EUROPEAN TREE RINGS AND CLIMATE IN THE 16TH CENTURY

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Abstract. We present a selective review of tree-ring variability and inferred climate changes in Europe during the 16th century. The dendroclimatological evidence is assessed within the context of the last 500 years and some interpretational problems are discussed. The tree-ring evidence is compared with various non-dendroclimatic evidence. The body of evidence shows that a large region of mid and northern Europe experienced a sharp cooling at around 1570/80 that, at least in the north, marked a shift towards a prolonged period of cool conditions. This region had its southern boundary in the Alps and there is little evidence for a major cooling in southern Europe.

1. Introduction

The dating accuracy achievable when building long continuous chronologies of tree-ring widths or tree-ring density provides us with the potential to infer aspects of past climate variability within a rigid and precise timeframe throughout Europe. In some situations, the data series are long enough to allow us to investigate climatic variability during the 16th century and so place this in a context of the last half millennium. The annual resolution also enables us to compare these records with other selected information that is at least as well resolved and similarly reliably dated. Hence, we have brought together here a number of tree-ring or tree-ring-derived climate time series that together provide an overview of climate in 16th century Europe, and we undertake some selected comparisons with relevant historical, ice core and climate data.

2. Evidence of Long Tree-Ring Chronologies

2.1. THE NORTHERN CONIFERS

In the northern latitudes of Europe and western Siberia, we are fortunate in that we are able to locate relatively long-lived trees (up to ~500 years) and well-preserved

Climatic Change **43**: 151–168, 1999.

dead and subfossil wood remains. At some locations, these can be pieced together to yield continuous ring-width and densitometric chronologies that span thousands of years and which demonstrate particular sensitivity to summer temperature. These chronologies provide us with an accurate picture of northern summer temperatures that includes variability on interannual and interdecadal timescales. Where appropriate methods have been used to construct them, these chronologies also have the potential to provide climate information on longer (intercentennial) timescales (Briffa *et al*., 1996). Figures 1 and 2 provide an illustration of two such tree-ring-derived summer temperature reconstructions, for northern Fennoscandia (based on Lake Torneträsk data) and the region of the northern Ural Mountains to the east (Briffa *et al*., 1992, 1995). Each extends back well beyond the 16th century and they have been plotted alongside the summer (June-Aug.) Central England temperature series (CET) Manley 1974; and updated in Parker *et al*., 1992, the summer Central European series (Pfister 1992), and a record of melt layers in an ice core from Svalbard (Tarussov, 1992), also indicative of changing summer temperatures.

It is apparent that northern Fennoscandia and the northern Urals suffered cool summers throughout the later part of the 16th century, but the initial cooling trend was earlier, during the first half of the century in the east (Figure 1). The early 1500s were warm in Fennoscandia, but became rapidly cooler during the 1570s. The Svalbard melt record suggests an intermediate period, around 1550 for the cooling. The tree-ring-derived records (and the Svalbard data) all indicate protracted cool conditions during the late 16th century.

The longer 1000-year context for these records (Figure 2) shows that the abruptness of the 16th-century cooling events in both Fennoscandia and the Urals was unprecedented, with the possible exception of a rapid cooling in the Fennoscandia record that occurred in the first half of the 12th century.

2.2. THE ALPINE CONIFER CHRONOLOGIES

Some early Alpine chronologies (or temperature series derived from them) provide evidence supporting the distinct late 16th century summer cooling, indicated in the various high and mid-latitude tree-ring data described above.

Using a combination of Austrian larch, spruce and stone pine chronologies made up of living and historical samples collected from relatively high elevation (~1000-2000masl), Eckstein and Aniol (1981) reconstructed summer temperatures (June/July mean) representing the region around Obergurgl from before 1500 to 1968. No information is given about what standardization of the data was employed, so it is difficult to judge the extent to which the more prolonged anomalies (timescales > several decades) in growth are realistically portrayed. Nevertheless, this reconstruction shows near normal or slightly cool summers through the first half of the 16th century and relatively warm summers in the mid to

