CLIMATIC VARIABILITY IN SIXTEENTH-CENTURY EUROPE AND ITS SOCIAL DIMENSION: A SYNTHESIS

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Abstract. The introductory paper to this special issue of Climatic Change summarizes the results of an array of studies dealing with the reconstruction of climatic trends and anomalies in sixteenth-century Europe and their impact on the natural and the social world. Areas discussed include glacier expansion in the Alps, the frequency of natural hazards (floods in central and southern Europe and storms on the Dutch North Sea coast), the impact of climate deterioration on grain prices and wine production, and finally, witch-hunts.

The documentary data used for the reconstruction of seasonal and annual precipitation and temperatures in central Europe (Germany, Switzerland and the Czech Republic) include narrative sources, several types of proxy data and 32 weather diaries. Results were compared with long-term composite tree ring series and tested statistically by cross-correlating series of indices based on documentary data from the sixteenth century with those of simulated indices based on instrumental series (1901-1960). It was shown that series of indices can be taken as good substitutes for instrumental measurements.

A corresponding set of weighted seasonal and annual series of temperature and precipitation indices for central Europe was computed from series of temperature and precipitation indices for Germany, Switzerland and the Czech Republic, the weights being in proportion to the area of each country. The series of central European indices were then used to assess temperature and precipitation anomalies for the 1901-1960 period using transfer functions obtained from instrumental records. The statistical analysis of these series of estimated temperature and precipitation anomalies yielded features which are similar to those obtained from instrumental series.

Results show that winter temperatures remained below the 1901-1960 average except in the 1520s and 1550s. Springs fluctuated from 0.3°C to 0.8°C below this average. Summer climate was divided into three periods of almost equal length. The first was characterized by an alternation of cool and warmer seasons. The second interval was 0.3°C warmer and between 5 and 6% drier than in the 1901-1960 period. It is emphasized that this warm period included several cold extremes in contrast to the recent period of warming. Summers from 1560 were 0.4°C colder and 4% more humid. Autumns were 0.7°C colder in the 1510s and 20% wetter in the 1570s. The deterioration of summer climate in the late sixteenth century initiated a second period of enlarged glaciers in this millennium (the first having been in the fourteenth century) which did not end until the late nineteenth century.

An analysis of forcing factors (solar, volcanic, ENSO, greenhouse) points only to some volcanic forcing. In order to understand circulation patterns in the sixteenth century in terms of synoptic climatology, proxy information was mapped for a number of anomalous months. Attempts to compare circulation patterns in the sixteenth century with twentieth-century analogues revealed that despite broad agreements in pressure patterns, winters with distinct northeasterly patterns were more frequent in the sixteenth century, whereas the declining summer temperatures from the mid-1560s seem to be associated with a decreasing frequency of anticyclonic ridging from the Azores' center of action towards continental Europe. The number of severe storms on the Dutch

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North Sea coast was four times greater in the second half of the century than in the first. A more or less continuous increase in the number of floods over the entire century occurred in Germany and the Czech lands. The Iberian peninsula and the Garonne basin (France) had the greatest number of severe floods in the 1590s.

The analysis of the effects of climate on rye prices in four German towns involved a model that included monthly temperatures and precipitation values known to affect grain production. The correlation with rye prices was found significant for the entire century and reached its highest values between 1565 and 1600. From the 1580s to the turn of the century wine production slumped almost simultaneously in four regions over a distance of 800 kilometers (Lake Zurich to western Hungary). This had far-reaching consequences for the Habsburg treasury and promoted a temporary shift in drinking habits from wine to beer. Peasant communities which were suffering large collective damage from the effects of climatic change pressed authorities for the organization of witch-hunts. Seemingly most witches were burnt as scapegoats of climatic change.

1. Introduction

It has been known for the last two hundred years that the final decades of the sixteenth century included a period of climatic deterioration. Based on accounts of herdsmen and on the positions of the outer moraines of glaciers reaching low altitudes in the Swiss Alps, the Bernese naturalist and statesman Bernhard Friedrich Kuhn (1762-1825) concluded in his "Essay on the Mechanism of Glaciers" (1787) that towards the end of the sixteenth century an "extraordinary revolution in nature" must have taken place, promoting "alpine glaciers to grow beyond their usual limitations and to extend into cultivated areas". Since then, Kuhn's main hypothesis of a far-reaching forward movement of Alpine glaciers culminating about 1600 has been confirmed by many investigations made in various parts of the Alps (e.g. Holzhauser and Zumbühl, this volume). In recent decades, results of sixteenth-century climate investigations have been included in several important books (e.g. Lamb, 1977, 1982, 1984; Grove, 1988; Mikami, 1992; Bradley and Jones, 1995).

Despite these efforts, many questions still remain unanswered: Was the period of cooling which triggered the rapid growth of Alpine glaciers restricted to central Europe? Was it also felt in the North and in the Mediterranean or even in larger parts of the northern hemisphere? How far and in what way were the final decades of the sixteenth century climatologically different from the times immediately preceding and following them? What might be the underlying shifts in the atmospheric circulation related to this unusual period? Can the underlying natural forcing factors be identified? How, if at all, did the frequency and severity of natural hazards change during the century? How outstanding were the major anomalies such as the severe drought of 1540 compared with those of the instrumental period? These questions are related to processes within the atmosphere, the cryosphere, the hydrosphere, the biosphere and their interaction. But the topics discussed in this volume extend beyond these spheres into the realm of human societies. Many of the fundamental questions in this field have yet to be raised. How did the long-term cooling in the late sixteenth century affect food prices and population trends? Were the impacts restricted to a few isolated crop failures? Did the deterioration of climate affect food production and hence food prices for several years or even several decades? How were these profound changes perceived by people who ascribed extreme natural events to God's punishment or to the acts of evil powers?

In order to tackle this array of questions, it was necessary to interlink preliminary results and data from the natural and social sciences during the research process. This volume is thus more than a mere juxtaposition of papers presented at a meeting. It is the fruit of intensive interdisciplinary cooperation involving the readiness of the participants to become familiar with the objectives, data requirements and the way of thinking of the "other side".

Within the framework of palaeoclimatic reconstruction, three significant types of events need to be distinguished: extreme weather events and natural hazards, decadal climate variations and the so-called "little ages". The latter term refers to centuries-long phases in the Holocene (O'Brien et al., 1995). Such important events take place on three fundamental time-scales: either short-term, per decade or per century. On a centennial time-scale, the sixteenth century belongs to the "Little Ice Age", although whether fully or only partly is still a matter of debate. Porter (1986) maintains that the "Little Ice Age" began around AD 1250. Lamb (1977) confined the "Little Ice Age" to the three centuries from 1550 to 1850. Grove (1988) left the matter open on account of the distribution of data then available; but as a result of the new data which has appeared since then, she is now convinced that the "Little Ice Age" was underway on a global scale by about AD 1250 to 1300 (Grove, submitted). In central Europe it began shortly after 1300 due to a pronounced drop in winter temperatures (Pfister et al., 1996, 1999).

The far-reaching advances of glaciers at the end of the sixteenth century must be viewed on a decennial time-scale and involve such matters as natural climatic fluctuations, air-sea-ice interaction, and solar and volcanic forcing and possibly mankind-induced changes to the land surface. Most extreme events which primarily affect societies, such as storms, floods, killing frosts, droughts, and heat and cold waves, occur on short-term time-scales from hours to years. The great challenge for palaeoclimatic studies is developing methodologies that allow investigations of how changes in the frequency and severity of extreme events are related to changes in average conditions on decennial and centennial time-scales, and how the latter are in turn related to external forcing or internal variability of the climate system. Severe floods in several parts of Europe are discussed in the paper by Brázdil et al. (this volume), whereas the contribution by de Kraker (this volume) investigates changes in the frequency and severity of storms on the coast of Flanders.

Whether the shift in climate in the final decades of the sixteenth century had any impact on the human world has been controversial. Many historians tend to overlook or at least discount the influence of climatic change on human affairs (e.g. Slicher van Bath, 1963; Hoskins, 1968; Abel, 1978; de Vries, 1981). Others believe in its importance, albeit in varying degrees (e.g. Dipper, 1991; Mieck, 1993). In writing about the Mediterranean area the famous French historian Fernand Braudel (1949, 1972) had the impression that "the early sixteenth century was everywhere favored by the climate; the latter everywhere suffered atmospheric disturbances". Swedish historian Gustav Utterström (1955) set out to prove from narrative accounts in chronicles that in Sweden a much milder climate existed towards the end of the fifteenth and in the first half of the sixteenth century, than in the periods before and after. He stressed that a cool and unpleasant period began around 1560, culminating in economically catastrophic years from 1596 to 1603. Utterström was subsequently criticized by the French historian Emmanuel Le Roy Ladurie (1971) for concluding that a direct connection exists between economic trends and meteorological conditions. Economic crises involving high food prices and high mortality rates might have been more likely to have resulted from non-meteorological factors such as plague, wars and social unrest. Le Roy Ladurie maintained that, in order for Utterström to prove his point, he would need to demonstrate, rigorously and with statistics, that these bad years all resulted from more or less comparable meteorological conditions and that they occurred with a higher frequency during the long period in question than in the years before and after. The French historian doubted strongly whether the long-term difference in annual mean temperature of <1°C (which was thought to have occurred within the last millennium) would have had any substantial influence on agricultural yields and other human affairs, even in the pre-industrial world. He argued that "the narrowness of the range of secular temperature variations, and the autonomy of the human phenomena which coincide with them in time make it impossible for the present to claim that there is any causal link between them" (Le Roy Ladurie 1971).

The English meteorologist Hubert H. Lamb (1982, 1988) became Le Roy Ladurie's most prominent opponent. Lamb was convinced that weather and climate had affected human affairs in the past and that humankind would do well to examine some of the lessons provided by nature. U.S. Vice-President Al Gore (1992) took up some of Lamb's arguments although, as a politician, he was well aware that such changes were only some amongst the many causes leading to historical events.

According to Le Roy Ladurie (1971) a conclusive investigation of the impact of climatic variations on societies should involve two steps. Firstly, climate in the pre-instrumental period should be studied for its own sake separately from its possible impacts on societies. In a second step, the evidence obtained would be used to set up models enabling the exploration of the impacts of climatic variations upon economies and societies. He suggested that such a picture of climate without man in the historical period might be reconstructed from data describing the meteorological nature of certain years, seasons, months and days; from long series of wine harvest dates; and, from engravings and paintings representing historical glaciers in the Alps, and that the ultimate goal should be the construction of continuous, quantitative and homogeneous series.

Le Roy Ladurie's recommendation lead the way for historical climatology in the following decades. The focus was placed on different kinds of documentary proxy data which were available in terms of time series. Le Roy Ladurie and Baulant (1980) set up an area-averaged series of grape harvest dates for the period 1484-1879 which they obtained from a hundred local series from western and central Europe. This main series was then used by Burkhardt and Hense (1985) to assess mean temperatures from April to July in Basle (Switzerland) for the period 1484-1768. Lauer and Frankenberg (1986) used documentary evidence concerning the amount and the sugar content of grapes harvested in the Rhineland-palatinate region of Germany to estimate sunshine in May, and summer temperatures from 1550. Lauscher (1985) presented information about grape harvests associated with the mid-sixteenth century weather anomalies for Retz in Austria.

Dendroclimatological reconstructions in Europe so far concern summer temperatures, mainly from northern Fennoscandia close to the northern tree line (Briffa et al., 1990; Briffa, 1992), as well as some from central Europe (Briffa and Schweingruber, 1992). Briffa et al. (1998) recently reconstructed northern hemisphere summer temperatures based on circum-hemispheric networks of temperature sensitive tree-ring density chronologies back to AD 1400. Dendroclimatic evidence from southwestern Europe and northwestern Africa was evaluated by Serre-Bachet et al. (1992). In this volume Briffa et al. present a selective review of tree ring variability and inferred climate changes in Europe during the sixteenth century, comparing tree ring data with various types of non-dendroclimatic evidence.

Some authors have tried to reconstruct climatic patterns based on several kinds of proxy data. Guiot (1992) reconstructed European temperature patterns at selected grid points during the last millennium by using both documentary and tree ring data. Bradley and Jones (1993) compiled a series of summer temperatures from the fifteenth century onwards for all of Europe, combining documentary evidence, glacial and tree ring data.

A focus involved the reconstruction of continuous series of temperature and precipitation indices based mainly on documentary evidence. A methodology using different kinds of proxy data was developed by Pfister (1980, 1988a, 1988b, 1992, 1999) for Switzerland. Similarly Glaser (1991, 1995, 1997) succeeded in deriving an uninterrupted series of temperature and precipitation indices for Germany from the beginning of the sixteenth century to the instrumental period. The density and abundance of high quality data available for Germany is related to the practice of keeping weather diaries, something which spread from the University of Cracow in Poland to German universities in the late fifteenth century (Pfister et al. [2], this volume). Series of indices were also derived for the "Pannonian Basin" i.e. "ancient Hungary" (Rácz, 1992) and for the territory of today's Czech Republic (Brázdil, 1992a, 1996; Brázdil et al., 1996, 1999). The reliability of the series of indices compiled for the central part of Russia and Ukraine (Lyakhov, 1984, 1987, 1988) and for Russia (Borisenkov 1988, 1992; Borisenkov and Pasetskiy, 1988) has still to be ascertained. This is because these Russian scholars were not fully aware of the pitfalls relating to the inclusion of data from non-contemporary compilations such as Hennig (1904) for Europe (see also Bernhardt and Mäder, 1987). Decadal frequencies of extreme temperature and precipitation seasons in Poland were compiled by Sadowski (1991). A list of severe winters in northern Italy was composed by Camuffo and Enzi (1992) for the period 1406-1985 on the basis of the reported freezing of rivers and the Venetian lagoon. Severe winters in Greece were studied by Repapis et al. (1989). Martín-Vide and Barriendos (1995) and Rodrigo et al. (1995) have recently demonstrated that records of rogation ceremonies in Spain are valid indicators for periods of meteorological stress, particularly with regard to crops (see also Pfister et al. [1], this volume). Descriptions of rogation ceremonies had been known since the 1950s but had not been systematically investigated. For Iceland there are very few contemporary sources between 1430 and 1560 because the country was ravaged by epidemics which disrupted society, but some contemporary evidence covers the period 1561-1600 (Ogilvie, 1991, 1992).

