Int J Biometeorol (2000) 44:121–127

ORIGINAL ARTICLE

Gianluca Piovesan · Bartolomeo Schirone

Winter North Atlantic oscillation effects on the tree rings of the Italian beech (*Fagus sylvatica* L.)

Received: 18 March 1999 / Revised: 29 February 2000 / Accepted: 1 March 2000

Abstract Climatic signals in beech tree-ring width series from Central Italy have been studied over different periods of time. Prewhitened tree-ring chronologies respond mainly to summer precipitation and they do not correlate in a significant manner with the winter North Atlantic oscillation (NAO) index. In this high-frequency pattern the NAO signs are only found on a small number of rings characterized by being very narrow or wide. By contrast, tree-ring width chronologies in which all the frequency components are conserved were significantly related to the NAO. The significant inverse correlation between actual measurements of ring width and NAO is a consequence of the availability of water in the soil at the beginning of the growing season. In fact, in the Mediterranean area the recharging of soil moisture depends on the amount of winter precipitation, which is inversely correlated with the NAO. Strong signals of winter precipitation and NAO are found in the low-frequency components of tree-ring growth.

Key words Apennines · Climatic variability · Dendroecology · Drought · *Fagus sylvatica* L. · Growth variations · Low-frequency variance · North Atlantic oscillation · NAO · Pre-whitening

Introduction

The North Atlantic oscillation (NAO) is, in addition to the southern oscillation, a major source of interannual variability of weather and climate around the world (Hurrell and van Loon 1997). The North Atlantic Ocean basin is characterized, especially in winter, by a strong north–south difference in pressure: when pressure is high in the Azores it tends to be anomalously low near Iceland, and vice versa (Visbeck et al. 1998). For this reason the fluctuation of the NAO is described by an index defined as the normalized sea level pressure (SLP) differences between a southern station (Azores, Lisbon, Gibraltar) and an Icelandic station (Rogers 1984; Hurrell 1995; Jones et al. 1997). In the Northern Hemisphere the winter NAO index (December to March) shows a significant relationship with storm track, temperatures and precipitation (Hurrell and van Loon 1997; Osborn et al. 1999).

Consistent evidence for relationships between the NAO and the fluctuations of ecological processes is becoming available for both marine and terrestrial ecosystems (Visbeck et al. 1998). In recent years different studies shown that the NAO has a strong influence on the biomes of the northern latitudes. On land surrounding the North Atlantic, the NAO controls plant phenology (Post and Stenseth 1999), tree growth (D’Arrigo et al. 1993; Cook et al. 1998), animal breeding and population dynamics (Forchhammer et al. 1998; Post and Stenseth 1999; Stenseth et al. 1999). However, in Europe the tree-ring chronologies south of 53° latitude do not seem to bear clear signals of the effects of the NAO (Cook et al. 1998). Yet during winters with a high NAO index the storm tracks shift much further towards northern Europe and drier conditions occur over the Mediterranean area (Hurrell 1995) where water is the limiting factor for plant life. In this region trees are very sensitive to the availability of water in the soil at the beginning of the growing season and it has been demonstrated that beech trees respond positively to winter precipitation, which controls the recharge level of water in the soil (Biondi 1993; Piovesan 1998). We therefore present evidence that NAO affects the growth of the Apennine beech (*Fagus sylvatica* L.) forests.

Materials and methods

Increment cores were extracted at breast height from beech trees belonging to stands selected throughout the Central Italian Apennines (Cimini Mountains, Sabini Mountains, Simbruini Mountains, Frentani Mountains), between 41.7° and 42.4° north latitude and

G. Piovesan (✉) · B. Schirone
Department of Forest Sciences, University of Tuscia,
Via SC de Lellis, I-01100 Viterbo, Italy
e-mail: piovesan@unitus.it
Tel.: +39-761-357391, Fax: +39-761-357389

Fig. 1 Map showing locations of the study sites (*black area*). The poles of the winter North Atlantic oscillation (*NAO*) are indicated by *S* (Stykkisholmur) for the Icelandic station and *L* (Lisbon, Portugal) for the southern station

between 12.1° and 14.1° east longitude (Fig. 1). The altitude range of the different beech stands is 700–1500 m above mean sea level.