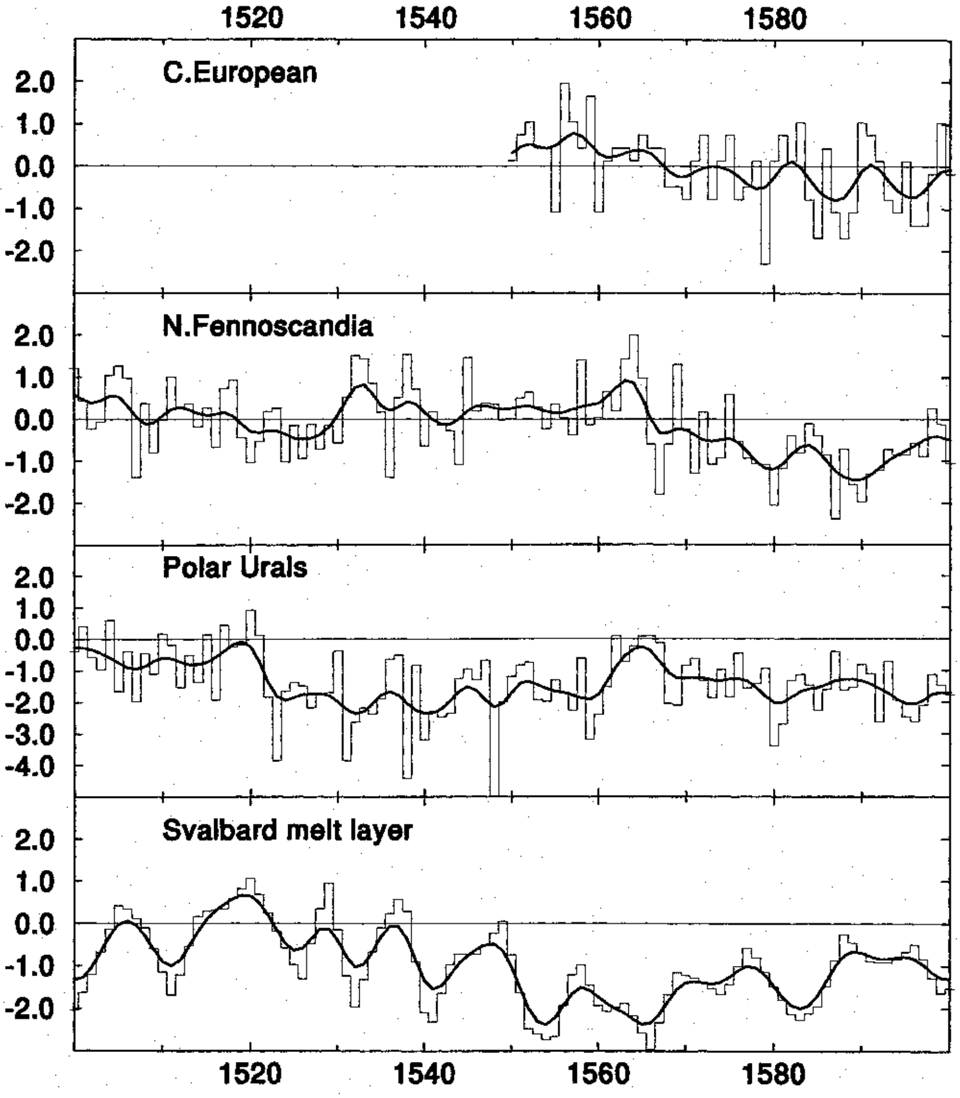

Figure 1. Yearly (histograms) and decadally-smoothed variability of summer temperatures during the 16th century in various European records: the historical Central European index of Pfister (1992); the northern Fennoscandian and Polar Urals tree-ring derived records (Briffa *et al.*, 1992; 1995) and the Svalbard Ice Melt Layer record (Tarussov, 1992). The data are expressed as °Celsius anomalies (1901-50 base).

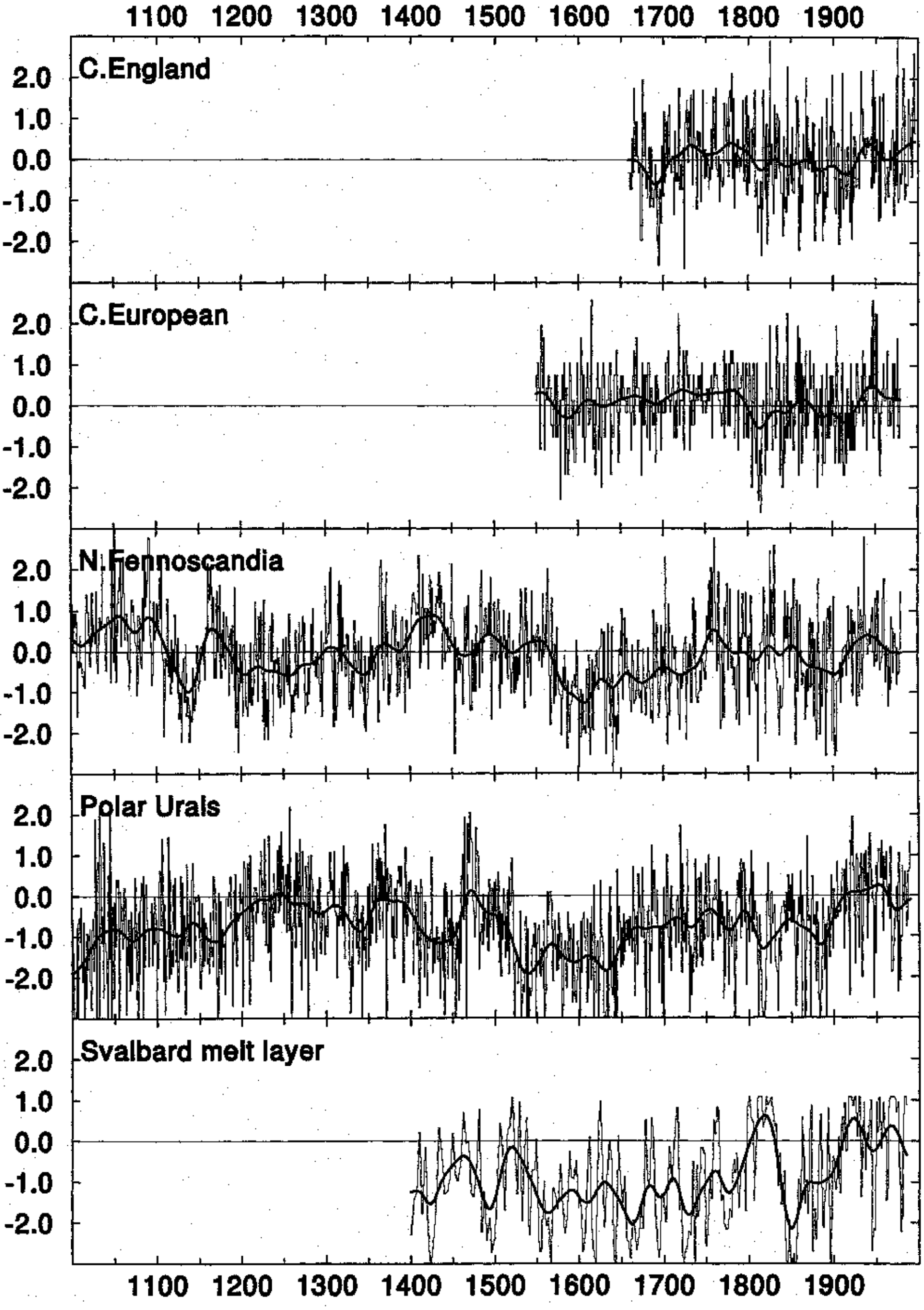

Figure 2. The same series shown in Figure 1, with the addition of the Manley (1974) Central England temperature record, here shown over the longer period from 1500.

later 16th century (~1550-1580). There is then a clear fall in temperatures and cool conditions persist during the late 16th and early 17th centuries (~1580-1660). Another Alpine chronology, made of densitometric measurements of spruce from the Swiss Alps (Schweingruber *et al.*, 1988) suggests relatively warm summer conditions in the Bernese Oberland during most of the 16th century, but also shows a sharp cooling starting at about 1570 with no amelioration until the second half of the 17th century.