2. Setting up Seasonal and Annual Proxy Series of Temperature and Precipitation Indices for Central Europe

2.1. THE APPROACH

Thus far, attempts to set up series of temperature and precipitation indices from documentary evidence have suffered from lack of standardization, and the validity of the resulting series of indices were not verified by statistical analysis. These shortcomings have been a source of doubt for many natural scientists, especially because of the combination of methodological elements from both natural and human sciences. The documentary evidence must be verified as reliable, using normal methods of source evaluation. The data reflecting climate-dependant physical or biological processes (such as the freezing of bodies of water or the times of flowering of plants) must then be calibrated against series of instrumental measurements. The core operation involves classifying temperatures and precipitation for a given month by comparing and cross-checking different types of concurrent, high-resolution natural and documentary proxy data. This comparative interpretation allows the assessment of unequivocal climatic tendencies. It cannot be formulated in mathematical terms because it involves methodological, sourcedependant, ecological and interpretative, individual assessments (Glaser, 1991). The lack of statistical rigor is the main reason why many scientists do not trust the "numbers" obtained from the analysis of documentary evidence. The improved methodology presented in this study incorporates for the first time a statistical testing of indices (Glaser et al., this volume). It is hoped, that in this way the shortcomings which have previously plagued historical climatology for such a long time will be reduced.

Seasonal as well as annual temperature (TI) and precipitation (PI) indices using the same approach were set up for four geographically adjacent countries, Germany, Switzerland, (ancient) Hungary and the Czech Republic. This yielded five temperature and five precipitation series for each country. The validity of these TI and PI series in terms of substitutes for instrumental measurements has been statistically assessed by Glaser et al. (this volume). As may be seen from the analysis of selected long temperature and precipitation series, the loss of information caused by transferring instrumental measurements into indices is surprisingly small (correlation coefficients between 0.86 and 0.93). This has shown that series of indices can be taken as good substitutes for instrumental measurements. The spatial correlations between series of measurements were then compared with those of indices based upon the same series. For temperature, this exercise showed that the coefficients of correlation for the indexed series were 0.01 to 0.15 lower than those obtained from measurements. The overall picture for precipitation was less clear as correlations for some of the indexed series were higher, and some considerably lower than those obtained from instrumental measurements.

In a further step, the correlations of the indexed series from the instrumental period were compared with those obtained from documentary data for the sixteenth century. For temperature, 100% of the spatial correlations involving the series of "documentary data indices" from Germany, Switzerland and the Czech Republic are significant, 40% of them being only slightly below those of the corresponding spatial correlations between "instrumental indices". Most of the coefficients involving ancient Hungary are not significant. For precipitation, 75% of the spatial correlations involving the series of "documentary data indices" from Germany, Switzerland and the Czech Republic are significant, 33% of them being even above those of the corresponding spatial correlations between "instrumental indices" (see Glaser et al., this volume). These results may be seen as a statistical validation of the "hybrid approach" which underlies the construction of indexed series from documentary evidence.

For this paper two area-averaged series - a central European temperature index (TICE) and a central European precipitation index (PICE) - were composed from the individual series from Germany, Switzerland and the Czech Republic using the method of weighted means. Weight factors were calculated according to the share of each country in the total area of 475,000 km^2, i.e. 75% for Germany, 16.6% for

Table I
Correlation coefficients between continuous instrumental temperature and precipitation series (1901-1960) and indexed instrumental temperature and precipitation series (TICEIN and PICEIN)

Series	Winter	Spring	Summer	Autumn	Year
TICEIN	0.89	0.93	0.91	0.94	0.92
PICEIN	0.92	0.85	0.91	0.89	0.90

the Czech Republic and 8.4% for Switzerland. The five TICE series were then calibrated by calculating a central European instrumental temperature series for the period 1901-1960 based upon the series - Frankfurt am Main, Potsdam, Basle and Prague used by Glaser et al. (this volume) - and applying the country-related weight factors to them. Seasonal and annual central European instrumental precipitation series (PICE) were correspondingly derived, all based on series of areal precipitation sums for Germany, Switzerland and the Czech Republic (see Glaser et al., this volume). In the case of the Czech Republic and Switzerland, TI and PI series are not available for the whole of the sixteenth century, especially prior to 1530 (see Pfister et al. [1], this volume). The TICE and PICE series for this earliest period were almost completely derived from those for Germany.

The next step comprised the transformation of the central European instrumental series (1901-1960) into indexed series for temperature (TICEIN) and precipitation (PICEIN) by calculating monthly means (x) and standard deviations These were used for the indexing procedure by taking a threshold of x + 0.75s and/or x - 0.75s for distinguishing between cold (index -1), average (0) and warm (1) months for temperature, and dry (-1), average (0) and wet months (1) for precipitation. Seasonal values ranging from +3 to -3 were obtained by summing up the monthly indices; those for winter included December of the preceding year. Subsequently annual indices ranging from -12 to +12 were obtained by summing up the seasonal indices. Two different series of seasonal and annual values were obtained in this manner.

Table I gives the linear correlation of the continuous instrumental temperature series with the TICEIN series and that of the continuous instrumental precipitation series with the PICEIN series. All values are statistically significant (significance level of 0.05). The loss of information from the continuous to the indexed series is very small. Correlations are somewhat better for temperature than for precipitation except in winter, where the correlation for precipitation is slightly higher. An attempt to derive transfer functions between corresponding instrumental and indexed series (TICEIN, PICEIN) following the approach outlined by Pfister (1988a) in order to estimate temperature and precipitation, yielded the following regression equation:

$$y = a + bx,$$

Table II
Transfer functions between instrumental and indexed series (TICEIN and PICEIN) for the period 1901-1960

Series	Winter		Spring		Summer		Autum		Year	
	a	b	a	b	a	b	a	b	a	b
TICEIN	-0.13	1.21	-0.10	0.69	-0.04	0.66	0.01	0.76	-0.08	0.20
PICEIN	3.44	29.76	2.86	21.27	-0.54	34.73	1.16	34.83	8.15	30.65

Table III
Estimated deviations per decade of TACE (°C) and PACE (%) series in the sixteenth century (reference period 1901 to 1960)

Period	Winter		Spring		Summer		Autum		Year	
	TACE	PACE	TACE	PACE	TACE	PACE	TACE	PACE	TACE	PACE
1500-09	-0.4	12.0	-0.1	-2.0	0.3	-2.3	-0.1	-1.2	-0.1	1.0
1510-19	-1.0	6.6	-0.5	-2.8	-0.1	3.0	-0.7	0.7	-0.6	1.6
1520-29	0.1	9.3	-0.8	1.6	-0.3	10.4	-0.1	10.4	-0.4	9.0
1530-39	-0.2	10.7	-0.5	7.5	0.4	-5.8	0.0	2.1	-0.1	2.4
1540-49	-0.6	8.0	-0.3	-3.8	-0.1	-5.6	0.2	-6.4	-0.2	-3.6
1550-59	0.0	5.2	-0.5	1.7	0.4	-5.3	0.2	3.4	0.0	4.1
1560-69	-0.6	13.4	-0.7	3.0	-0.1	0.9	-0.2	9.8	-0.4	7.0
1570-79	-0.6	8.0	-0.6	6.5	-0.3	4.1	-0.5	20.1	-0.5	11.2
1580-89	-0.3	10.3	-0.6	0.4	-0.5	-0.1	-0.3	5.5	-0.5	4.0
1590-99	-1.2	14.0	-0.6	1.7	-0.5	8.9	0.0	3.8	-0.5	8.3

where y is measured (estimated) temperature (deviation from 1901-1960 average in °C) or precipitation (% of 1901-1960 average), x is the corresponding index and a and b are regression coefficients (Table II).

Seasonal and annual temperature and precipitation anomalies (respectively TACE and/or PACE) from these transfer functions were estimated for sixteenth-century central Europe in terms of deviations from 1901-1960 means. Seasonal and annual TACE and PACE series are presented in Figures 1 and 2. Corresponding temperature (TACE) and precipitation (PACE) series based on decennial means (Table III) were calculated from seasonal and annual anomalies.

2.2. SOME STATISTICAL CHARACTERISTICS OF TACE AND PACE SERIES

Some selected statistical characteristics of TACE and PACE series are presented in Table IV. All seasons and the year as a whole were cooler and wetter in the sixteenth century than in the reference period of 1901-1960. This applies mainly to winter and spring temperatures (cooler by about 0.5°C) and winter and autumn precipitation (about 9.8 and/or 5.1% respectively). Winter temperatures and autumn precipitation are the most variable. With the exception of autumn,

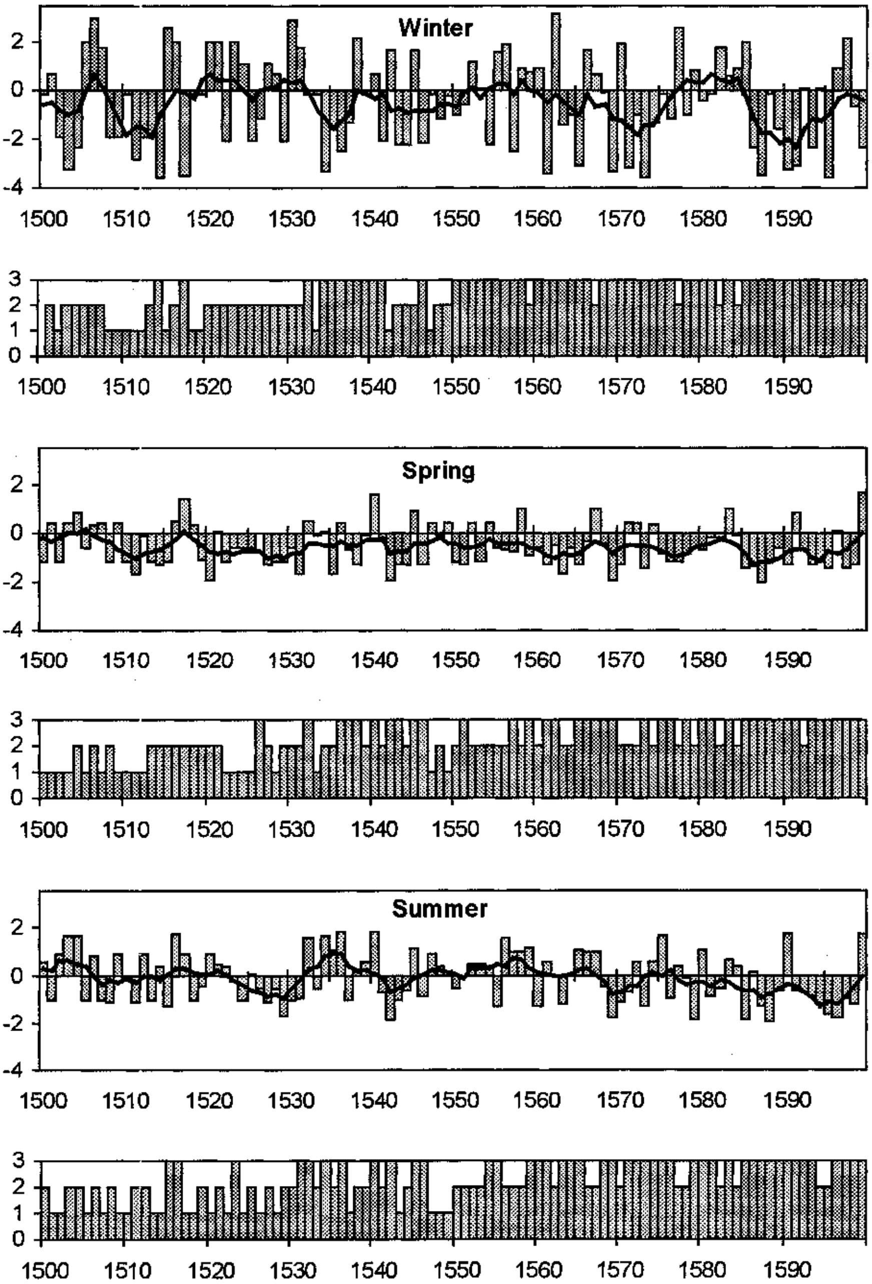

Figure 1. Fluctuations of seasonal and annual TACE anomalies (°C, reference period 1901-1960) smoothed by a 10-year Gaussian filter (always upper panel) and number of countries (number of seasons in the case of annual values, i.e. four seasons for one country) (always lower panel) in the sixteenth century.

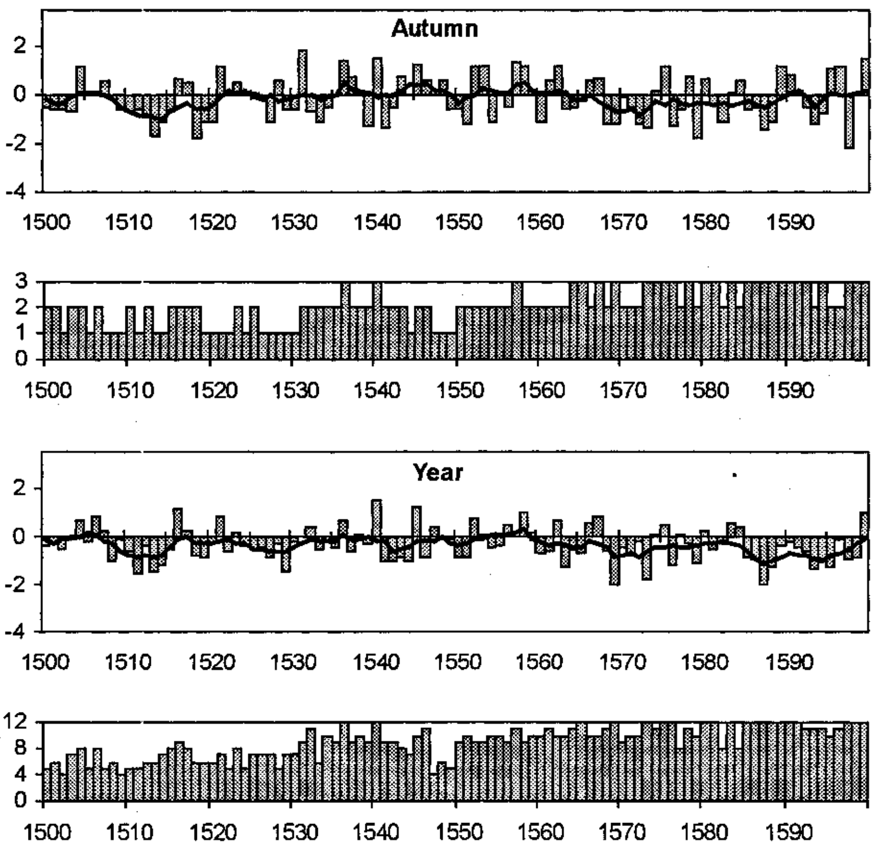

Figure 1. (Continued)

a decreasing tendency for TACE series is typical, although statistically significant only in summer. On the other hand, all PACE series show an increasing trend, albeit not statistically significant. A general decrease of temperatures and increase of precipitation confirms the hypothesis about deterioration of climatic patterns in the second half of the sixteenth century (see e.g. Lamb, 1984).