All cores were polished by hand and visually cross-dated, and ring widths were measured to the nearest 0.01 mm by a binocular microscope and a sliding-stage micrometer interfaced with a personal computer (Aniol 1987). The individual series were checked for errors, using computer-aided techniques. In this phase, visual and statistical synchronization of individual series with a beech mean site chronology from the Sabini Mountains was particularly helpful (Bernabei et al. 1996). Altogether, 118 individual tree-ring width series were constructed for the 1931–1995 period.

Since, in the Mediterranean area, the winter NAO is inversely correlated with winter precipitation (Hurrell 1995) we investigated the effects of the winter season on tree-ring growth over different periods of time. Three approaches were followed to study the climatic signals in the tree-ring width series of the Central Apennine beech.

In the first part of the analysis individual tree-ring series were pre-whitened using the ARMA (Autoregressive moving average) model (Guiot 1986) to remove age-related and competition effects. The individual pre-whitened tree-ring width series belonging to each beech stand were averaged in a site chronology and, overall, 11 tree-ring width site chronologies were constructed. To summarize the large-scale spatial information, a principal-component analysis (PCA) was carried out on these pre-whitened tree-ring width site chronologies distributed throughout the mountains of Central Italy. The first-component scores were compared with the seasonal climatic series (temperature, precipitation and NAO index) by Pearson correlation statistics. During this phase of the analysis, the influence of climate on tree-ring growth was analysed for the year of ring formation (current year) and the year preceding the growing season (previous year or year^{-1}). Precipitation series for the 1931–1995 period were obtained by averaging the data registered in two Central Italy meteorological stations (Viterbo and Poggio Mirteto) placed next to beech stands that provided several sampling sites. The temperature series were selected from the station in Rome (Collegio Romano). The winter NAO index was obtained from the Climate Analysis Section (Colorado, USA) internet home page (http://www.cgd.ucar.edu/cas/climind/). The winter (December to March) index of the NAO was based on the difference of normalized SLP between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland, from 1864 to 1999. The SLP anomalies at each station were normalized by division of each seasonal pressure by the long-term (1864–1983) standard deviation (Hurrell 1995). Moreover the influence of climate on beech growth was analysed by carrying out a climatic comparison between years with first-component scores greater than 1 and years with component scores less than –1. Large positive score values characterize years with exceptionally wide tree-rings, while negative values occur when the tree-rings are very narrow. Finally a multiple linear regression was carried out using the winter precipitation of the current and previous year, and the summer precipitation of the current year and of 1 and 2 years before ring formation, as independent variables.

In the second part of the analysis a simple standardization of tree-ring width site chronologies was done: only the deviation of each single value from the mean value of the total chronologies was calculated. PCA was carried out on these standardized tree-ring width site chronologies in which all the frequency components of radial growth were conserved. The climatic analyses were carried out with the procedure described above. Since the first-component scores conserved the autocorrelation, we adjusted the degrees of freedom for tests of significance to account for autocorrelation (Barlett 1946): $N'=N[(1-a_1a_2)/(1+a_1a_2)]$, where N is the number of paired observations and a_1 and a_2 are the coefficients of autocorrelation for each of the series (see also Post and Stenseth 1999). A master chronology of Central Apennine beech was constructed by averaging all 118 individual tree-ring width (raw values) series. Merging the raw series into a mean regional chronology is statistically a procedure very similar to that of constructing a first-component score series in which only the variance common to all samples is conserved. Both procedures conserve all the climatic signals and the ageing phenomenon, but should remove competition trends. Since tree-ring growth is expressed in the master chronology with the actual measurement, it is very advantageous to use this chronology to study growth/climate relationships (see Results).

Finally, to study low-frequency fluctuations, the climatic series and the Central Apennine master chronology were smoothed by using a running 11-year mean (cf. Fritts 1976).

Results

Climatic signals in the pre-whitened tree-ring width site chronologies of Central Apennine beech

The first component of the 11 pre-whitened tree-ring width site chronologies explained 55.5% of the total variation and all the component loadings had positive values (0.57–0.86) (see also Biondi and Visani 1996). Correlation of the first-component scores with precipitation data demonstrated that the pre-whitened tree-ring width is positively correlated with the amount of summer (June to August) and winter (December to March) precipitation (Table 1). First-component scores are inversely correlated with summer temperature. The negative correlation with the NAO index is not significant. Correlations with the year preceding the growing season maintain the same sign, but are not significant.