2.3. THE EUROPEAN OAK MASTERS

Other sources of long, continuous tree-ring records in Europe are the multitude of archaeological and other historical timber contained in the various European dendrochronology laboratories. Many of these have been engaged for decades, developing oak chronologies for dating purposes within which are incorporated thousands of variously-sourced and often relatively short ring-width measurement series, though generally drawn from reasonably coherent geographical regions. These long, composite chronologies contain strong, and invariably widely-representative patterns of distinctive high-frequency variability: short periods of interannual growth changes or 'signatures' that represent the primary dating 'signals' in these data (Baillie, 1983). These may be interpretable (at least as regards central west Europe and Britain) as evidence of particular European-scale synoptic climate patterns (e.g. Kelly *et al.*, 1989), but the longer term (decadal and above) climate information contained in the chronologies has not been sufficiently well defined or understood and is likely to be confused by changes in the make up (i.e. the changing source concentration and regional definition), chronology construction methods, and changing temporal replication of the data. Work is currently underway to explore these issues. Here we provide a representative sample of the variability of these data on medium- (multidecadal) and high-frequency (years-to-decades) timescales through the 16th and subsequent centuries. Figure 3 compares a smoothed (to emphasise multidecadal and longer variability) version of the Fennoscandian temperatures with a similarly smoothed mean European scale oak chronology. This oak series is an amalgam of up to 15 various regional series forming a transect from Ireland across Europe as far as Poland (Baillie, 1996). These data have been produced using a variety of techniques so that their different timescales of growth variability are portrayed with varying degrees of reliability. In this large-scale average series, multidecadal variations may be considered generally indicative of real large-scale forcing.

During the 16th century, it is clear that, as with the Fennoscandian trees, averaged European oak growth declined. Periods of relatively high growth are apparent before, and low growth after, about 1570. We can provisionally interpret the lower growth trends (as for the distinct individual year negative 'signatures') as suggesting a change towards drier, possibly warmer, conditions in west central

Europe, in spring and summer, associated with anomalously higher pressure (or at least a potentially more meridional circulation) over central Europe and lower pressure and cooler (wetter) conditions over Scandinavia. The reverse situation, higher pressure and warm, sunny conditions in the north and lower pressure with wetter conditions in Europe, produces good growth in the northern pines and European oaks. The comparison over a longer period (cf. Figure 3) between the two records indicates that there is some degree of parallelism between high northern pine and central European oak growth during the last half millennium, but that this is by no means always so (see the opposite trends in the early 1600s, the early 1700s and the early 1900s).

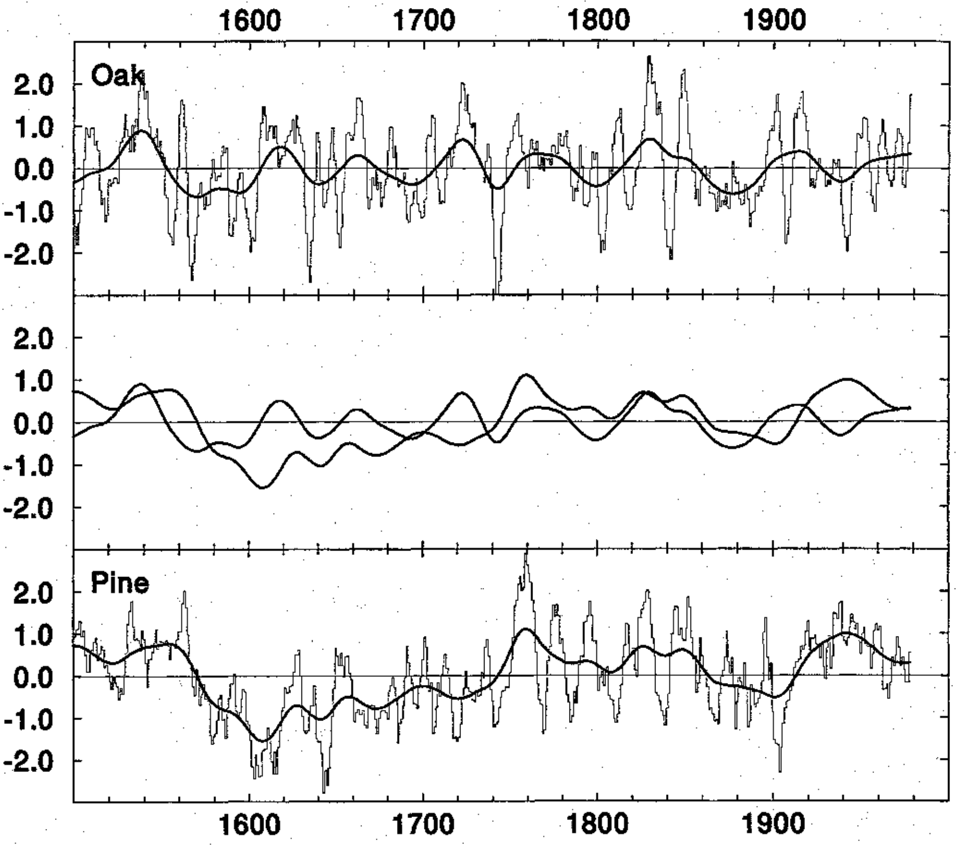

Figure 3. 5-year smoothed (histograms) and multidecadal (smooth lines) records of northern Fennoscandian summer temperatures derived from pine (lower curves) and the averaged growth of various European oak series (upper curves). For ease of comparison, the two longer trend curves are shown superimposed in the central panel. The data are shown as standardised anomalies from a 1901-50 base period.