The frequency distribution of TACE and PACE series presented in Figure 3, shows that seasonal and annual distributions are different from the Gaussian ones, as well as from coefficients of skewness and kurtosis (Table IV). TACE series show a positive and PACE series a negative asymmetry, while all series studied are characterized by negative kurtosis (for the Gaussian distribution, both coefficients are zero). This can signal different climatic patterns during the sixteenth century as well as an overestimation or underestimation of corresponding TI or PI values based on documentary evidence.

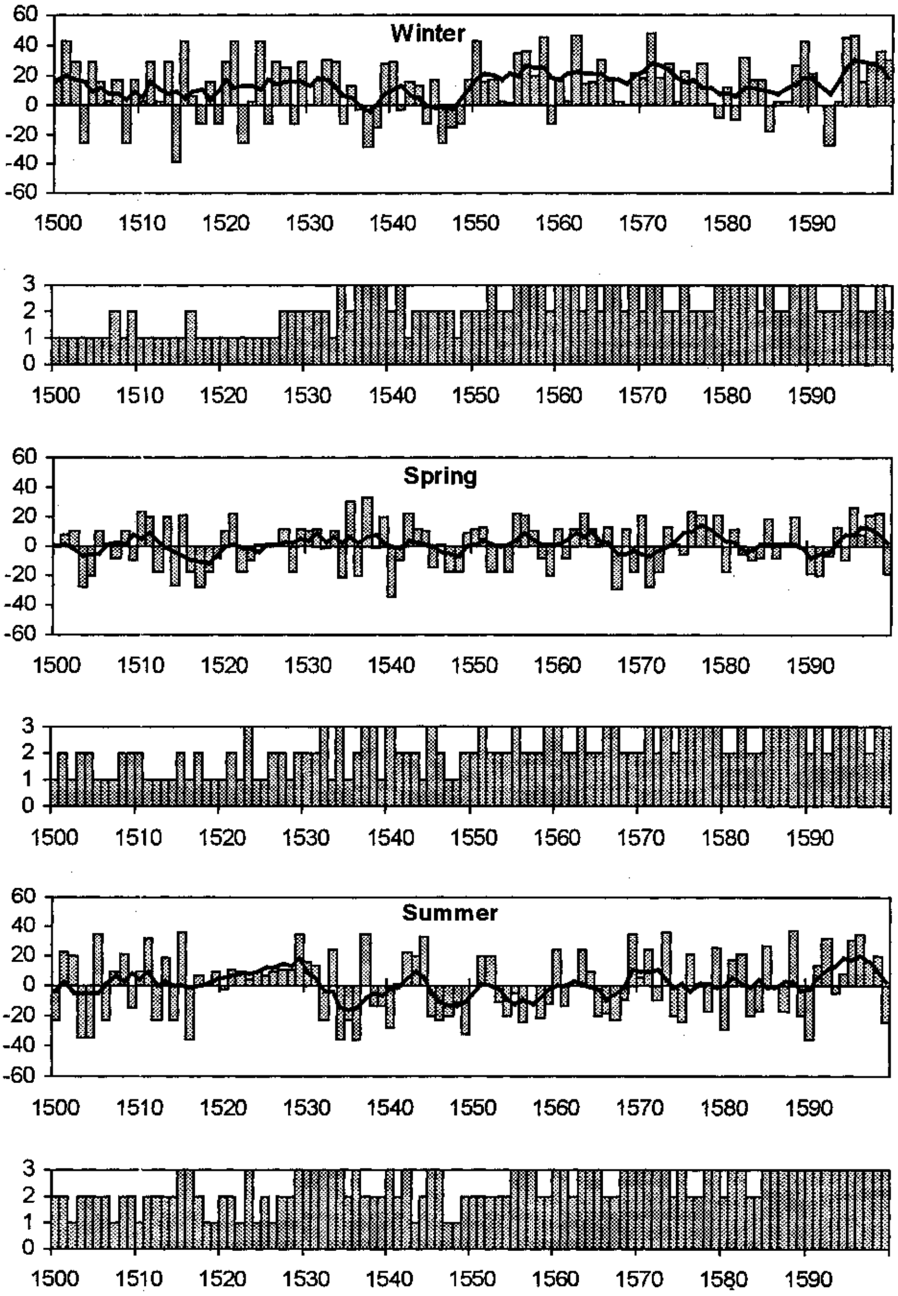

Figure 2. Fluctuations of seasonal and annual PACE anomalies (%, reference period 1901-1960) smoothed by a 10-year Gaussian filter (always upper panel) and number of countries (number of seasons in the case of annual values, i.e. four seasons for one country) (always lower panel) in the sixteenth century.

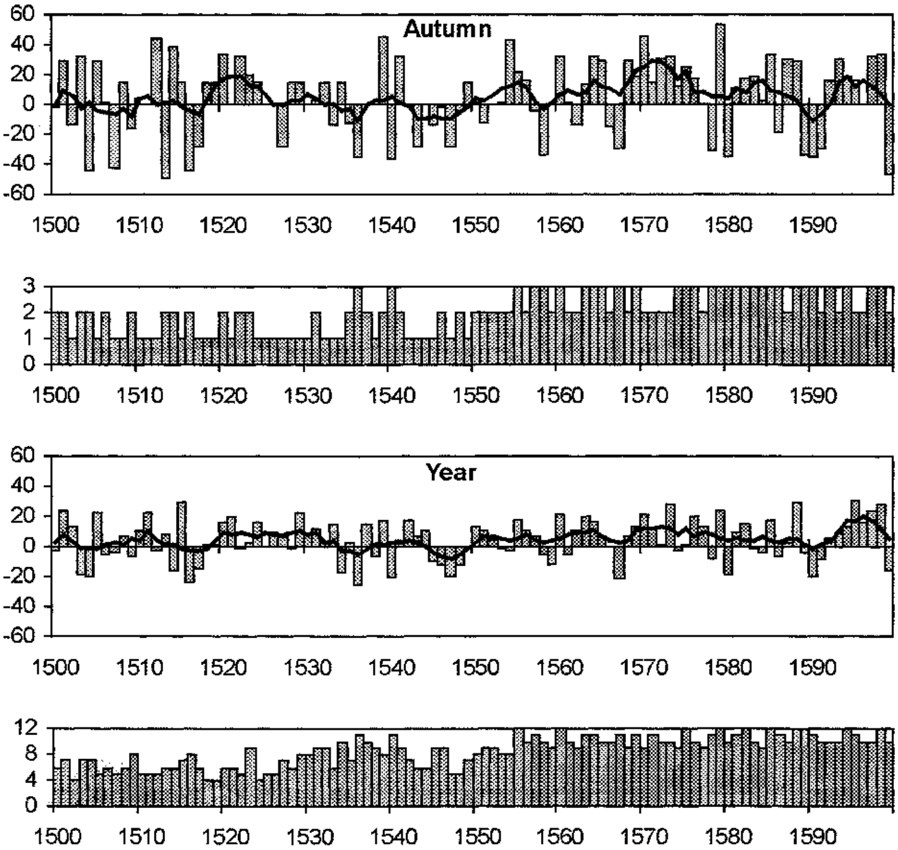

Figure 2. (Continued)

Table IV

Selected statistical characteristics of TACE and PACE series during the sixteenth century (x = mean, s = standard deviation, cs = coefficient of skewness, ck = coefficient of kurtosis, lt = linear trend per 10 years.; x, s, lt in °C for TACE, in % for PACE). Bold values of lt are statistically significant for level of significance 0.05.

	Winter		Spring		Summer		Autum		Year	
	TACE	PACE	TACE	PACE	TACE	PACE	TACE	PACE	TACE	PACE
x	-0.5	9.8	-0.5	1.4	-0.1	0.8	-0.1	5.1	-0.3	4.5
s	1.9	20.1	0.9	16.5	1.1	21.6	0.9	24.4	0.7	13.8
cs	0.02	-0.34	0.53	-0.20	0.15	-0.01	0.15	-0.38	0.19	-0.20
ck	-1.12	-0.53	-0.52	-1.09	-1.15	-1.25	-0.85	-0.62	-0.06	-0.71
Lt	-0.04	0.96	-0.03	0.44	**-0.06**	0.35	0.01	0.91	-0.03	0.64

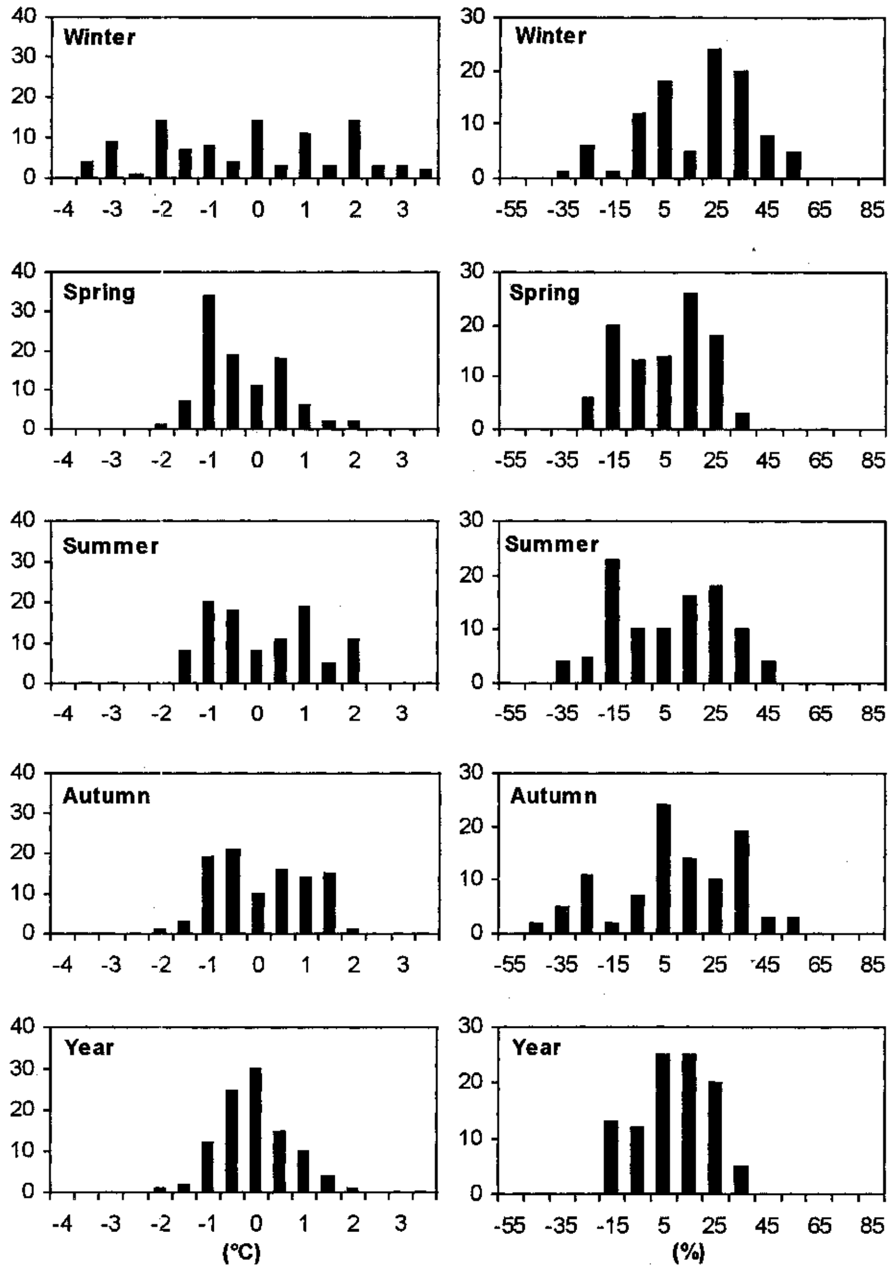

Figure 3. Frequency distribution (%) of seasonal and annual TACE (left column) and PACE (right column) series in the sixteenth century. On the x-axis the upper limit of the corresponding interval is given.

The occurrence of cyclic components in the TACE and PACE series was investigated using the method of power spectrum analysis by Blackman and Tukey (1958). Corresponding normalized power spectra are shown in Figure 4. The significance level of 95% is exceeded in the autumn TACE series although only for a period of 4.5 years; other non-significant peaks in power spectra show similar pictures. In the spring, summer and annual TACE series the clearly expressed period of 7 years is similar to the 7.7 years found to be the most frequent by Schönwiese et al. (1986) in their analysis of 51 central European temperature series in the period 1881-1980. A time span of about three years is dominant for the winter, summer and annual PACE series, corresponding with periods of 3.0 - 3.3 years found in the central European series of areal precipitation sums (Brázdil, 1986, 1992b). The period of 2.2 years (similar to the autumn PACE series) appears in the PACE series based on the sequence of all seasonal values that corresponds to the quasi-biennial cycle belonging to the clearest cycles in the meteorological time series (see e.g. Brázdil and Zolotokrylin, 1995). These results confirm that TACE and PACE series express analogous cyclical features known from the analysis of instrumental series.

3. Temperature and Precipitation Fluctuations During the Sixteenth Century

TACE and PACE anomalies per decade (Table III) are presented along with the fluctuations of TACE (Figure 1) and PACE series (Figure 2). The discussion includes evidence for other European countries based on published literature as well as tree ring analysis results (Briffa et al., this volume).