The *t*-tests indicate that the mean climatic condition for a sample size of 8 years with scores below 1 (narrow rings) is different from the 9-year sample with scores

Table 1 Climatic signals in the first-component scores of the pre-whitened site chronologies of Apennine beech for the 1932–1995 period. *r PC1 scores* Pearson correlation coefficient of the first component scores with the average precipitation of two Central Italian stations (Viterbo and Poggio Mirteto), with the Rome mean temperatures and with the North Atlantic oscillation (*NAO*) index. *Δ* The mean climatic difference between narrow and wide rings; for precipitation, this is given as mm day^{-1}. *DJFM* (December to March), *JJA* (June to August)

Climatic variable	*r* PC1 scores	PC1 scores <–1 mean value of a sample size of 8 years: narrow rings	PC1 scores >1 mean value of a sample size of 9 years: wide rings	*P*	Δ
Precipitation (mm)					
Winter (DJFM)	0.25*	260	382	0.003	–1.0
$\text{Winter}_{\text{year}-1}$	0.20	234	389	0.013	–1.3
Summer (JJA)	0.50***	79	186	0.000	–1.2
$\text{Summer}_{\text{year}-1}$	0.20	95	156	0.099	–0.7
Temperature (°C)					
Summer (JJA)	–0.39**	24.8	23.7	0.005	1.2
$\text{Summer}_{\text{year}-1}$	–0.04	24.6	24.1	0.181	0.4
Winter NAO index	–0.19	1.3	–1.1	0.020	2.4
Winter NAO $\text{index}_{\text{year}-1}$	–0.11	1.4	–1.1	0.012	2.5

*$P<0.05$ **$P<0.01$ ***$P<0.001$

greater than 1 (wide rings) (Table 1). Confirming the results from the correlation analyses, in the Apennine beech stands a very narrow tree-ring is formed when a winter drought is followed by a hot dry summer. By contrast, beech trees respond to a rainy winter and "moist–cool" summer with a wide tree-ring. Narrow rings are generally characterised by a winter NAO index greater than 1, while wide rings are associated with a winter NAO index below –1. The difference in precipitation rate between winters preceding narrow tree-rings and those preceding wide tree-rings corresponds to –0.98 mm day^{-1}, a value very close to that of –0.8 mm day^{-1} reported for the differences in precipitation in Rome between winters with an NAO index above 1.0 and those with an index less than –1.0 (see Table 1 in Hurrell 1995). However, the major difference we found in the precipitation rate is probably due to the stronger inverse correlation between NAO index and results from these two Central Italian stations (r=–0.64 $P<0.001$) relative to that reported for Rome (r=–0.37 $P<0.01$ Hurrell 1995). Moreover, with reference to precipitation and NAO analyses, it is interesting to note that these climatic differences between the two groups of rings are also observed during the year preceding the growing season: low precipitation and high NAO index indicating narrow rings and high precipitation and low NAO index indicating wide rings.

The multiple linear regression between the first-component scores and five predictors (winter and summer precipitation of the current and previous growing season and summer precipitation values for 2 years preceding tree-ring growth) was highly significant and explained 51% of the total variance for the 1933–1995 period (Fig. 2). Winter precipitation and summer precipitation of the current year and the previous year correlate positively with tree-ring width, while a negative correlation is apparent with the summer precipitation for the 2 years preceding ring growth. The different response to the summer precipitation 2 years earlier may be linked with reproductive activity. Beech trees tend to show high seed production years (mast years) when the summer is moist 2 years preceding fruiting (Piovesan and Adams, unpublished results). The antagonistic behaviour between vegetative and reproductive growth is confirmed by the opposite response to the precipitation of the summer preceding mast year or ring growth: a drought depresses ring width but stimulates floral induction (Piovesan and Adams, unpublished results). Minimum-factor scores (narrow rings) often coincide with years of high seed production (e.g. mast years 1991 and 1994). During a mast year beech trees spend a lot of energy on reproduction (Holmsgaard 1962; Piovesan and Bernabei 1997) and this fact could also explain the difference between observed and predicted values during those years (see Fig. 1; cf. Woodward et al. 1994).