Further elucidation of the longer-term trends and the climatic interpretation of the European oak database requires further work to define more homogeneous regional chronologies. However, one interesting additional aspect of the high-frequency variability of these data is illustrated in Figure 4. This shows various combinations of the European oak masters randomly averaged to form different mean chronologies. However, here, only interannual-to-decadal timescale variability is represented, the longer trends in the original series having been removed using a 30-year high-pass filter. What is clear from this Figure is that the general patterns of year-to-year variability across Europe are robustly represented by the variously combined series, except for certain periods in which greater spatial variability is apparent. One such period is the late 1560s and early 1570s, contemporaneous with the trend to lower growth that we observed in the pine and oak series in Figure 3. This might be associated with greater spatial climate variability across central Europe, a possible consequence of increased meridional (great summer blocking) circulation.

3. Large-Scale Mean Densitometric Chronologies

We have constructed simple, but large-scale, regional average series of temperature sensitive maximum-latewood-density chronologies. The chronologies were sampled as part of a hemispheric network intended to maximise sensitivity to large-scale temperature forcing. These data demonstrate large regional coherence

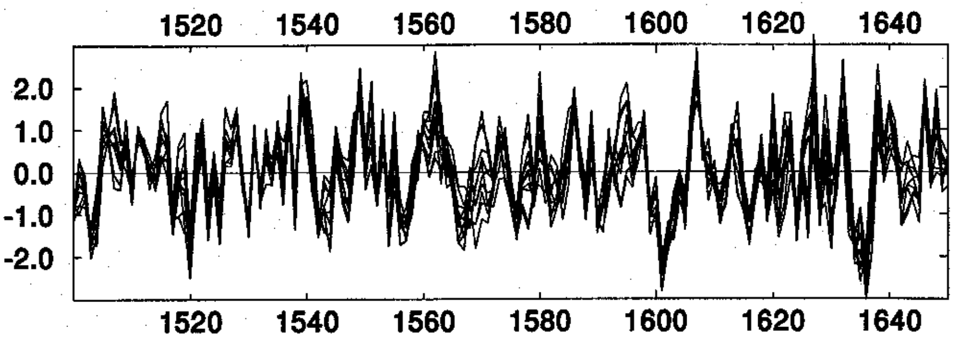

Figure 4. High-frequency variability of large-scale Europe oak growth (dimensionless indices) in the 16th century, represented here as various superimposed chronologies made from various permutations of the available European master chronologies.

(Schweingruber *et al.*, 1992; Schweingruber and Briffa, 1996; Waldner and Schweingruber, 1996). We have thus produced 'northern' and 'southern' European series, each made up of data from many sites, with the intention of representing major common tree-ring density variability and hence large regional-scale common temperature forcing in northern and southern Europe (Figures 5 and 6). These series correlate significantly with equivalent-region instrumental temperatures averaged over an April-Sept. season, despite an apparent divergence in the decadal-timescale trends between density and measured temperatures that is becoming increasingly apparent during the last 50 years, and which is believed to be related to some, as yet unexplained and possibly anthropogenic, environmental disturbance (Briffa *et al.*, 1998).

The 'northern' density record implies a clear shift from warmer to cooler summers occurring in the last quarter of the 16th century. With only a minor period of relative sustained amelioration around the mid 18th century, this shift seems to have marked the start of a prolonged epoch of relatively cool summers. The same, however, cannot be said of the southern series, which shows cooler summers in the early 16th century and only briefly in 1560s. There is no clear mean temperature difference between the pre and post 1560 periods in these southern data, as is seen in the northern regions. However, again it should be stressed that the method of chronology construction can limit, to some extent, the preservation of long-term trends in derived climate reconstructions. The fact that the same multidecadal trends are captured in the northern density series, as were evident in the northern Fennoscandian temperature reconstruction, argue against the likelihood that any significant trends have been removed in the southern series which is made up of chronologies constructed in the same manner.

4. Comparing Early Tree-Growth and Historical Climate Indices

4.1. HISTORICAL TREE-GROWTH RESPONSE FUNCTIONS

In this section, we demonstrate the potential for more detailed interpretation of specific climate forcings that might be achievable in regions smaller than those represented by large area average chronologies. The approach compares the growth reactions of different tree species together in the same year, the rationale being that different species' responses might provide a more complete picture of various meteorological phenomena that together make up that year's climate. Detailed regional tree-ring data can be thus compared with historical or other documentary evidence of climate conditions (e.g. Glaser *et al.*, this volume), either as an aid to the interpretation of the local tree-ring patterns or to provide mutual support for the interpretation or validation of both sources of information.

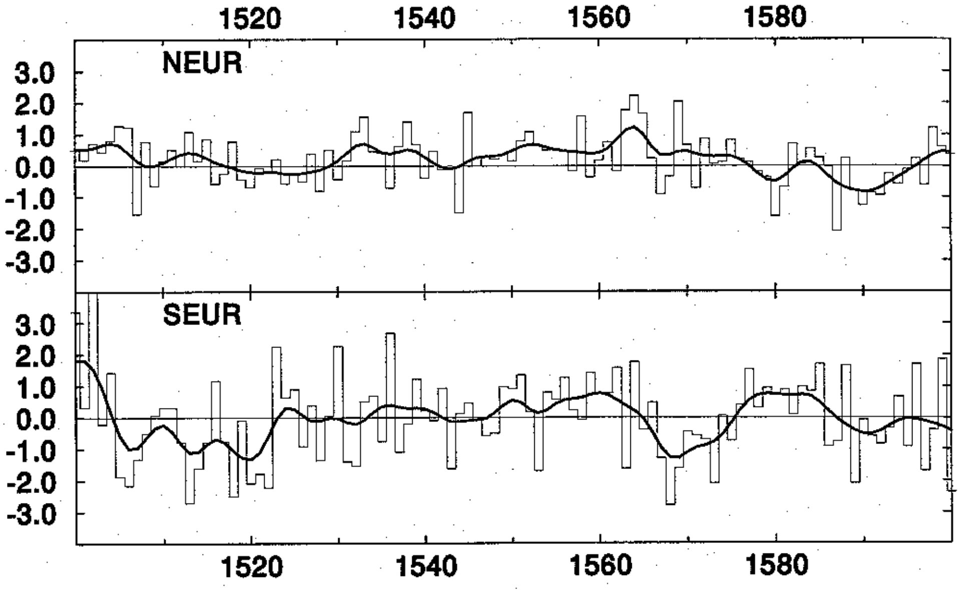

Figure 5. Two large-scale regional average series of maximum-latewood densities (shown as standardised anomalies from a 1901-50 base period) incorporating data from many sites in northern and southern Europe. Annual and decadal timescales of variability are shown for the 16th century.