3.1. WINTER

Winter temperatures in sixteenth-century central Europe were below the 1901-1960 average except in the 1520s and the 1550s (Table III). An almost uninterrupted sequence of cold winters stands out from 1586 to 1595, only the winters of 1592 and 1594 being slightly above average. Temperatures in this interval may have been -2.0°C below the 1901-1960 mean. This almost matches the severity of the periods 1691-1700 and 1886-1895 (Pfister, 1999) which were the coldest decades in Switzerland in the last five centuries. Somewhat shorter clusters of severe winters occurred from 1508 to 1514 and again from 1571 to 1576. Winters, in general, seem to have been somewhat wetter than in the referenceperiod throughout the century, in particular in the 1590s. This is puzzling as very cold winters have been found to be predominantly dry in sixteenth-century Switzerland. It remains unclear whether precipitation north of Switzerland was actually more frequent and abundant, or whether the apparent difference results from different interpretations of the documentary evidence. Snowy winters in the

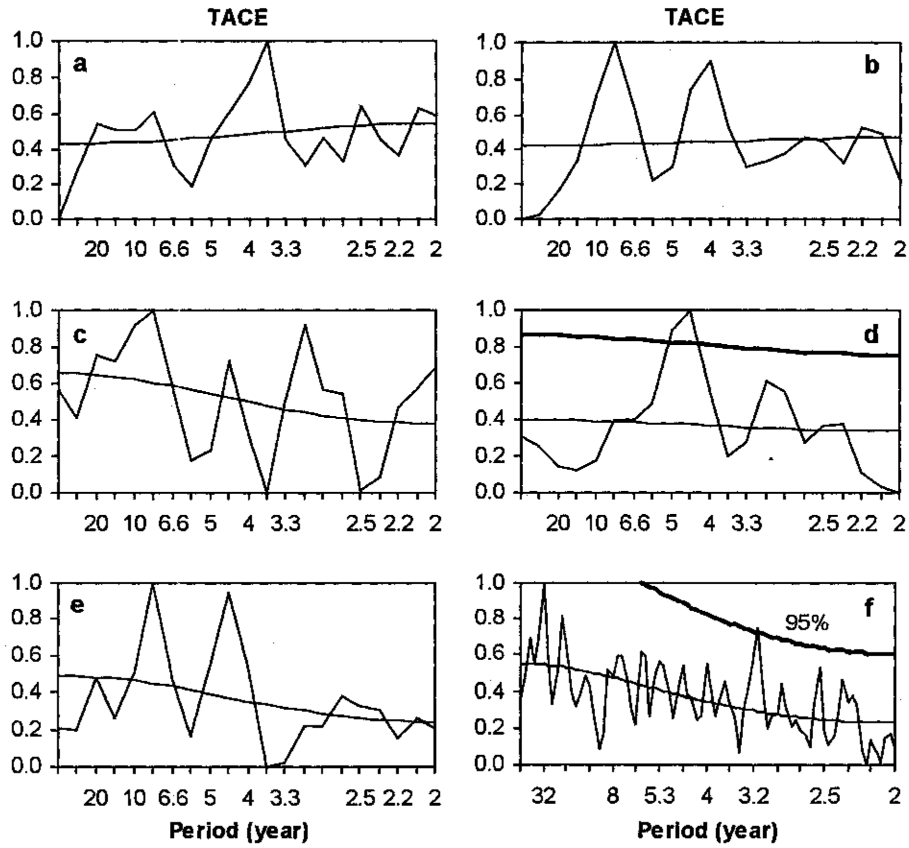

Figure 4. Normalized Blackman and Tukey power spectra of seasonal and annual TACE and PACE series: a) winter, b) spring, c) summer, d) autumn, e) annual, f) series consisting of all seasonal values in corresponding time sequence. Full line denotes level of red noise, bold line 95% significance level.

German and Czech records were coded wet, while wetness was assessed from the Swiss records by the number of days with precipitation. Taking this criterion for northern central Europe, none of the careful weather diaries that were kept between 1500 and 1530 supports the notion of wetter winters (Pfister et al. [2], this volume). The characteristics of winters during the period 1585-1600 were derived from the meticulous weather diaries kept by Tycho Brahe (1546-1601) on the Danish Sound island of Hven and by David Fabricius (1564-1617) in eastern Friesland. The picture of winter climate obtained from these two first-class sources is coherent (Lenke, 1968): The winter half-year (October to March) was more often dominated by winds from northeasterly directions than in the period 1891-1930 which was used as a reference because more recent data were not available.

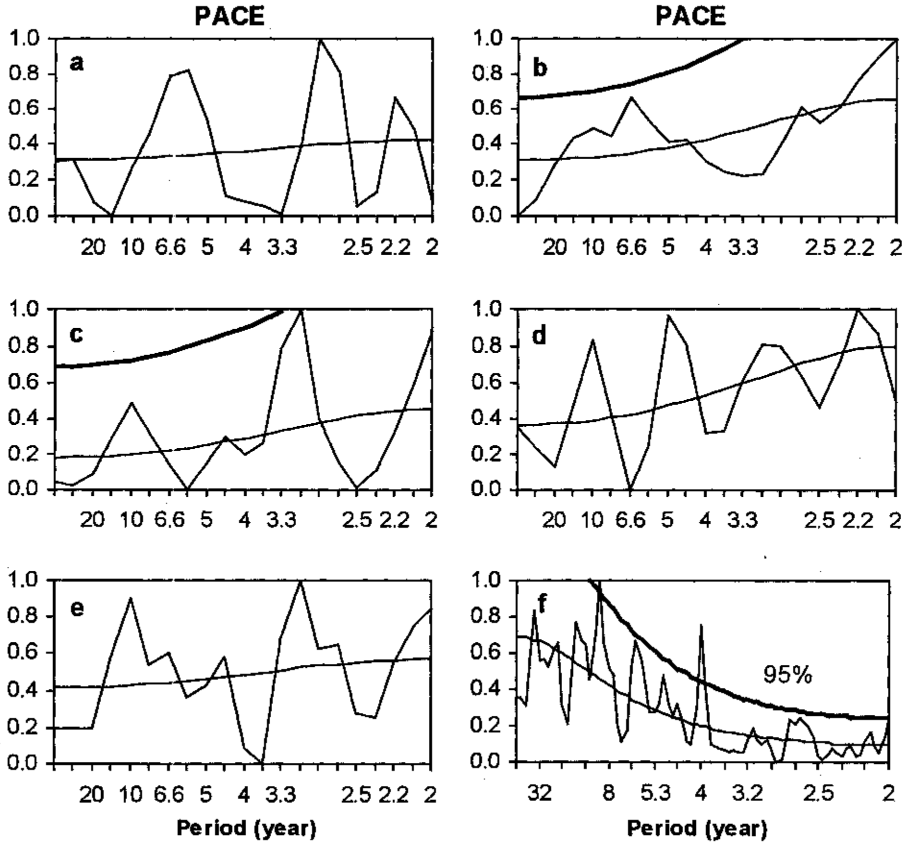

Figure 4. (Continued)

Accordingly, days with precipitation were less frequent and a greater percentage of precipitation fell in the form of snow. This tendency agrees with the result obtained from the detailed observations made by the naturalist Renward Cysat (1545-1613) in the Swiss city of Lucerne, where winters were also drier and snowier than present.

Sixteenth-century central European winters can be compared with ice conditions in the western Baltic described in the ice winter index (IWI) developed by Koslowski (1989) and extended to the period 1701-1993 (Koslowski and Glaser, 1995) and 1501-1995 (Koslowski and Glaser, 1999). The IWI is based on the accumulated two-dimensional ice volume which is divided into seven classes and has values between 0 and +/-3. A good example of the coincidences of winter ACE and IWI with the significant coefficient of correlation of 0.70 is seen in Figure 5.

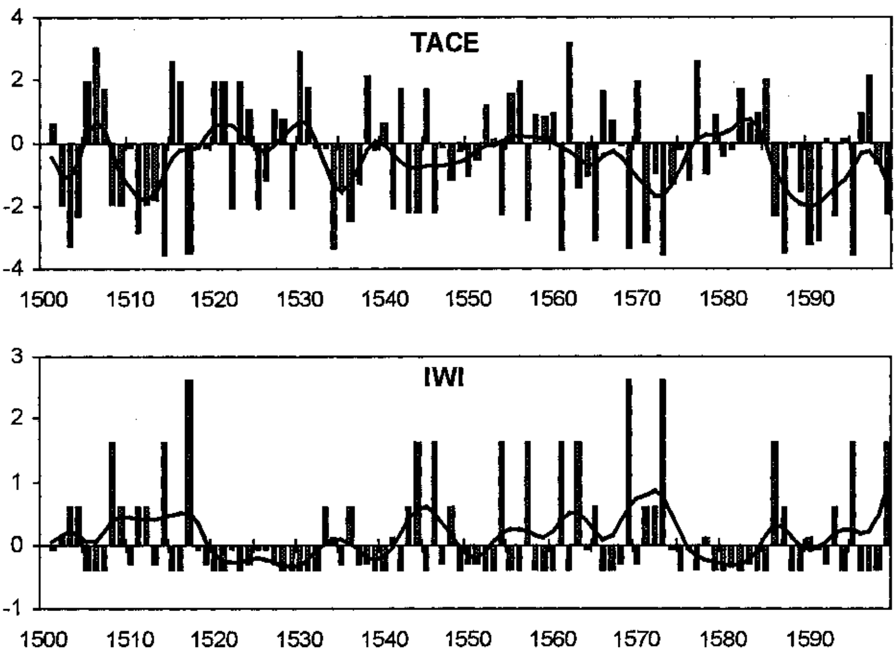

Figure 5. Fluctuations of winter TACE (°C) and IWI anomalies (reference period 1901-1960) smoothed by a 10-year Gaussian filter in the sixteenth century. Data of IWI were derived from Figure 2 in Koslowski and Glaser (1999).

Although this review is focused primarily on continental Europe, it is interesting to note what is known regarding conditions in Iceland in the sixteenth century. As discussed by Ogilvie (1984, 1992, 1996) the sea ice reaching the coasts of Iceland in certain years has long been considered an extremely valuable potential proxy climate indicator for winter severity. Conditions regarding the ice are summarized as follows by Ogilvie and Jonsdottir (1996). The ice consists mainly of either winter ice from the seas north of Greenland, old ice from the Arctic sea, or icebergs calved from Greenland glaciers. Causes of the presence of sea ice off Iceland are a complex amalgam of variations in ocean currents and atmospheric circulation, i.e. more specifically, the quantities of ice present at any given time in the East Greenland current; variations in salinity and sea-surface temperatures in Denmark Strait and the Iceland Sea; and, prevailing local winds. From a contemporary Icelandic source containing weather and sea-ice data, Gottskalsannal, Ogilvie (1991) concludes from the frequent presence of sea ice on the coast that the 1560s were mainly cold. The 1570s, by contrast, were described as mainly mild in this source. Two important treatises on Iceland, *Qualiscunque descriptio Islandiae* written by Oddur Einarsson in ca. 1589 and *Brevis Commentarius de Islandia* written by Arngrímur Jónsson in 1592, contain interesting descriptions of sea ice (Ogilvie, 1992). It may be inferred from these accounts that the climate in the 1580s was severe due to the presence of sea ice. Several mainly non-contemporary Icelandic sources refer to cold years in the 1590s (Ogilvie, 1991).

Winter episodes of heavy rain leading to excessive flooding were unusually frequent in Spain during the last 15 years of the sixteenth century (Brázdil et al., this volume; Glaser et al., this volume). On the island of Crete, five out of eleven winters from 1586 to 1596 were very severe and three were severe. Snow fell down to the coast during three of these winters. In 1595, snow and rain fell almost continuously for three months. Conversely, drought in 1596 was so extreme that many cattle died (Grove and Conterio, 1995). The unusual frequency of wet and cold winters in the eastern Mediterranean during the decade around the 1590s points to a southward displacement of the polar front jet stream.

3.2. SPRING

With the exception of the 1500s, decennial spring temperatures in central Europe fluctuated from 0.3 to 0.8°C below the 1901-1960 average. The 1520s and the 1560s were the coldest decades, followed by those from the 1570s to the 1590s. It seems that warm springs were particularly rare in the sixteenth century (Figure 1). Precipitation per decade fluctuated marginally around the 1901-1960 average (Figure 2). The Swiss series indicates that spring in southern central Europe was somewhat drier than farther north (Glaser et al., this volume). In Spain this season was dominated by dry spells throughout the century except in the 1590s when excessive rainfall and flooding are reported from many places (Barriendos and Martín-Vide, 1998).

3.3. SUMMER

As far as summer temperatures are concerned, the sixteenth century is clearly divided into three periods of almost equal length. The first two decades were characterized by an alternation of cooler and warmer summers compared with the 1901-1960 reference period. A sequence of cooler summers stands out from 1526 to 1531. The summer of 1529 was among the coldest and wettest of the last five centuries (Pfister et al. [2], this volume). Summers in the second period from 1532 to 1567 were 0.2°C to 0.3°C warmer than in the reference period 1901-1960. This is mainly connected to two clusters of warm and mostly dry summers (1534-1536 and 1556-1559). On the other hand a cluster of cool and wet summers appeared in 1541-1544. In the last third of the century summer temperatures were about 0.4 °C below the 1901-1960 mean (Table III). This cooling was connected with the cluster of 14 summers from 1585 to 1598 when only two, that of 1586 and especially that of 1590, were warmer than the 1901-1960 average. The uninterrupted sequence of eight cool summers from 1591 to 1598 may have been unique in the last 500 years (Pfister, 1998). The overall cooling trend began in the mid-1550s and went on with varying ups and downs for forty years up to 1596. Following this extremely cold and wet anomaly, summer temperatures began to rise gradually (Figure 1). To some extent, trends in precipitation mirror those of temperature, as warmer summers correspond more or less to drier summers and vice versa. During the first third of the century a long-term rise in summer precipitation culminating in 1529 is observed. Not a single even moderately dry summer was recorded from 1521 to 1531 (Figure 2). In the second third of the century summers, on an average, were 6% drier than those from 1901 to 1960. Rainy summers were rare during this period. Dry summers were frequent and repeatedly occurred in clusters (e.g. 1534-1536, 1545-1549). In the last third of the century summers were 4% wetter than those in the 1901-1960 period (Table III). This was mainly due to clusters of rainy summers, in 1569-1573 and 1591-1598 (Figure 2). Analyses of weather diaries show that the excess of rainy days in the first and the last third of the century occurred mainly in mid-summer, especially in July (Pfister et. al. [2], this volume). The wetness anomalies between 1585 to 1598 were seemingly more pronounced in Switzerland than farther north. This could reflect frequent upstream blocking along the northern slope of the Alps with prevailing upper-level northwesterly winds leading to abundant snow-fall. According to the Swiss naturalist Renward Cysat, most of the summer rains in the 1590s were cold; it snowed "almost every fortnight" in the Alps. Cysat also mentions that local (i.e. thermal) thunderstorms rarely occurred during that time (Pfister, 1988a). This corresponds very well with the results obtained by Lenke (1968) from the Fabricius weather diary written in eastern Friesland during the same period.