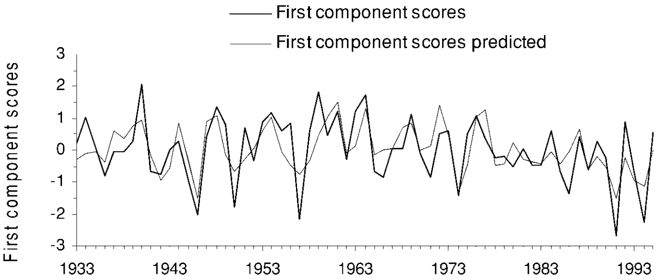

Fig. 2 Comparison of observed and predicted first-component scores of the pre-whitened tree-ring width beech site chronologies for the 1933–1995 period. Estimates were obtained from multiple regression (r^2=0.51 $P<0.001$), using as predictors the summer precipitation of the current year (t=4.76), and that of 1 (t=1.94) and 2 years (t=–3.52) before the growing season and the amount of winter precipitation of the current year (t=2.42) and that of 1 year before the growing season (t=2.86). Durbin-Watson D statistic=2.26

Climatic signals in the Central Apennine beech chronologies in which all the frequency components are conserved

The first component of the standardized tree-ring width site chronologies explained 52.7% of the total variation and all the component loadings had positive values (0.38–0.88). The correlations with climatic series show that, in this first-component score series, in which all the frequency components are conserved, there are also clear

Table 2 Climatic signals in the first-component scores of the standardized site chronologies of Apennine beech for the 1932–1995 period. *r PC1 scores* Pearson correlation coefficient of the first-component scores with the average precipitation of two Central Italian stations (Viterbo and Poggio Mirteto), with the Rome mean temperatures and with the North Atlantic oscillation (*NAO*) index. *Δ* The mean climatic difference between narrow and wide rings; for precipitation, this is given as mm day^{-1}

Climatic variable	*r* PC1 scores	PC1 scores <–1 mean value of a sample size of 7 years; narrow rings	PC1 scores >1 mean value of a sample size of 9 years: wide rings	*P*	Δ
Precipitation (mm)					
Winter (DJFM)	0.43**	251	445	0.002	–1.6
Winter$_{\text{year–1}}$	0.45**	201	398	0.001	–1.6
Summer (JJA)	0.35**	106	142	0.16	–0.4
Summer$_{\text{year–1}}$	0.42**	72	142	0.039	–0.8
Temperature (°C)					
Summer (JJA)	–0.41**	24.9	23.9	0.02	0.9
Summer$_{\text{year–1}}$	–0.33	25.0	24.1	0.01	0.9
Winter NAO index	–0.44**	1.9	–2.1	0.000	4.0
Winter NOA index$_{\text{year–1}}$	–0.42**	1.9	–1.7	0.000	3.6

$^*P<0.05$ $^{**}P<0.01$ $^{***}P<0.001$

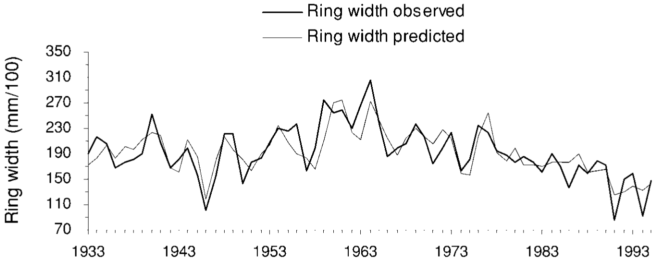

Fig. 3 Comparison of observed and predicted first-component scores of the Central Apennine beech master chronology for the 1933–1995 period. Estimates were obtained from multiple regression (r^2=0.68 P<0.001) using the same climatic predictors as in Fig. 2 plus the ring width of the year before the growing season. Durbin-Watson *D* statistic=1.88

climatic signals from the year preceding the growing season (Table 2). In particular, the correlation coefficient with the NAO index proves an important predictor.

Comparison of the mean climatic conditions associated with narrow and wide tree-rings confirmed the results of the correlation analyses: very strong differences in the winter precipitation and NAO index beginning from the year preceding the growing season.

The first-component scores of the standardized tree-ring site chronologies and the Central Apennine beech master chronology show an identical pattern of fluctuation, which is expressed in scores or actual measurements. In the multiple linear regression we preferred using the Central Apennine beech master chronology where the time-series variations are expressed in actual values of ring growth. A multiple regression model, calculated with the same five climatic independent variables as above, explained 58% of the total variance for the 1933–1995 period, but residuals are affected by lag one autocorrelation. Inclusion of the tree-ring width of the previous year as an independent variable solves this problem (Fig. 3).