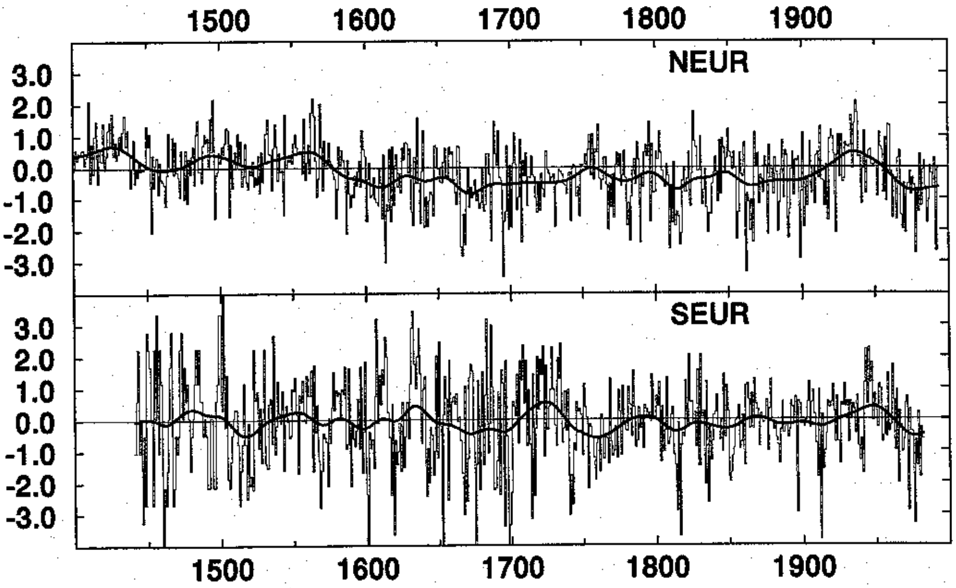

Figure 6. Regional North and South European density series as in Figure 5, but shown over the period 1400 to the present.

The example we show here (drawn from the Doctoral research of Ralph Vogel) uses raw tree-ring width data from the Swiss Plateau, corresponding to the deciduous forest zone in Europe and to the transitional region between deciduous and coniferous forests. Chronologies of mean raw ring-width measurements were constructed for spruce, fir and oak the sources of which were numerous historical buildings (see acknowledgements). At least 100 tree samples were involved in each chronology. The high-frequency (interannual) variability of each chronology, covering the period 1531-1630, was compared with the Pfister (1984, 1998) historical monthly indices of precipitation and temperature. These are deduced precipitation and temperature, month by month, on a scale ranging from +3 to -3, based on a variety of records such as snowcover, freezing dates of lakes, phenological observations, vine harvest records and weather diaries.

The comparison was made using the coefficient of parallel variation or 'Gleichläufikeit'(Eckstein and Bauch, 1969) which measures the level of agreement in the signs of the first differences in two parallel series. This is somewhat akin to a correlation coefficient calculated on extreme high-pass filtered series.

Figure 7 is a graphical representation of the significant associations between the chronologies of the different tree species and the various monthly historical climate indices. This indicates a clear negative relationship between spruce growth and summer temperature and shows a corresponding enhancement of growth associated with above average precipitation in summer. A similar picture is apparent for fir, though growth is enhanced more particularly by cool temperatures in June and perhaps by greater precipitation in April. To some extent in the spruce, but more clearly in the fir, warm winters also appear to promote better growth in the following growing season. This is not associated with wetter winters (which might be thought to enhance soil moisture levels during the following months) but might be related to a lower incidence of severe frosts which have been shown to have greater adverse affects on the growth of fir than spruce (Lenz *et al.*, 1988). Good growth in oak is apparently promoted by cool and wetter late springs. Hence, while it is clear that growth in all chronologies is enhanced primarily when soil moisture stress is low (Kienast *et al.*, 1987), we are able to detect variations in the apparent magnitude and specific timing of intraannual climate variability between the different species. Examining the similarities and differences in the simultaneous growth of a number of species in a region may therefore enable deductions to be made concerning the details of seasonal climate parameters.

4.2. REGIONAL MULTI-SPECIES TREE-GROWTH MAPS

Detailed yearly maps of comparative tree growth along a north/south transect from northern, through central and southern Germany and into Switzerland are currently under construction. So called 'pointer intervals' are first identified within localised groups of data such as originate from a single village or town. Here, these are