Comparison of summer TACE with other proxies is presented in Figure 6. The summer TACE series shows the best fit with the series of April-July temperatures for Basle reconstructed by Burkhardt and Hense (1985) according to the series of grape harvest dates in western and central Europe by Le Roy Ladurie and Baulant (1980). The significant coefficient of correlation between these two series is 0.64. The body of tree ring evidence presented by Briffa et al. (this volume) agrees well with the summer TACE series (Figure 6) although the correlation between the two series is not significant (0.10). In Fennoscandia the cooling in the first third of the century was somewhat less pronounced than in central Europe. Warm summers prevailed in the second third of the century. After the mid-1560s a sharp cooling marked a shift towards a prolonged period of cool weather. The magnitude of the cooling was accentuated in northern Europe by virtue of the relatively warm conditions that had prevailed in the early sixteenth century. The Alps formed the southern boundary of the region in which the temperature dropped pronouncedly; there is little evidence for a major cooling in southern Europe based on tree rings. Two extremely cold episodes are documented in the memory book of Jeronim Saconomina, a Catalan lawyer in Girona (Catalonia). On 5-6 June 1586, heavy

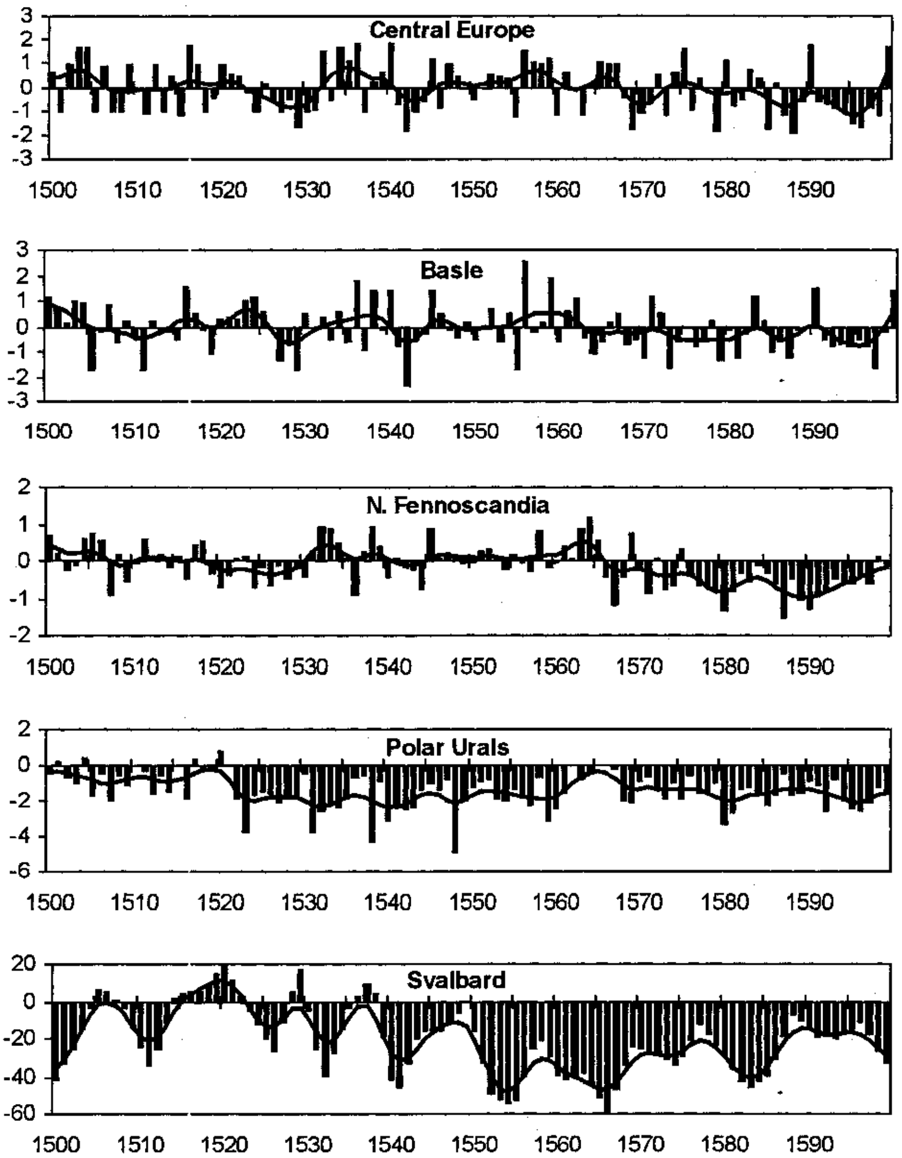

Figure 6. Fluctuations of anomalies of summer TACE, April-July Basle temperatures (see Burkhardt and Hense, 1985), summer temperatures from tree ring records in Fennoscandia and in the polar Urals (°C) and a melt-layer record from Spitsbergen (see Briffa et al., this volume) smoothed by a 10-year Gaussian filter in the sixteenth century. Reference period 1901-1960.

snowfall was recorded in the town (98 m above sea level) and in the nearby mountains (1000-1700 m above sea level). Such an extreme cold spell at this time of the year has never occurred since. A second rainy and cold episode followed from the 2nd to the 4th of July 1594. Snow fell in Montseny (1710 m above sea level) and in the Canigo Mountains (2750 m above sea level) (Barriendos, pers. comm.).

The cooling of summers in the late sixteenth century was a large scale phenomenon. It began around 1560 in southern Europe, in the late 1560s in Switzerland and around 1575 in Scandinavia. The timing does not coincide between Fennoscandia and the Alps on the one side and adjacent regions of northern Europe on the other (see Briffa et al., this volume). Bradley and Jones (1993) also refer to the rapid decline of summer temperatures after 1560 based on series compiled from other European proxy data. A rapid cooling is observed around 1520, i.e. almost synchronous with central Europe (Figure 6), in a tree ring series from the polar Ural Mountains and in a melt-layer record from the Norwegian island of Spitsbergen. However, the second, more pronounced cooling of the mid-1560s is not reflected in these two series. On the contrary, the cooling on Spitsbergen continued after 1530 to the late 1560s, i.e. during the period of warm summers in Fennoscandia and central Europe. In the subsequent period of cooling in Fennoscandia and central Europe a slight warming is observed on Spitsbergen.

In a longer, millenial context the abruptness of the sixteenth-century cooling events in both Fennoscandia and the Urals was unprecedented, with the possible exception of a rapid cooling noted in the Fennoscandia record in the first half of the twelfth century (Briffa et al., this volume). In central Europe, this cooling period is unique, more for its long duration than for its abruptness, at least in the last 700 years (Pfister, 1988b, 1992; Glaser, 1997).

3.4. AUTUMN

The most pronounced cold phase stands out between 1509 and 1520 when 10 of 12 autumns were below the 1901-1960 average. The negative anomaly of the first decade is 0.7°C. As may be concluded from the analysis of Marcin Biem's (ca. 1470-1540) weather diary (Pfister et al. [2], this volume), "frost" in the sense of freezing of water and/or the ground was 11% more frequent in Cracow (Poland) in the first third of the century than in the twentieth century. From the early 1520s to the mid-1560s temperatures fluctuated around the average with the warmest decade of autumn in the 1540s. A cooling is then noted which is synchronous with that in spring and in summer, although it is less pronounced and does not include the 1590s (Figure 1). Variations in precipitation are more pronounced. Three wet periods stand out: a minor one between 1518 and 1524, a very pronounced one from1568 to 1576 and a shorter one in the 1590s (Figure 2). During the 1570s precipitation was as much as 20% above the 1901-1960 average (Table III).This is by far the largest anomaly of precipitation per decade in the sixteenth century. In Switzerland, precipitation in the 1570s was only 4% above the 1901-1960 average. This resulted from frequent wet spells in October, while November was somewhat drier than nowadays (Pfister, 1988b).

3.5. ANNUAL AVERAGE

Annual averages integrate the seasonal trends into a composite picture. They may mask or intensify the elements which are needed for an analysis depending on whether the object is to search for forcing factors and for impacts on the human world or to compare past trends to recent ones. Annual values are needed as a yardstick for the greenhouse debate. From this point of view attention must be given to two features (Figure 1). Firstly, only a few years were considerably warmer than the 1901-1960 average, for instance 1540, during which the belt of Mediterranean climate was expanded into central Europe for about ten months (Glaser et al., this volume; Jacobeit et al., this volume). Secondly, and more importantly, the warm years always alternated with cold ones, even during the warm period from 1530 to 1560. Thus the alternation of warm and cold years is entirely different from the pattern observed in the 1990s when the cold years disappeared (Houghton et al., 1996).

During the period 1500-1530 annual temperatures were 0.3°C below the 1901-1960 average (Table III). This was primarily due to the cold decade of the 1510s, to a lesser degree of the 1520s. The thermal deficit in the 1510s must be credited mainly to winter and autumn and to a lesser degree to spring. In the 1520s, spring and to a lesser degree summer were colder than 1901-1960. The three decades 1530-1560 were nearly as warm as the period 1901-1960 in central Europe. A thermal deficit in winter and spring was almost compensated by an excess in summer and to a lesser extent in autumn. From 1560 to 1600 annual average temperatures were 0.5°C below average. The coldest seasons in the 1560s and 1570s were winter and spring, in the 1580s spring and summer, and in the 1590s winter and to a lesser extent spring and summer. Analysis of the Fabricius diary (1585-1612) shows that frosts were at most 27 days later, and 37 days earlier than 1891-1930 (Lenke, 1968). In Spain a greater number of cold months was recorded between 1560 and 1590 (Barriendos, pers. comm.). The cold episodes in the 1590s mainly affected the eastern Mediterranean (see Chapter 3.1.).

Annual TACE series are significantly correlated with grid-point temperature series derived from different kinds of documentary evidence for Europe (Guiot, 1992). With four selected grid-points, correlation coefficients are between 0.50 for that of 10°E, 45°N and 0.29 for that of 20°E, 50°N. All four grid-points show a dramatic onset of cooler patterns in the 1560s (Figure 7), although, with the exception of the most southern selected grid-point, there is a relatively quick return

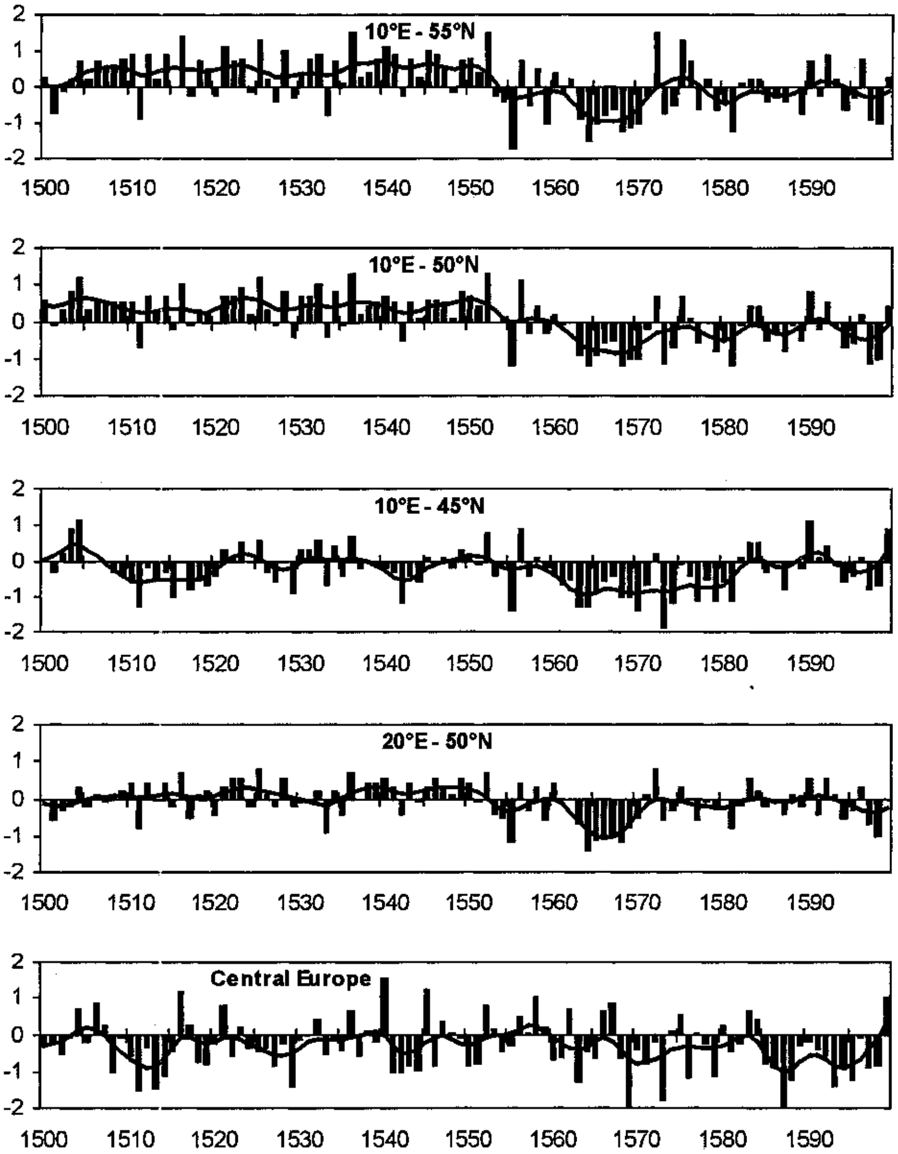

Figure 7. Fluctuation of annual anomalies of grid-point temperatures (°C) derived from European documentary evidence (Guiot, 1992) and TACE series smoothed by a 10-year Gaussian filter in the sixteenth century; reference period 1901-1960.

to average values. There is also a continuous period of positive anomalies between the 1500s and the 1550s which does not correspond with annual TACE.