The first-component scores of the standardized tree-ring site chronologies and the Central Apennine beech master chronology have important characteristics with respect to

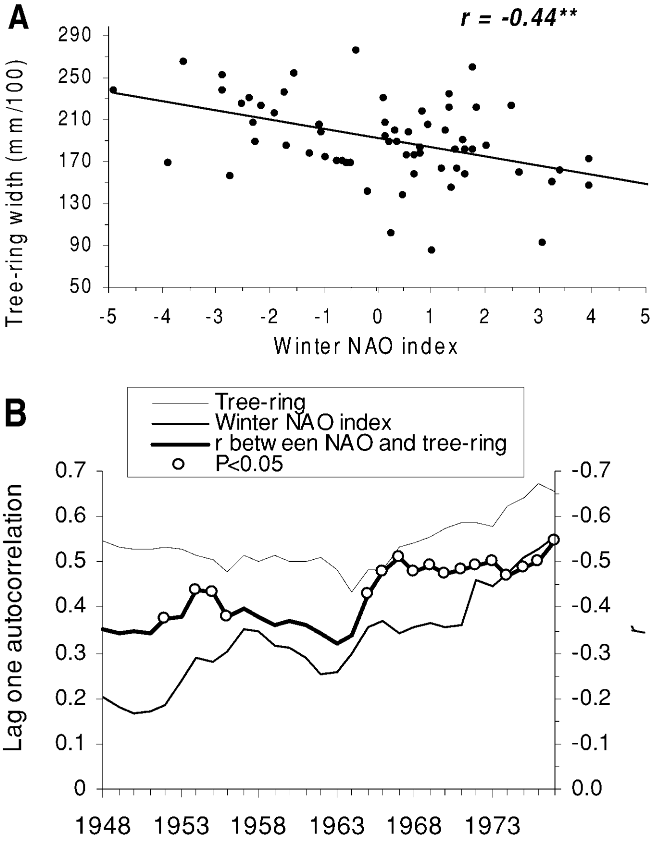

Fig. 4 **A** linear regression between winter NAO index and actual ring measurement of Central Apennine beech master chronology for the 1931–1995 period. **B** Lag one autocorrelation coefficient variation for winter NAO index and Central Apennine beech master chronology. The lag one autocorrelation coefficient is calculated over a 35-year interval and is assigned to the middles of the 35-year window. The bold line shows the moving correlation (*r*) for the same periods between winter NAO index and Central Apennine beech master chronology