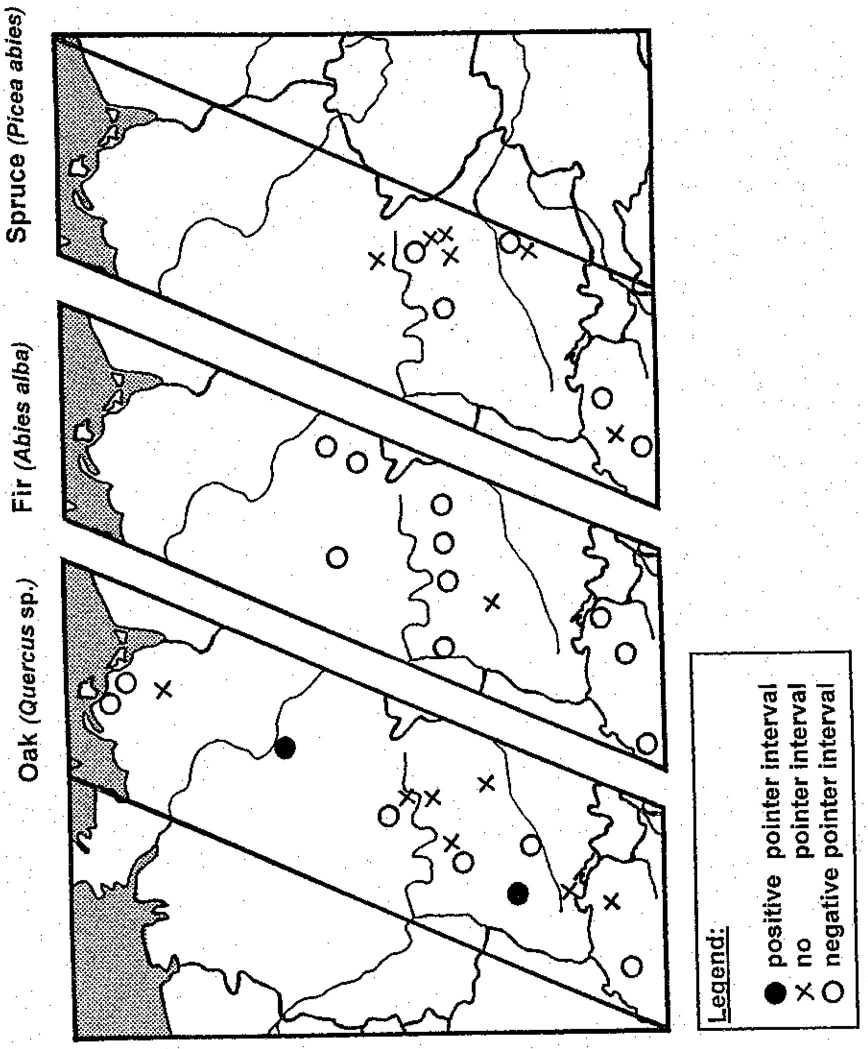

Figure 7. Schematic representation of the high-frequency relationships between Swiss chronologies of various species and the monthly historical temperature and precipitation indices of Pfister (1998), defined over the period 1531-1630 (see text).

defined as years when at least 75 per cent of samples show the same direction of growth (positive or negative) compared to the previous year (Huber and Giertz-Siebenlist, 1969; Schweingruber *et al.*, 1991). Figure 8 shows the spatial pattern of pointer intervals for different species along the transect in 1587. Because the natural ranges of spruce and fir do not extend to lowlands, there are no data for these species in the north. Both spruce and fir display widespread negative growth trends, though more uniformly in the fir. The oak, however, shows no uniform pattern. It is known that frost and drought are able to reduce tree growth synchronously over large areas of Europe (Becker *et al.*, 1990) and severe winter frost is known to cause large-scale decreases in the growth of fir (e.g. Lenz *et al.*, 1988; Müller-Stoll, 1951). In 1929 and 1956, strong outbreaks of cold continental air caused extensive damage to fir in both Switzerland and southern Germany (Becker *et al.*, 1990; Elling, 1993). The growth pattern observed in 1587 is consistent with such an event and can be compared with the synoptic weather pattern for 1587 produced by Jacobeit *et al.* (this Volume). Obviously, further detailed climate interpretation of such tree ring maps require further development of the pointer interval patterns and further work to 'calibrate' and interpret them in the light of recent climate records and additional historical data.

5. Climate Reconstructions Integrating Various Proxies

An attempt to reconstruct mean annual temperatures using the combined information contained in an array of various European climate proxies was made by Guiot (1992). He assembled 23 predictor series. These comprised various tree-ring data: oak ring-width series from Germany, Ireland and Scotland, together with a number of pine and larch series from Italy and France, cedar data from Morocco; data derived from historical sources: Icelandic sea ice records, grape harvest indices for France and Switzerland, and the Pfister (1984) thermal index for Switzerland; several ice-core oxygen isotope records from Greenland; and more direct meteorological observations: the Manley (1974) CET and a southwesterly wind frequency record for London. Most of these predictor series extend back to before the start of the 16th century and a few are long enough to enable reconstructions from before 1100. A principal component regression scheme was used, in which temperatures on short (interannual) and longer timescales were separately estimated and recombined to produce extended reconstructions at 20 locations making up a European grid stretching from 10°W to 20°E and 35°N to 55°N (Guiot, 1992). Here, we present 4 series (2 centred on 52.5°N, at 0 and 10°E; and two on 42.5°N at the same two longitudes - see Figures 9 and 10) that are averages of some of the 20 series but which summarise the salient features of Guiot's original data over western Europe.