Precipitation was above the 1901-1960 level throughout the century except in the 1540s. Particularly long wet periods with virtually no dry years occurred from 1518 to 1533, from 1568 to 1577 and again from 1592 to 1598. The excess of 4% precipitation between 1500 and 1530 compared with 1901-1960 is almost entirely due to the wet winters, summers and autumns of the 1520s. From 1530 to 1560 precipitation was only 1% above the 1901-1960 level. From 1560 to 1600 it rained 7.6% more; winter and autumn were the wettest seasons during the first three decades and in the 1590s, winter and summer.

In summary, from 1560, coldness and wetness in central Europe increased in all seasons and this tendency culminated between 1587 and 1597 (c.f. Figures 1 and 2). A recent study focusing on the climatic interpretation of extreme temperature anomalies during the last five centuries in Switzerland concludes that cold and dry anomalies associated with persistent blocking anticyclones over the North Sea or Scandinavia and advection of cold and dry continental air masses (negative mode of the North Atlantic Oscillation [NAO]) significantly increased after the mid-1560s (Pfister, 1999; Heino et al., 1998). This tendency is reflected in a popular dictum in the alpine canton of Valais wherein the chilly northeasterly wind known as "Bise", said to be unknown previously, was seen as a divine punishment for the increasing tension between Catholics and Protestants in Switzerland in the late sixteenth century (Pfister, 1988b).

4. Synoptic Interpretation of Selected Climatic Anomalies

Attempts to compare circulation patterns in the sixteenth century with twentieth-century analogues have been made by a group of synoptic climatologists (Jacobeit et al., this volume). For a number of anomalous seasons in the sixteenth century the known characteristics of European weather patterns and their sequences allowed an inference of the prevailing processes of lower tropospheric advection of typical air masses and the assessment of the position and strength of major surface pressure centers. The results show that there are broad coincidences between the sixteenth and the twentieth centuries: pressure patterns associated with a positive mode of the NAO dominated during *warm winters* in the sixteenth as well as in the twentieth centuries, with either a direct relationship to warm advection from the southwest (January 1530, 1577) or to marked high pressure above the Iberian peninsula (January 1566). The main types of pressure pattern for *cold winter conditions* (1514, 1561, 1565, 1569, 1571, 1573, 1587, 1595) are also similar to those from the recent century. However, patterns with distinct easterly components were more frequent in the sixteenth century (e.g. January 1565, 1573) than patterns with northerly components. It is possible to distinguish different sub-periods for the winter situations:

- those with an enhanced zonal circulation over the northeast Atlantic (1521-1553, 1577-1592), and
- those with a weakened westerly flow and a more frequent incidence of blocking 1situations (1554-1576, after 1592).

Warm summer months have been characterized by various types of anticyclonic ridges not only in the twentieth but also in the sixteenth century (1503, 1516, 1534, 1536, 1540, 1590). For example, a diagonal ridge with SW-NE orientation including Great Britain and southern Scandinavia as in July 1983 also occurred in the sixteenth century (June and July 1540). Less concurrence is found between pressure patterns for *cold summer months* in the sixteenth (1542, 1588) and the twentieth centuries. This could be related in part to lower SSTs in the North Atlantic area inducing a somewhat colder summer climate even at the front of the British low. The declining summer temperatures in central and northern Europe from the mid-1560s have been associated with a decreasing frequency of anticyclonic ridging from the Azores towards continental Europe.

5. Glacier Fluctuations and the Frequency of Natural Hazards

Interrelationships of the seasonal series of temperature (TACE) and precipitation (PACE) to three climate-related natural processes operate on several time-scales.

1. Advancing and melting back of glacier tongues result from a combination of temperature and precipitation patterns on a (multi-) decennial time-scale, according to glacier size and position (Holzhauser and Zumbühl, this volume).
2. Severe river floods (e.g. induced by continuous heavy rain, sudden melting of a deep snow cover or ice damming) are related to meteorological forcing factors on time-scales from days to seasons (Brázdil et al., this volume).
3. Violent storms relate to stochastic, short-term synoptic processes. However, changes in the frequency levels of these events over several decades may be interpreted in terms of climatic variations (de Kraker, this volume).

The cooling and increased wetness of (mid-)summers in the last three decades of the sixteenth century, particularly during the period 1585-1597, changed the mass balance of Alpine glaciers in such a way that the Lower Grindelwald Glacier and the Rhône Glacier were pushed forward to their most advanced positions in historical times around 1600. Written documents describing disastrous outbursts of glacier lakes and the destruction of buildings, meadows, travel routes and irrigation channels by advancing ice masses in the late sixteenth century are known from many parts of the Alps (Holzhauser and Zumbühl, this volume). This indicates that prior to the 1580s Alpine glaciers represented no serious threat to valley dwellers. Larger bodies of ice such as the Grosser Aletsch Glacier and the Gorner Glacier reached their most advanced positions during the seventeenth century. The Grosser

Aletsch Glacier provides an example of how the advances of Alpine glaciers at the end of the sixteenth century and during most of the seventeenth century can be reconstructed by accurate dendrochronological dating of trees which were overrun by the ice. The deterioration of summer climate in the late sixteenth century lead into a prolonged period of enlarged glaciers that ended in the mid-nineteenth century.

Sound descriptive data concerning extreme natural disasters covering the last five to seven centuries can be gleaned from documentary data for most regions of western and central Europe. Early observers were very sensitive to anomalies and natural hazards. The greater the magnitude of a disaster, the more reports are available and the more lengthy and fully the effects are described. In most cases this allows cross-checking of the evidence, an attempt at a rough quantification and the possibility of getting some idea of the possible causes of the event, as in the case of studies of river floods and storms on the coast of Flanders.

The severity and frequency of floods were investigated for an array of rivers in central and southern Europe including the middle and upper Elbe with its tributaries, the Main and the Rhine (Germany), the Garonne (France), rivers in northern and central Italy, as well as rivers in Catalonia and Andalusia (Spain) (Brázdil et al., this volume). A more or less continuous increase in the number of floods is observed in Germany and the Czech lands. To some extent this may be connected with the increase in record density (Pfister et al. [1], this volume), however the precipitation values were undoubtedly larger in the second half of the century. The maximum frequency of severe floods peaked in Germany and in Switzerland in the 1560s and in the Czech lands in the 1570s and again in the 1590s. Flood patterns in the Mediterranean were more complex. Floods in the Po Basin were more or less regularly distributed throughout the sixteenth century. Relative maxima of floods in northern Italy in the 1540s and in the 1590s are mirrored in Catalonia. The Iberian peninsula as well as the Garonne basin (France) had the greatest number of severe floods in the 1590s. This coincides with Spanish precipitation indices (see Glaser et al., this volume). To what extent deforestation interfered with the run-off process is still to be determined.

Accounts concerned with the maintenance of dikes on the Flemish coast provide a continuous source of contemporary information allowing the assessment of the frequency and severity of storms (de Kraker, this volume). The analysis involved classification of storms into three classes of severity following the example of Lamb (1985). The results show that overall storm activity increased by 85% in the second half of the century as compared to the first half. A closer look at the three classes reveals that after 1550 the number of moderate storms was somewhat smaller whereas the number of severe storms skyrocketed by 400%. A graphical comparison with the TACE (winter) series showed a kind of negative correlation between the frequency of storms and winter temperatures. Storm activity was the least during periods of warm or average winters (around 1500, in the 1540s and around 1580) whereas it increased during phases of winter cooling (1505-1510, 1550-1570, 1585 to the late 1590s). The relationship between the frequency of storms and the thermal gradient in the Atlantic area is still an open question. Studies of longer series of storms including those in more recent centuries are needed in order to shed more light on this problem.

6. Possible Forcing Factors which Affected Sixteenth-Century Climate

The long-term cooling of summers is the fundamental characteristic of the European climate in the sixteenth century. It is a unique phenomenon within the last millennium which, as will be shown, had a significant impact on both the economy and the mentality of contemporary societies (see Bauernfeind and Woitek, this volume; Landsteiner, this volume; Behringer, this volume). For these reasons it becomes worthwhile to consider the problem of natural forcing.

Solar and volcanic activities, together with fluctuations in the atmosphere and ocean systems are known to be the main natural factors which force climate on annual, decennial and centennial scales (see e.g. Rind and Overpeck, 1994; Rind, 1996; Mann et al., 1998). Recent greenhouse forcing is seen as a man-made phenomenon; before the industrial revolution the concentration of greenhouse gases was controlled by natural processes. Disentangling various natural forcing factors would need an instrumental record covering a period of several centuries. This, of course, is not available. Moreover, in the case of ENSO and the solar factor the physical mechanism underlying the forcing of climate is not yet sufficiently known. An attempt to study climatic forcing factors in the sixteenth century is handicapped by the degree of accuracy of both climatic proxy data and forcing factors compared to the period of instrumental measurement. For this reason the following considerations are speculative.

6.1. SOLAR FORCING

A great number of investigations of sun/climate relationships have been made (see e.g. Schönwiese et al., 1992; Nesme-Ribes et al., 1993; Bradley and Jones, 1995; Lean et al., 1995; Mann et al., 1998). However, the statistical validity of the findings is often insufficient and the physical mechanisms underlying the relationship of solar forcing and climate not clearly addressed. Different proxies of solar output variations are used to express solar variability (Beer et al., 1996). One of them, ^{10}Be records of polar ice cores, is available for the sixteenth century (Beer et al., 1994a). Higher levels of ^{10}Be occurrence are related to a reduced solar activity and vice versa. A reduction in the solar wind facilitates the penetration of cosmic rays in the outer atmosphere and thus increases the production of cosmic isotopes such as ^{10}Be and ^{14}C (Beer et al., 1994b; Bradley and Jones, 1995).

Table V
Correlation coefficients of ^{10}Be indices with seasonal and annual TACE and PACE series in the sixteenth century (a - smoothed by a 7-year Gaussian filter, b - decennial averages); bold numerals denote statistical importance for the significance level of 0.05

Series		Winter	Spring	Summer	Autumn	Year
TACE	a	0.11	-0.09	-0.02	-0.02	0.00
	b	0.29	-0.30	-0.08	-0.28	-0.13
PACE	a	**-0.22**	0.10	0.13	-0.19	-0.05
	b	-0.42	0.11	0.25	0.03	0.01

In addition to solar modulation, ^{10}Be concentration is affected by the intensity of the geomagnetic dipole field, atmospheric mixing (stratosphere - troposphere) and the resulting precipitation as rain or snow (Beer et al., 1996). It was possible to show (Beer et al., 1994a, 1994b) that curves of ^{10}Be series share some mutual relations with temperature series (Bradley and Jones, 1995, note "intriguing correlations") but without any detailed quantitative analysis.

The ^{10}Be data used for this analysis originate from Dye 3 Greenland ice cores. The ^{10}Be measurements cover the period from 1423 to 1985 (Beer et al., 1994a). The ^{10}Be values in the sixteenth century were highest between approximately 1510 and 1535 (Figure 8). Smaller local maxima may be seen around 1575, 1585 and at the end of the sixteenth century. The lowest values were recorded in the period 1500-1505, in the 1560s and around 1595. Comparison of ^{10}Be series with TACE and PACE records reveals little similarity and low correlations (Table V). The correlation coefficients for TACE and PACE were opposite in sign, fluctuating around zero. Only that for PACE (winter) was statistically significant, although at -0.22 it was very low. Although correlation coefficients calculated for the decennial averages of the ^{10}Be indices and the two climatic series were higher, as expected, none proved to be statistically significant.

A Blackman and Tukey power spectrum analysis of ^{10}Be records in the sixteenth century shows the greatest share of variability in a domain of long-term periods (Figure 9). Spectral values above the corresponding 95% confidence level exist for a period between 5 and 24 years. Comparison of this spectrum with TACE and PACE spectra by coherency analysis only shows significant coherency over a period of three to five years for precipitation. In the case of temperature, which was very pronounced in TACE spectra, the highest coherency is found for a period of seven years but is not significant statistically.