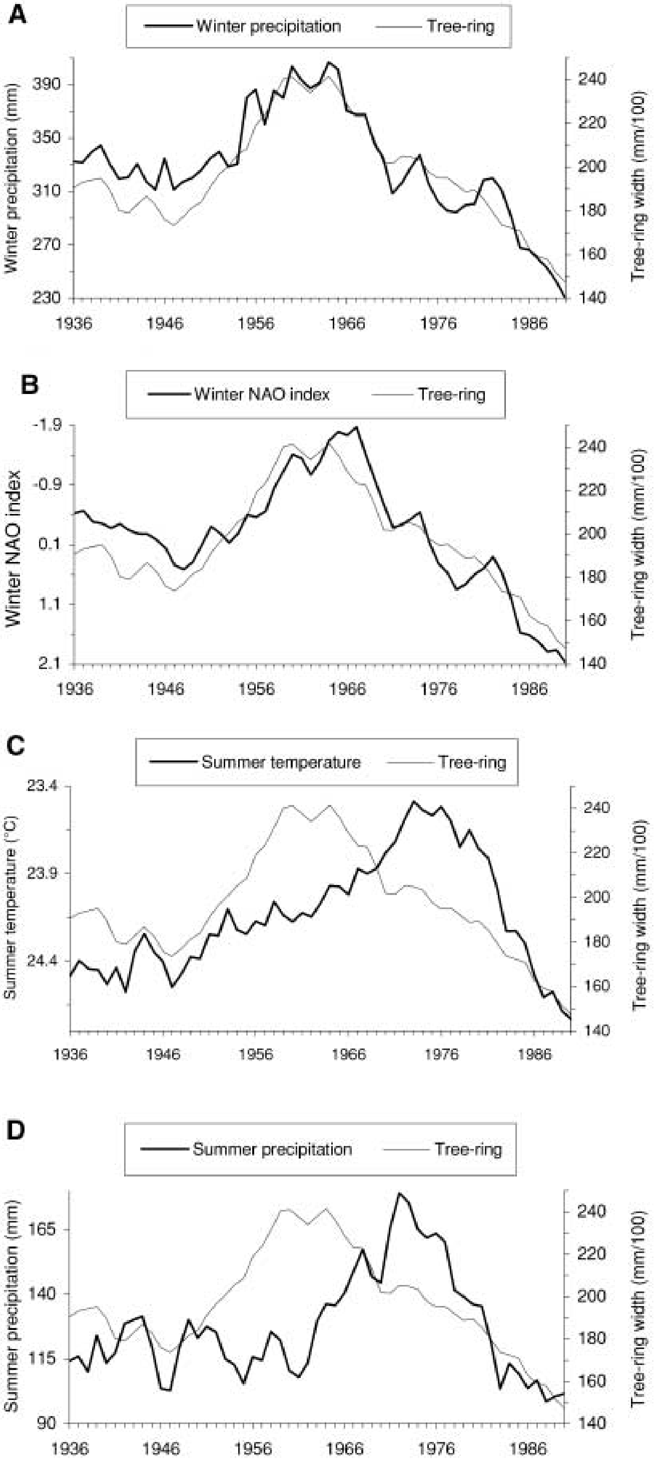

Fig. 5A–D Visual synchronization between Central Apennine beech master chronology and winter precipitation (**A**), winter NAO index (**B**), summer temperature (**C**) and precipitation (**D**); series were smoothed by using a running 11-year mean and values are assigned to the middles of the 11-year window. The axes of the winter NAO index and summer temperature are inverted to emphasize the negative correlations between tree-ring width and these two climatic factors

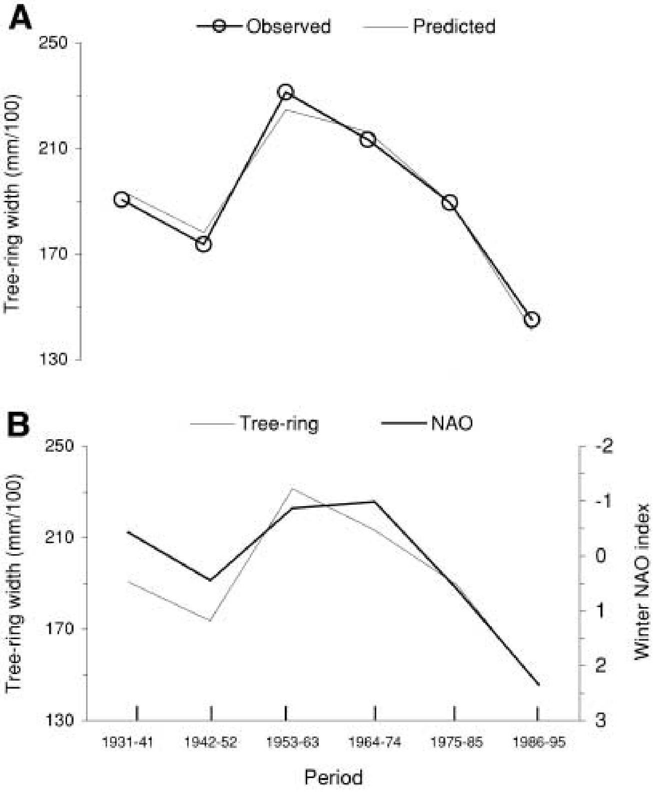

Fig. 6 **A** Comparison of observed and predicted non-overlapping 11-year mean series of Central Apennine beech master chronology. The value for the last period results from a 10-year average (1986–1995). Estimates were obtained from multiple regression (r^2=0.98 P<0.001) using as predictors the value of the non-overlapping 11-year average series of winter (t=8.61) and summer precipitation (t=2.95). Durbin-Watson D statistic=2.46: **B** Visual synchronization between the non-overlapping 11-year average series of Central Apennine beech master chronology and winter NAO index (r=–0.92 P<0.01)

the pre-whitened first-component scores: they are characterized by a positive lag-one autocorrelation (0.55). This is a statistical problem for the multiple regression theory, but eliminating the autocorrelation from the tree-ring series alters the relationships between NAO and tree-ring width. The significant inverse correlation between tree-ring width (or first-component scores of the standardized site chronologies) and winter NAO index (Fig. 4A; cf. Table 2) is probably due to conservation of the autocorrelation structure in the series, since the correlation of the pre-whitened series is not significant (cf. Table 1). The moving correlation over a 35-year period between winter NAO index and Central Apennine beech master chronology suggests non-stationary behaviour with a significant correlation coefficient associated with periods in which the lag one autocorrelation in the NAO index is rising (Fig. 4B). In particular around the 1960s, a synchronous increasing trend began in the lag one autocorrelation in both the NAO and Central Apennine beech tree-ring series. Moving to the most recent interval (1960–1994), the highest correlation coefficient (r=–0.55 P<0.05) between the two series is associated with an NAO window characterized by an increasing trend from the highly negative phase of the 1960s to the highly positive phase of the 1990s.