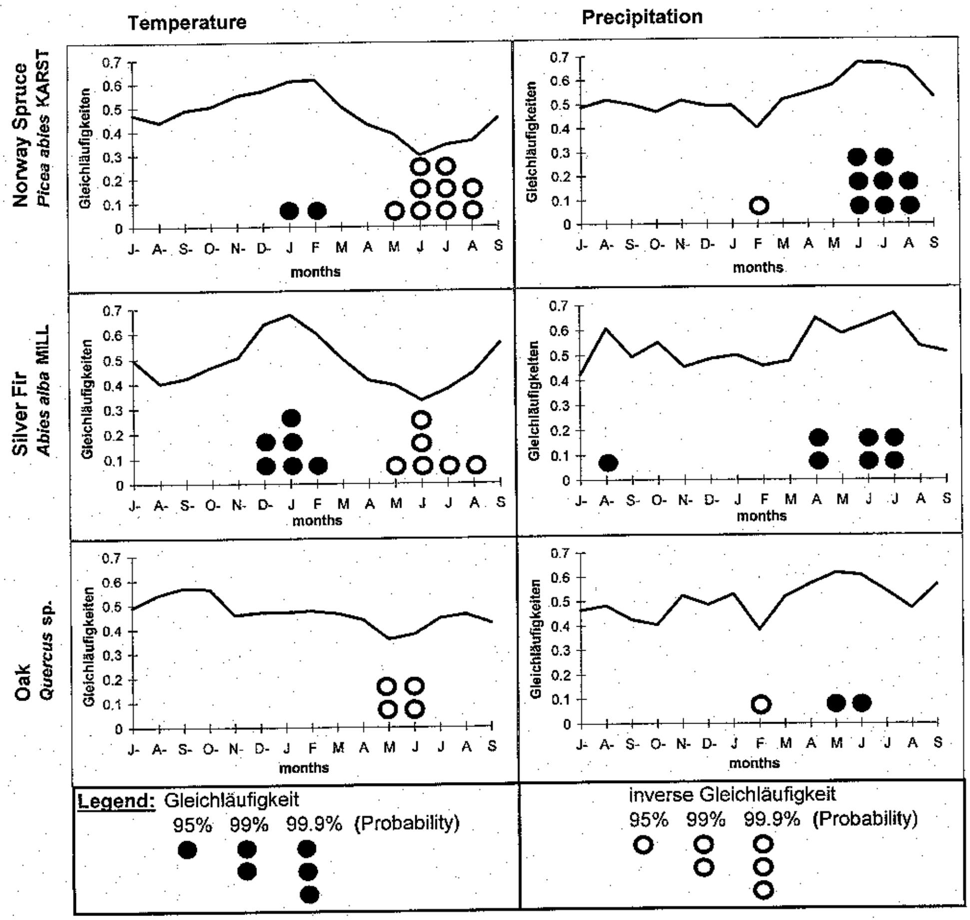

Figure 8. Maps of positive and negative growth anomalies in different tree species distributed over Germany and Switzerland. The maps show the areas of distinct positive or negative growth change between 1586 and 1587 - so called 'pointer intervals'.

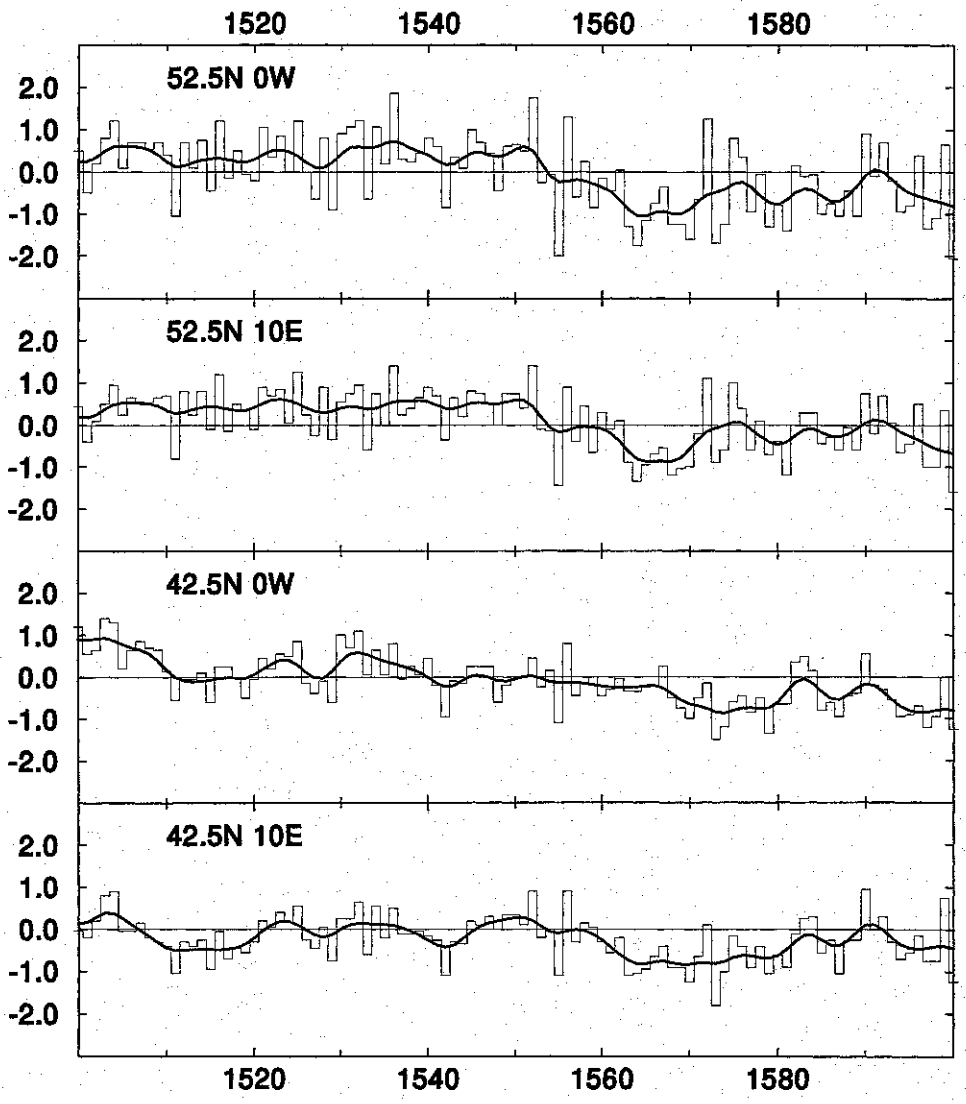

Figure 9. Annual (histograms) and decadally smoothed European regional reconstructions of mean annual temperature during the 16th century from the data produced by Guiot (1992). The predictors included a range of instrumental, historical tree-ring and other high-resolution proxies. The data are anomalies from a 1951-70 base period.

