer et al. (2000) used false rings of Austrian pine in order to reconstruct the precipitation series. This, together with early-wood width, might explain as much as 31% of May precipitation variability but these results cannot be confidently compared with those from the current research.

5. CONCLUSIONS

Fir growth in southern Moravia between the 14th and 20th centuries was understandably affected by a number of natural factors, among which the most significant were found to be air temperature and precipitation. Whilst air temperature cannot be used with great confidence in dendroclimatological reconstruction, precipitation reconstructions for the period March–July are known to provide much more reliable results. This implies that water availability in these months is the limiting factor of fir growth. The utilisation of a long-term ring-width chronology has, by this means, facilitated the reconstruction of the March–July precipitation in southern Moravia from 1376 onwards whilst at the same time explaining 38% of its variance. A high level of correlation was also achieved with the Brno instrumental series. A lower level of association was found between the southern Moravia and the Prague-Klementinum precipitation series. The latter was, however, compiled on the basis of the quantitative interpretation of documentary evidence and instrumental measurements. If one also takes into consideration the nature of precipitation from March through to July (when local convective precipitation becomes important, thereby contributing to greater spatial variability of the precipitation field) and the limitations following from the ecology of the fir tree, the correlations with the reconstructed series can be considered as being surprisingly good.

The reconstructed March–July precipitation series reveals the interannual and interdecadal fluctuations, but is less informative regarding any low-frequency signal. This might result, on the one hand, from the absence of a low-frequency signal in the precipitation series or, on the other, it could point to limitations of tree-rings for dendroclimatological reconstructions (see Briffa et al. 1996). The Moravian fir standard chronology was compiled from individual tree-ring series over a period of 50 to 180 yr; this might itself limit the possibility of detecting a low-frequency signal. Moreover, because of natural growing trends caused by the increase in stem diameter, the ageing of the cambium and the competitive influences in stands, it was necessary to detrend individual tree-ring series with the use of digital filters. This process also suppress some of the low-frequency variation, even when using a spline function over 67% tree-ring series length.

The results of this paper are an unquestionable contribution to the reconstruction of precipitation patterns in the central European region, where hitherto reconstructions in the pre-instrumental period have been based largely on documentary evidence (Pfister 1988a, Brázdil 1996, Glaser et al. 1999, Glaser 2001). On the whole, the satisfactory degree of agreement between the extremes of the 2 different types of proxy data (documentary evidence and tree-rings) points to the fact that in combination they will yield better results regarding the precipitation variability in a given region. The cross-checking of reconstructions from different sources of proxy data is an important method if further progress in improving our knowledge about the past climates at local and regional scales is to be made.

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