Climatic signals in the low-frequency fluctuations of Central Apennine beech master chronology

As the NAO spectrum tends to become redder throughout the 20th century (Hurrell and van Loon 1997) a smoothing of the series helps to show the effect of NAO on Apennine beech growth.

When the high-frequency variance of the series is removed by using a running 11-year mean, the good synchronization between Central Apennine beech master chronology and winter precipitation or NAO series is evident (Fig. 5). In fact, the correlation coefficient of the smoothed series increases to 0.91 for the comparison between beech master chronology and winter precipitation (Fig. 5A) and –0.9 for that between beech master chronology and NAO (Fig. 5B), while the correlation with summer precipitation becomes weaker (0.33) (Fig. 5D). The correlation between Central Apennine beech master chronology and temperature is –0.46, suggesting that, on this time scale, summer temperature is a secondary factor (Fig. 5C).

The multiple-regression model of non-overlapping 11-year mean series of the Central Appennine beech master chronology, calculated with a non-overlapping 11-year mean series of winter and summer precipitation, shows that, on this time scale, the multiannual variation of tree-ring growth can be reproduced easily by using winter precipitation, controlled by the NAO, and secondarily summer precipitation (Fig. 6A). The effect of NAO in the low-frequency pattern is quite evident in this case also (Fig. 6B).

Discussion

Our dendroecological analyses confirm that, in Central Italy, beech growth is mostly influenced by both winter and summer precipitation and by summer temperature (Biondi 1993; Piovesan 1998). The analyses of climatic signals on Central Appenine beech tree-ring series agree with the important role of the year preceding tree-ring growth, as reported in various studies (Fritts 1962; Eckstein and Frisse 1982; Gutierrez 1988; Dupouey et al. 1993). It has long been known that the growth of trees is preconditioned by the environmental conditions of the preceding year (Kramer and Kozlowski 1979). In this Mediterranean region we found evident signs of winter precipitation affecting tree-ring width, as predicted by Fritts (1976) for a climate characterized by lack of precipitation during the summer. However, the response of beech growth to the different climatic factors depends on the time scales of the analysis.

Removing the autocorrelation from the beech tree-ring width series permits the climate/growth relationships in the high-frequency domain to be studied. On this time scale, summer precipitation is a very important factor. In fact, summer precipitation has a double controlling effect on beech biology: the vegetative and the reproductive growth tend to respond in opposite manner to this climatic factor (Holmsgaard 1962; Piovesan and Adams, unpublished results). According to Cook et al. (1998) there are no strong effects of NAO in the high-frequency variance of tree-ring series. On this time scale, only narrow and wide rings are associated with extreme NAO years.

However, tree-life history is also characterized by long-term correlations in which important aspects of the environment are recorded (Fritts 1976; Halley 1996). By conserving the memory of the system – the autocorrelation structure-in which there are not only the effects of competition and age, but also growth fluctuations linked to the low-frequency variance of the climate, other important relationships emerge. After removal of the high-frequency variance from the tree-ring series, this study has shown that Mediterranean beech forests receive a fundamental growth spur from water stored in the soil, recharged by winter precipitation, whereas the scant summer precipitation, insufficient to balance evapotranspiration, is basically useful in alleviating water stress (see Biondi 1993). As in the Mediterranean area winter precipitation is inversely correlated with the NAO (Hurrell 1995), we found signs of the NAO in the multiannual variation of tree-ring growth. Gradual decline in the growth of the Apennine beech, first noted in the 1970s, thus finds its origin in the persistence of NAO in a positive phase (Hurrell 1995; Hurrell and van Loon 1997).

We have demonstrated that the low-frequency variation of beech growth is strongly influenced by the NAO. Therefore, this effect must be taken into consideration for sustainable forest management in the Mediterranean environment.

Acknowledgements We thank J.W. Hurrell for the critical revision of the text.