6.2. VOLCANIC FORCING

Volcanic eruptions are important aerosol sources, which increase atmospheric albedo and thereby affect subsequent incoming solar radiation. They may cause a warming of the stratosphere and cooling of the troposphere for several years (see

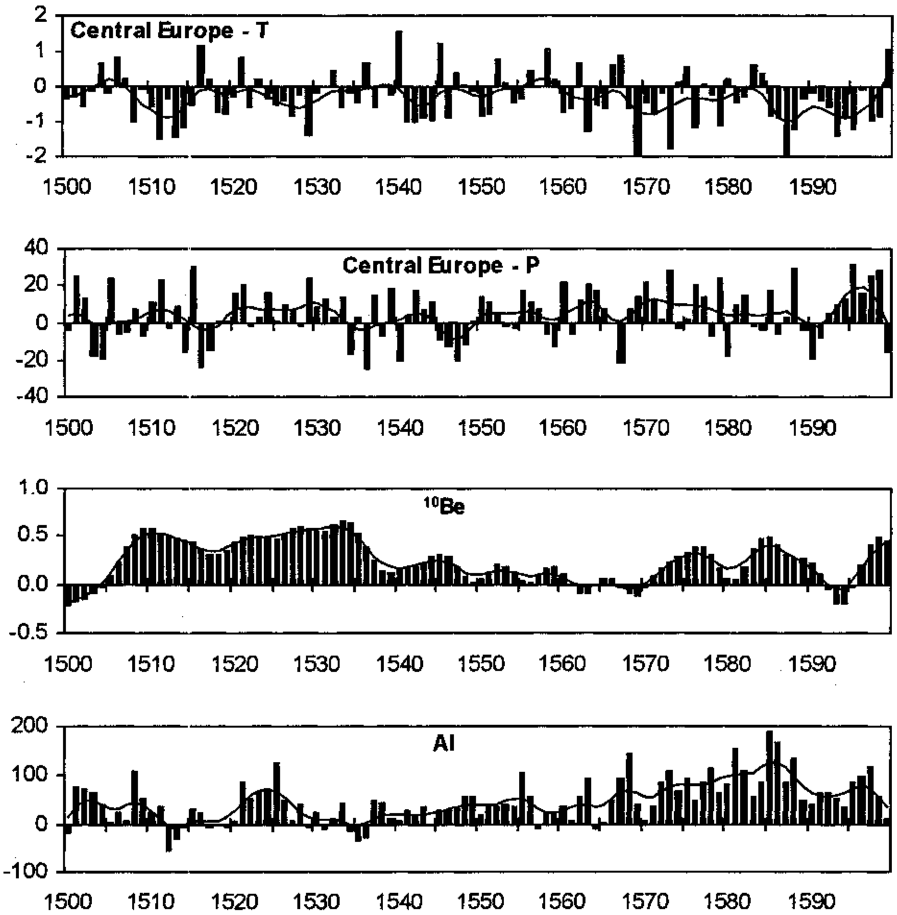

Figure 8. Fluctuations of annual anomalies of TACE (°C), PACE (%), ^{10}Be and AI series (reference period 1901-1960) smoothed by a 10-year Gaussian filter in the sixteenth century.

e.g. Cress and Schönwiese, 1990). The extent of surface temperature cooling after some important eruptions has been investigated using instrumental records (e.g. Bradley, 1988; Schönwiese, 1988; Cress and Schönwiese, 1990; Briffa et al., 1998). Various indices have been used for the characterization of long-term changes in volcanic activity (see e.g. Schönwiese, 1988; Cress and Schönwiese, 1990; Bradley and Jones, 1992; Robock and Free, 1996). Besides large individual eruptions, closely spaced multiple eruptions can clearly reduce hemispheric temperatures on decadal and multi-decadal timescales (Briffa et al., 1998)

The acidity index (AI) obtained from a Crete ice core in Greenland, covering the period 553-1972 (Hammer et al., 1980), was used for the analysis of volcanic

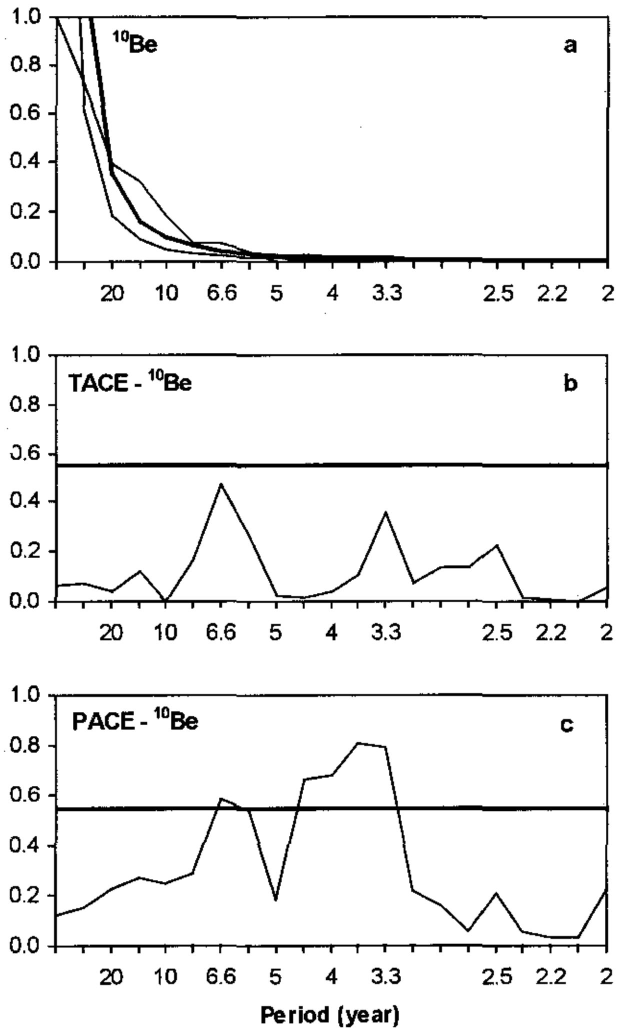

Figure 9. Normalized Blackman and Tukey power spectrum of ^{10}Be records (a) and coherency of ^{10}Be series with TACE (b) and PACE (c) series, dashed lines denote 95% significance levels.

influence on the TACE and PACE series. While the AI series has no gaps in it, it is possible that others, such as the dust veil index (DVI), the volcanic explosivity index (VEI) and the Smithsonian volcanic index (SVI), may omit some important sixteenth century eruptions (see also Bradley and Jones, 1992). Due to the local bias of the data, Cress and Schönwiese (1990) proposed a latitudinal correction in two versions:

Table VI

Maximal correlation coefficients between AI (AI1, AI2) values and seasonal and annual TACE and PACE series with a lag of zero to five years during the sixteenth century; significant coefficients are denoted bold; numerals in brackets always give corresponding lag of TACE and/or PACE series, respectively

Couple	Winter	Spring	Summer	Autumn	Year
AIxTACE	-0.13 (1)	-0.17 (5)	**-0.27** (0)	-0.16 (1)	**-0.23** (1)
AI1xTACE	0.12 (4)	-0.12 (1)	**-0.26** (3)	-0.04 (1)	-0.13 (1)
AI2xTACE	0.09 (5)	-0.16 (2)	**-0.32** (3)	0.07 (2)	-0.16 (3)
AIxPACE	**0.25** (3)	0.18 (0)	**0.22** (0)	0.16 (0)	**0.22** (0)
AI1xPACE	0.16 (3)	0.16 (0)	0.18 (3)	0.15 (1)	0.19 (3)
AI2xPACE	**0.24** (3)	0.14 (3)	**0.24** (3)	0.16 (1)	**0.28** (3)

AI1: 20°S-20°N = 3, 21°N-50°N = 2, 51°N-90°N = 1

AI2: 20°S-20°N = 2, 21°N-50°N = 1, 51°N-90°N = 0.5.

Using these corrections, they calculated the new AI1 and AI2 series for 1500-1972 which enhanced the signal of climatically important but very distant eruptions on Greenland.

It can be taken from Figure 8 that all AI values were above the 1901-1960 average during most of the sixteenth century. After a local maximum in the 1500s and in the early part of the 1520s, an increase of volcanic activity followed from 1535 up to the mid-1580s. Until the end of the century AI values remained comparable with the two local maxima in the first part of the sixteenth century.

Correlation coefficients between acidity index (AI1, AI2) values and seasonal and annual TACE and PACE series with a lag of up to five years are given in Table VI. As expected, correlation coefficients for TACE are negative (with the exception of some cases in winter and autumn) and for PACE, positive. Significant values were reached in summer (lag 0 or 3 years), in annual data (lag 1) for TACE, and in winter (lag 3), summer (lag 0 or 3) and annual (lag 0 or 3) values for PACE.

Comparison of the AI spectra, which show no significant periodicity in the sixteenth century (the greatest variability is connected with long-term trends - see Figure 8) with those of TACE and PACE (Figure 10), reveals no significant coherence, although clear responses are seen in the pronounced three year period in the PACE series and the four and a half-year period in the TACE series (see Figure 4).

6.3. ENSO FORCING

The ENSO (El Niño - Southern Oscillation) effect is connected with important changes in SST and atmospheric circulation in the tropical Pacific Ocean. It is

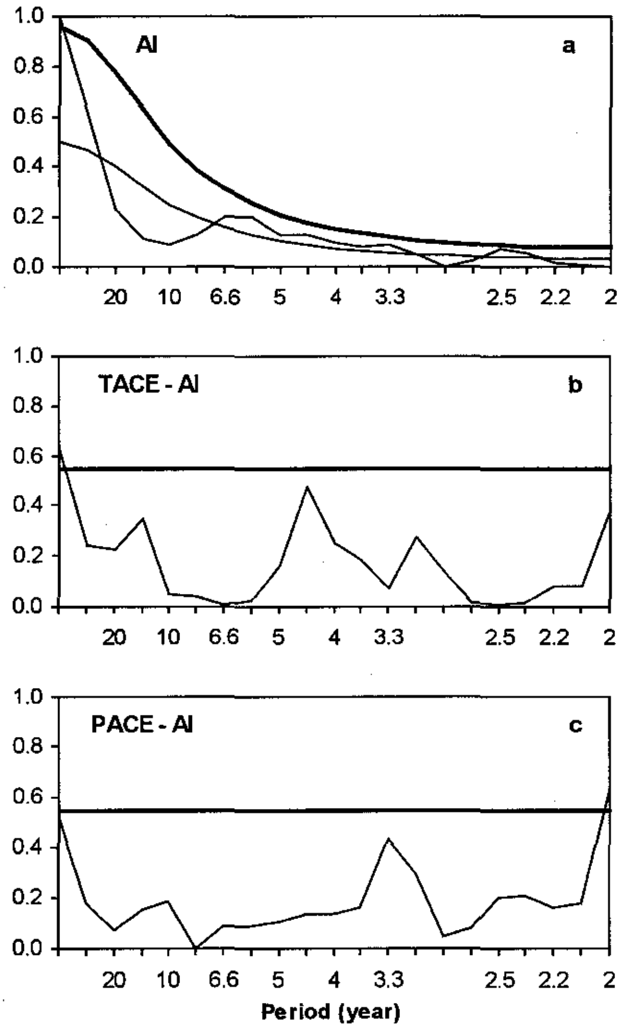

Figure 10. Normalized Blackman and Tukey power spectrum of AI records (a) and coherency of AI series with TACE (b) and PACE (c) series; dashed lines denote 95% significance levels.

known to affect climatic patterns in the whole Pacific area strongly (see e.g. Philander, 1990; Diaz and Markgraf, 1992; Glantz, 1996). There also seem to be climatic teleconnections with other parts of the world (see e.g. Glantz et al., 1991). Possible teleconnections with Europe have thus far only been studied in a few papers because the signals are rather weak (see e.g. overview of papers in Fraedrich, 1994; Brázdil and Bíl, 1998). Nevertheless, GCM simulations of ENSO impacts on atmospheric processes in the Atlantic-European region suggest possible

Table VII

Years (YEAR) of strong (S) and moderate (M) El Niño events (ENSO) and their confidence (CONF) during the sixteenth century according to Quinn (1993). Signs + or - are added for intermediate values, E - early part of the year

YEAR	1525-E26	1531-E32	1535	1539-41	1544	1546-47	1552-53	1558-E61
ENSO	M	M	M+	S	M+	S	S	S
CONF	2	2	2	2	3	2	3	3

YEAR	1565	1567-68	1574	1578-79	1581-82	1585	1589-91	1596
ENSO	M+	S+	S	S	M+	M	S	M
CONF	2	3	2	3	3	2	3	2

mechanisms of teleconnection (May and Bengtsson, 1996).

Historical series of El Niño (warm) events were compiled by Quinn and Neal (1992) and Quinn (1993). Quinn (1993) listed eight moderate and eight strong ENSO events in the sixteenth century (Table VII), all with only low or mean confidence ratings. His ratings from minimal (1) to complete (5) depend on the quantity and quality of the information available.

The possible influence of ENSO on TACE and PACE series was studied for an idealized two-year period centered on the year of occurrence of the ENSO event (year 0) with half a year preceding (year -1) and following it (year 1). For example, for winter -1/0 December from the year preceding the event is taken and January and February from the year of the event. For each event given in Table VII, only the first year is taken as the year of ENSO in order to avoid repeating the same season for calculations. Corresponding mean values and frequencies of occurrence of positive and negative values in TACE and PACE series were calculated (see Table VIII) for each season in an idealized two-year ENSO period.

As is clear from Table VIII, during all ENSO events (M+S) differences regarding the seasonal centennial means are highest for autumn 0 (0.53°C), due to the prevalence of the negative values (75% of cases), and for winter 0/1 (0.47°C), although the frequency of positive and negative values in winter remains equal. This means that during the ENSO event autumn 0 and winter 0/1 were warmer by about 0.5°C than the corresponding centennial autumn and winter averages. On the other hand, prevailing negative frequencies (69%) are typical for both springs 0 and 1. The greatest differences in precipitation between centennial seasonal means and ENSO period means are obtained for spring 1 (6.1%), with its prevailing negative values (62%), and autumn 0 (5.1%), where positive values (62%) also prevail. This means that both seasons were drier during ENSO events than the corresponding centennial seasonal averages. On the other hand, a clear prevalence of positive values is observable for autumn -1, winter -1/0 and spring 0 (62, 69 and 81%, respectively).

These results correspond in general with analyses of pressure, temperature and

Table VIII
Characteristics of seasonal TACE and PACE series during the idealized two-year ENSO period of moderate (M) and strong (S) events according to Table VII

Air temperature (TACE)

ENSO		Au -1	Wi -1/0	Sp 0	Su 0	Au 0	Wi 0/1	Sp 1
	A	-0.14	-0.48	-0.53	-0.07	-0.14	-0.48	-0.53
M	a	0.20	-0.55	-1.00	-0.45	0.23	0.14	-0.18
	b	+0.34	-0.07	-0.47	-0.38	+0.37	+0.62	+0.35
	c	5	3	1	3	5	4	3
	d	3	5	7	5	3	4	5
S	a	-0.10	-0.44	0.01	0.27	0.55	-0.16	-0.39
	b	+0.04	+0.04	+0.54	+0.34	+0.69	+0.32	+0.14
	c	4	3	4	5	7	4	2
	d	4	5	4	3	1	4	6
M+S	a	0.05	-0.50	-0.49	-0.09	0.39	-0.01	-0.28
	b	+0.19	-0.02	+0.04	-0.02	+0.53	+0.47	+0.27
	c	9	6	5	8	12	8	5
	d	7	10	11	8	4	8	11

Precipitation (PACE)

ENSO		Au -1	Wi -1/0	Sp 0	Su 0	Au 0	Wi 0/1	Sp 1
	A	4.8	13.1	1.4	0.8	4.8	13.1	1.4
M	a	2.4	3.5	12.0	10.9	8.2	19.5	-1.9
	b	-2.4	-9.6	+10.6	+10.1	+3.4	+6.4	-3.3
	c	6	4	8	6	7	7	3
	d	2	4	0	2	1	1	5
S	a	2.2	14.4	-2.5	-14.6	-8.8	5.2	-7.5
	b	-2.6	+1.3	-3.9	-15.4	-13.6	-7.9	-8.9
	c	4	7	5	1	3	5	3
	d	4	1	3	7	5	3	5
M+S	a	2.3	9.0	4.8	-1.8	-0.3	12.4	-4.7
	b	-2.5	-4.1	+3.4	-2.6	-5.1	-0.7	-6.1
	c	10	11	13	7	10	12	6
	d	6	5	3	9	6	4	10

A - average for 1500-1599 (°C for air temperature; % for precipitation)
a - mean values (°C and/or %)
b - mean values minus centennial averages A (°C and/or %)
c - frequency of positive values
d - frequency of negative values
Abbreviations of seasons: Wi - winter, Sp - spring, Su - summer, Au - autumn

precipitation fields during the warm and cold phases of ENSO in Europe during the twentieth century (Brázdil and Bíl, 1998). It is impossible to make a direct comparison of results as summer 0 and winter 0/1 for air temperature and summer 0 and autumn 0 for precipitation were the most sensitive to the ENSO effect for central European stations (Brázdil and Bíl, 1998).