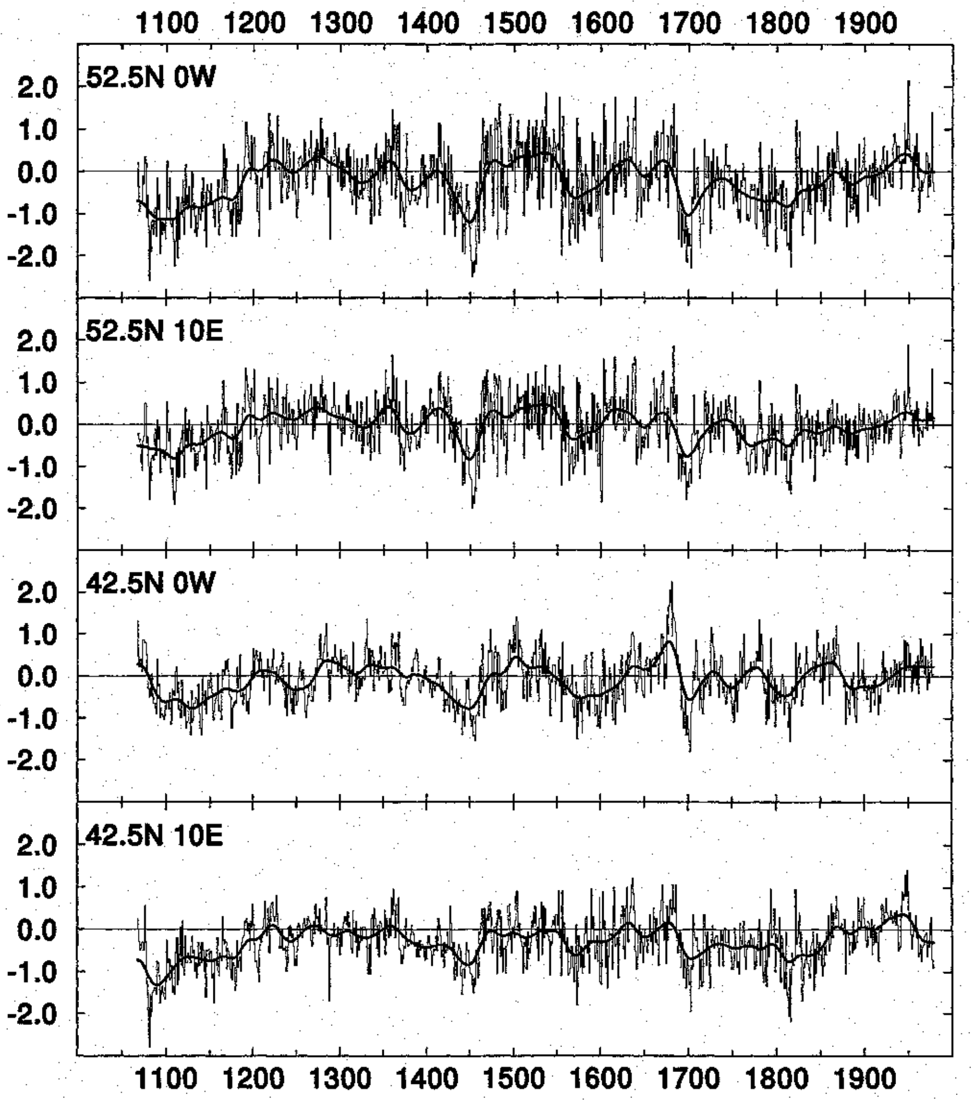

Figure 10. The same European reconstructions shown in Figure 9, but here plotted from 1500.

Greater interannual variability is apparent at the more northern locations, but Figure 9 clearly shows the same general fall in multidecadal average temperatures in the northern and more southwestern series during the third quarter of the 16th century, as was evident in many of the largely independent records we have described. The cooling also appears more abrupt and more severe in the more northern series, accentuated by the greater average warmth reconstructed in the first half of the 16th century in the northern as opposed to southern regions. Note, however, that the late 16th century cooling is barely perceivable in the southeastern area (over the northern Mediterranean). This is consistent with the independent 'southern' European density series (see Figure 5) and other tree-ring reconstructions of Mediterranean regional temperatures (Serre-Bachet *et al.*, 1991) that show northern Italy experienced cool summers between about 1540 and 1570, but little evidence for any pronounced climate shift during the 16th century. The longer term (almost 1000 year) context for the northern and central European mid-century cooling (Figure 10) reveals that it was equalled and even surpassed in cool periods in the mid 15th century and in the few decades centred on about 1700. In the four average series we have made up from Guiot's (1992) data, the latest of these events marks the start of a prolonged (~150-year) period of sustained low annual mean temperatures in all but the southwestern area. In none of them, however, is the 16th century cooling maintained much beyond the end of the century.

6. Conclusions

The various European tree-ring and accompanying data that we have described here, lead us to conclude that there was a marked reduction in average summer, and probably annual, temperatures over much of Europe during the 16th century. In northern Europe and in the Alps, this occurred abruptly at around 1570 and marked the start of a prolonged period of generally cool summers which lasted well into the next century. The magnitude of the cooling was accentuated in northern Europe by virtue of the relatively warm conditions that prevailed in the early 16th century. In eastern Europe (western Siberia), the cooling occurred earlier in the century. Central European summers may have become drier with greater spatial climate variability in the later, as opposed to the first, half of the century. There is evidence that a cooling occurred in southern Europe (northeast Italy) at around 1540, but this was comparatively minor and lasted only until about 1570. Hence the major cooling and climatic shift of the late 16th century was probably most abrupt and marked in north and western Europe and had its southern boundary at the Alps.

Acknowledgements

We acknowledge the support of the European Community (DGXII) Environment and Climate Programme for ADVANCE-10K (under contracts EV5V-CT94-0500 and ENV4-CT95-0127; the Swiss National Science Foundation; the UK NERC. We thank Dieter Eckstein, Hamburg, and Joel Guiot, Marseilles, for kindly providing their original European temperature reconstructions. Ralph Vogel wishes to thank H. Egger (Boll); U. Ruoff, F. Walder (Zurich); R. Kontic (Basel) and P. Gassmann (Neuchâtel) for provision of Swiss tree-ring data and W. Tegel (Singen), A. Billamboz (Hemmenhofen); F. Herzig (München); J. Hofmann (Nürtingen) and K. Heussner (Berlin) for German data. The results presented in Section 4 form part of his doctoral research. Dieter Eckstein and Matti Eronen, Helsinki, make valuable suggestions for improving an earlier version of the manuscript.

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(Received 29 April 1998; in revised form 6 October 1998)