References

Aniol RW (1987) A new device for computer assisted measurement of tree-ring widths. Dendrochronologia 5:135–141

Barlett MS (1946) On the theoretical specification of sampling properties of autocorrelated time series. J R Statist Soc [Suppl] 8:27–411

Bernabei M, Lo Monaco A, Piovesan G, Romagnoli M (1996) Dendrochronology of beech (*Fagus sylvatica* L.) from Sabini Mountains (in Italian with English summary). Dendrochronologia 14:59–70

Biondi F (1993) Climatic signals in tree rings of *Fagus sylvatica* L. from the Central Apennines, Italy. Acta Oecol 14:57–71

Biondi F, Visani S (1996) Recent developments in the analysis of an Italian tree-ring network with emphasis on European beech (*Fagus sylvatica* L.). In: Dean JS, Meko DM, Swetnam TW (eds) Tree rings, environment and humanity. Radiocarbon, University of Arizona Tucson, pp 713–725

Cook ER, D'Arrigo RD, Briffa KR (1998) A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. Holocene 8:9–17

D’Arrigo RD, Cook ER, Jacoby GC, Briffa KR (1993) NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector. Q Sci Rev 12:431–440

Dupouey JL, Leavitt S, Choisnel E, Jourdan S (1993) Modelling carbon isotope fractionation in tree rings based on effective evapotranspiration and soil water status. Plant Cell Environ 16:939–947

Eckstein D, Frisse E (1982) The influence of temperature and precipitation on vessel area and ring width of oak and beech. In: Hughes MK, Kelly PM, Pilcher JR, LaMarche VC (eds) Climate from tree rings. Cambridge University Press, Cambridge, p 12

Forchhammer MC, Post. E, Stenseth NC (1998) Breeding phenology and climate. Nature 391:29–30

Fritts HC (1962) The relation of growth ring widths in American beech and white oak to variations in climate. Tree-Ring Bull 25:2–10

Fritts HC (1976) Tree ring and climate. Academic Press, New York

Guiot J (1986) Arma techniques for modelling tree ring response to climate and for reconstructing variations of paleoclimates. Ecol Model 33:149–171

Gutierrez E (1988) Dendroecological study of *Fagus sylvatica* L. in the Montseny mountains (Spain). Acta Oecol 9:301–309

Halley JM (1996) Ecology, evolution and 1/*f* noise. Trends Ecol Evol 11:33–37

Holmsgaard E (1962) Influence of weather on growth and reproduction of beech. Commun Inst For Fenn 55:1–5

Hurrell JW (1995) Decadal trends in the North Atlantic oscillations: regional temperatures and precipitation. Science 269:676–679

Hurrell JW, Loon H van (1997) Decadal variations in climate associated with the North Atlantic Oscillation. Clim Change 36: 301–326

Jones PD, Jónsson T, Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and southwest Iceland. Int J Climatol 17: 1433–1450

Kramer PJ, Kozlowski TT (1979) Physiology of woody plants. Academic Press, Orlando, USA

Osborn TJ, Briffa KR, Tett SFB, Jones PD, Trigo RM (1999) Evaluation of the North Atlantic Oscillation as simulated by a coupled model. Clim Dyn 15:685–702

Piovesan G (1998) Analisi di problemi assestamentali nella foresta montana dell’Appennino centrale. PhD Thesis, University of Tuscia, Viterbo, Italy

Piovesan G, Bernabei M (1997) Influence of summer precipitation on growth and reproduction of beech in a southern site of the range. In Italian with English summary. Ital For Mont 6: 444–459

Post E, Stenseth NC (1999) Climatic variability, plant phenology, and northern ungulates. Ecology 80:1322–1339

Rogers JC (1984) The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. Mon Weather Rev 112:1999–2015

Stenseth NC, Chan KS, Tong H, Boonstra R, Boutin S, Krebs CJ, Post E, O’Donoghue M, Yoccoz NG, Forchhammer MC, Hurrell JW (1999) Common dynamic structure of Canada Lynx populations within three climatic regions. Science 285: 1071–1073

Visbeck M, Stammer D, Toole J, Chang P, Hurrell J, Kushnir Y, Marshall J, McCartney M, McCreary J, Rhines P, Robinson P, Wunsch C (1998) Atlantic climate variability experiment prospectus. US-CLIVAR project office, Washington DC (http://www.ldeo.columbia.edu/~visbeck/acve)

Woodward A, Silsbee DG, Schreiner EG, Means JE (1994) Influence of climate on radial growth and cone production in subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*). Can J For Res 24:1133–1143