6.4. GREENHOUSE FORCING

Due to their influence on output of long-wave irradiance, water vapor and greenhouse gases such as CO_2, CH_4, N_2O and O_3, are responsible for the natural greenhouse effect. The dramatic increase in the levels of these gases since the pre-industrial period, caused by human activity, is recognized as important for the forcing of present and future climate (Houghton et al., 1996). CO_2 concentrations have only been measured since 1957, but proxy evidence of earlier values, as with CH_4, is available from analyses of air trapped in polar ice cores. CO_2 and CH_4 records covering the last millennium indicate fluctuations of about only 10 ppm for CO_2 (Siegenthaler and Sarmiento, 1993) and 70 ppbv for CH_4 (Blunier et al., 1993). According to Raynaud et al. (1996) these oscillations may reflect oceanic and/or continental biospheric responses to climatic changes including the "Little Ice Age" and the "Medieval Warm Period". However, another possible explanation could be the response of the oceanic or continental biospheric reservoirs to high-frequency natural climate variability. As the concentration levels of both these greenhouse gases were more or less constant during the sixteenth century, it is improbable that they had much influence on temperature fluctuations. This is in agreement with Mann et al. (1998) who have shown that greenhouse gas changes during recent centuries had hardly any climatic significance until the twentieth century.

6.5. OVERALL FORCING

There is some evidence that seasonal temperature (TACE) and precipitation (PACE) series may have been affected by volcanic activity, but no meaningful relationship has been found between temperature and precipitation data and solar influence, represented by the ^{10}Be values. Fluctuations in trace gas values were evidently unimportant, while an investigation of possible teleconnections between ENSO events and central European temperature and precipitation patterns was inconclusive. Changes in North Atlantic Deep Water formation (Broecker et al., 1985) are known to have major effects on circulation patterns in the Atlantic-European region, and more particularly on the North Atlantic Oscillation (NAO) (Gordon et al., 1992; Delworth et al., 1993, 1997). This oscillation influences European temperature and precipitation patterns strongly, especially in winter (see e.g. van Loon and Rogers, 1978; Hurrell, 1995, 1996; Hurrell and van Loon, 1997; Malberg and Bökens, 1997; Wilby et al., 1997; Jacobeit et al., this volume). In addition, interannual and interdecadal sea level pressure patterns during the sixteenth century were probably connected with different sea surface temperatures and sea-ice distribution in the northern North Atlantic as shown in studies based on observed data from the twentieth century (e.g. Ikeda, 1990; Peng and Mysak, 1993; Kushnir, 1994). This is also assumed for the late Maunder Minimum (1675-1715) by Luterbacher et al. (1998).

The possible climatic effects of forcing factors may be evaluated using general circulation models (GCMs) (see e.g. Rind and Overpeck, 1994; Rind and Lean, 1994), as well as by more traditional approaches based on analysis of meteorological records. Moreover GCMs can be run without external forcing in order to investigate the magnitude of internal variations of the oceanic-atmospheric system, on century-to-millennium time-scales, which are believed to be of the order of 0.2°C-0.3°C per century (Bradley and Jones, 1995). Despite the existence of many uncertainties, GCM experiments appear to have great potential value as tools for investigating the influence of forcing factors on past climates (Rind, 1996). It is hoped that the new evidence of the characteristics of sixteenth century European climatic variability presented in this volume will motivate further GCM studies.

7. Impacts and Perceptions

The studies following this introductory overview include accounts of investigations by economic and social historians of the extent to which long-term cooling in the late sixteenth century affected food prices and population trends, and of the ways in which the poor who suffered most from the impact of changing climate, viewed the situation.

The theory of pre-industrial trade cycles associated with Labrousse et al. (1970) considers the harvest, and thus the underlying climatic determinants of grain yield the critical determinant influencing urban income, via its influence on grain prices and rural employment levels. Bauernfeind and Woitek (this volume) analyzed the quantitative impact of seasonal temperatures and precipitation on the price fluctuations of several agricultural commodities such as rye, butter and honey at Nuremberg, Cologne, Augsburg and Munich during the period 1490-1620. They showed that for these products the variability of the rye price series was by far the most important, most of the increase occurring after 1560. Grain provided no less than 70% of calorie requirements for the population. There was no substitute for grain and therefore price elasticity was low. The correlation of the Swiss and German temperature and precipitation indices with the rye price series was then examined using the model by Pfister (1988b). It was shown that temperatures in the spring were negatively related to grain prices, but the correlation with rain during the harvest was much lower than expected, possibly because the relationship between rain during the harvest period and grain prices is non-linear, moderate rains having no effect whereas long rainy periods lead to a sharp increase in prices. The unweighted index +1/-1 which was used for the analyses does not mirror these differences adequately. Despite these shortcomings the correlation between climatic variables and grain price fluctuation is positive and quite substantial. The correlation increases during the period of observation; the maximum being reached in the 1565-1600 period. It may therefore be concluded that in the last third of the sixteenth century climate change became the most significant element affecting food prices. This contradicts the mainstream opinion of most economic historians who generally explain the sixteenth century "Price Revolution" by means of population levels (without providing a continuous quantitative and homogeneous record) and increases in the money supply (e.g. Hennig, 1991; Mathis, 1992). It also negates the influential views of Le Roy Ladurie (1971) and Abel (1978), both of whom claimed that climate effects are randomly distributed in time. These results also suggest that climatic change was involved in the generation of long-term cyclical movements (i.e. the Kuznets or perhaps even the Kondratieff cycles).

Although the effects of climatic deterioration on population (e.g. Galloway, 1994) have not been investigated in detail, some remarks need to be made in the present context. Bauernfeind and Woitek (this volume) show that there are periods during the sixteenth century where the correlation between "climate" and rye prices is low or even negative. They attribute this to population shocks (possibly as a result of plague, for example) and therefore to changes in demand. There are great problems in reconstituting the condition of the population in central Europe for any period of time earlier than the eighteenth century, when primitive statistics were first systematically gathered. The picture obtained for sixteenth-century population from a broad variety of proxy data can only be approximate (Pfister, 1995): Between 1520 and 1560 the number of dwellings grew at an average rate of 0.7 per cent per year. Over the following four decades the growth rate declined continuously to 0.3 per cent annually in the period 1590-1600. This slow-down suggests that the population grew faster during the period of favorable climate in the second third of the century and that growth was throttled back in the last third of the century when climatic conditions were deteriorating. If the population had been the dominant variable for price formation, as most textbooks suggest, it should have been particularly large in the last third of the century when the "Price Revolution" actually took place. From the evidence of climate and the population trends it must rather be assumed that the long-term fall in real wages resulting from the long-term rise in prices was an effect of the deteriorating climate superimposed on continuing slow population growth. Climatic variability leading to harvest failures is just one of several causes (along with war or plant, animal and human diseases) of regional food shortage, though by far the most important one. Whether and how food shortage manifests itself at the household level or at the level of the individual, depends on food demand, i.e. on the population and the rules according to which food is distributed, which in turn depends on the social structure of a society. Food shortage generates hunger only to the extent to which it translates into individual food deprivation of some or all members of a household (Millman and Kates, 1990).

Landsteiner (this volume) has investigated the impact of changing climate on wine production. Viticulture in central Europe is at its northern limits and therefore the growth, the yield and the sugar content of grapes are related to climate (Lauer and Frankenberg, 1986; Pfister, 1992; Guerreau, 1995). Wine was an important source of income for institutions and the landed gentry in terms of tithes, taxes or sharecropping (in a sharecropping contract, the owner of the vineyard received a share of the vine harvest, usually half of it). Thus, continuous proxy series of wine production are obtainable from institutional book-keeping records over a period of several centuries. In his analysis Landsteiner compared wine production for the period 1550-1630 in four areas: Lake Zurich (Switzerland), Württemberg (Germany), Lower Austria and western Hungary. The most striking feature in all four series is a slump in wine production in the 1580s initiating a consecutive series of crop failures which continue until the late 1590s or the early 1600s. These crop failures began in 1585 in Switzerland, in 1586 in Württemberg and in 1587 in Lower Austria and western Hungary some 800 km further east. These patterns fit with the long sequence of cold and wet summers at the end of the century. As wine growing was an important activity and a main source of income, such harvest failures had far-reaching consequences. In Lower Austria the collapse of wine production leading to high prices and the low sugar content of the product motivated the public to switch from wine to beer consumption. At the same time it cut back the revenues of the Habsburg treasury which drew a substantial part of its income from the wine economy. The emperor had to double the heavy export duty on wine in order to be able to pay the interests on the state debt. Moreover harvest failures put a severe strain on the budgets of urban wine producers, and deficient grain harvests reduced the real wage of the vine-dressers by 50%.

The way in which such changes were perceived in a society highly vulnerable to meteorological shocks has been investigated by Behringer (this volume). He considers a theme that he has pursued in several other places, i.e. the connection between large-scale witch-hunting and the distinctly worsening weather in central Europe between the fifteenth and the late seventeenth centuries. He rates human reactions to climatic changes as an important indicator for the beginning, the periodization and the end of the "Little Ice Age", a subject beyond the scope of this volume. Nonetheless, it must be noted that Behringer has long called attention to the dramatic increase in witch burnings after the early 1560s, i.e., after the onset of the worsening climate. Most witches were burned for weather-making which was perceived as having caused crop failures, floods and cattle diseases related to "unnatural weather", i.e. to weather sequences or single extremes that nobody had known or experienced before. In many cases historical climatology can demonstrate that these events were indeed extremely rare or even unique within several generations. Such conditions, however, were interpreted as an attack by evil powers. "Witches" under torture confessed to being involved in devilish plans to destroy vineyards and grain for several years in order to create hunger and disease so that people would be forced to become cannibals. Results obtained by Bauernfeind and Woitek (this volume) and by Landsteiner (this volume) clearly show that the notion of an extremely long sequence of small vine and grain harvests was not a product of popular imagination. Rather, accusations were based on a cocktail of outstanding cold shocks which were beyond the known experience of the peasant villages suffering large collective damage. Not surprisingly these communities were the most active promoters of witch-hunts. It seems therefore that witches were burnt as scapegoats for climatic change. Behringer (this volume) goes so far as to consider the frequency of witch-hunts to be a new kind of proxy climatic indicator for "Little Ice Age" events.

The orthodox Lutheran Church tried to stop witch burning by insisting that only God was responsible for the weather, not human beings. For many observers, the deterioration of climate at the end of the sixteenth century was proof that the "End of the World" was near (Lehmann, 1986). In a publication which appeared in Magdeburg in 1595, the Reverend Daniel Schaller, pastor in Stendal in the Prussian Altmark region, noted that some unmistakable change in climate was occurring: "There is no real, constant sunshine, neither a steady winter nor summer; the earth's crops and produce do not ripen, are no longer as healthy as they were in bygone times. The fruitfulness of all creatures and of the world as a whole is receding; fields and grounds have tired from bearing fruits and even become impoverished, thereby giving rise to the increase of prices and famine, as is heard in towns and villages from the whining and lamenting among the farmers." (Lehmann, 1986). There is some evidence from the Swiss canton of Solothurn for a decline of wild animals in the late sixteenth century. From the state accounts of this small republic, Körner (1993) drew up the number of mice and moles captured and turned over to the authorities for a small payment during the period 1538-1643. There would seem to be some kind of relationship between the mouse population and climatic change. The number of mice and moles delivered to the authorities declined drastically after 1565. The low level of deliveries was maintained until the turn of the century. After the climate improved around 1600, the mice and mole population gradually recovered.

Renward Cysat, naturalist and chancellor of Lucerne, was another observer who matter-of-factly noted the changes in nature at the end of the sixteenth century. In about 1600 he took a retrospective view of the recent past in the foreword to his "*Collectanea*", a miscellany of interesting facts which includes very detailed weather accounts, and maintained that "...in years not long past, the weather and other things have taken such a peculiar and astounding course and undergone such extraordinary alterations" that he "was able to do nothing other than record the same as a warning to future generations, for, unfortunately because of our sins, for already some time now the years have shown themselves to be more rigorous and severe than in the earlier past, and deterioration amongst creatures, not only among mankind and the world of animals but also of the earth's crops and produce have been noticed as well as extraordinay alterations of the elements, stars and winds" (Schmid, 1969).

8. Concluding Remarks

It is hoped that the contents of this article and the papers following in this volume will improve the standing of documentary data in the view of many natural scientists. As far as sixteenth century climate is concerned, more evidence is needed for the northern and the eastern part of Europe. In particular the rich archival material buried in Swedish archives is needed to obtain a clearer view of the changes in the high latitudes. Moreover, it would be worthwhile to attempt a reconstruction of gridded monthly mean sea-level air pressure (SLP) patterns for the North Atlantic-European region with objective (statistical) methods based on proxy information according to the example of Luterbacher et al. (1998). More detailed demographic studies are needed. The models relating grain prices to climatic variables should be still further refined and improved. Natural disasters before the age of instrumental measurements have hardly been explored as yet. The articles on floods and severe storms are examples of what might be obtained from careful analyses of documentary data. It is hoped that these investigations will be continued in order to fill the gap between the sixteenth and the early twentieth century. The largest gap remaining is the impact of the known climate changes upon the economies and societies of Europe and beyond. Some beginnings have been made here pointing the way for future research. It is particularly hoped that the present research will stimulate social scientists to explore further the ways in which climatic changes were felt and perceived by contemporaries.

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