European spring and autumn temperature variability and change of extremes over the last half millennium

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[1] We evaluate variability, trends, uncertainties, and change of extremes of reconstructed and observed European spring and autumn temperature back to 1500. Spring and autumn temperature experienced systematic century-scale cooling compared to present conditions. The coldest springs appeared during the Maunder Minimum ($\Delta T = -1$ K wrt 1901–2000). The amplitude of spring temperature variations at decadal and multidecadal scales doubles that of autumn and is most expressed in northeastern Europe. The decade 1995–2004 was very likely the warmest of the last half millennium. Anomalously warm springs and autumns have generally become more extreme in recent decades. However, the recent changes are statistically not significant with respect to the pre-industrial period. **Citation:** Xoplaki, E., J. Luterbacher, H. Paeth, D. Dietrich, N. Steiner, M. Grosjean, and H. Wanner (2005), European spring and autumn temperature variability and change of extremes over the last half millennium, *Geophys. Res. Lett.*, *32*, L15713, doi:10.1029/2005GL023424.

1. Introduction

[2] One promising direction in paleoclimatology is the development of seasonally resolved climate maps and associated errors [*Jones and Mann*, 2004]. Field reconstructions provide insight into the mechanisms or forcings underlying observed climate variability and are particularly important in comparison with AOGCM integrations [*González-Rouco et al.*, 2003; *Shindell et al.*, 2003; *Zorita et al.*, 2004; *Rutherford et al.*, 2005; *van der Schrier and Barkmeijer*, 2005]. Past and future climate changes can have a strong seasonal dependency. For instance, volcanism, solar irradiance, greenhouse gases and anthropogenic aerosols, all may influence the annual cycle in a different manner. While the anomalous nature of recent trends and variability in global or hemispheric averages is often highlighted in climate change discussions, changes and extremes at continental or regional scale as e.g. the heat wave of summer 2003 in Europe have much greater environmental, socio-economic and health impacts [*Schär and Jendritzky*, 2004; *Stéphan et al.*, 2005].

[3] Past temperature variations for spring and autumn have not been investigated so far neither at hemispheric nor continental scale due to limited information in climate proxies for these seasons [*Jones and Mann*, 2004; *Brázdil et al.*, 2005]. *Luterbacher et al.* [2004] presented a European temperature history for winter, summer, and annual averages back to 1500. Here, we analyze European spring (MAM) and autumn (SON) temperature variability, reconstructed on the basis of monthly instrumental temperature time series in combination with temperature index series derived from documentary evidence that provide the most reliable source of independent temperature reconstructions prior to the late 17th/early 18th centuries [*Pfister*, 1999; *Mann*, 2002; *Jones et al.*, 2003; *Luterbacher et al.*, 2004; *Brázdil et al.*, 2005; *Guiot et al.*, 2005].

[4] A key issue of the present study is whether extremely warm spring and autumn anomalies averaged over Europe have become more extreme in recent decades than before. We first discuss the evolution of seasonal European spring and autumn temperature, uncertainties and trends for more than half a millennium. In a second step, return values of extremely warm springs and autumns are estimated and their changes over the last 505 years are assessed. This thorough proceeding allows for uncertainty estimates in the extreme value and the statistical significance of the respective changes.

2. Data and Methods

[5] We performed a multivariate calibration of the large-scale information in the combined instrumental and documentary proxy data network against gridded instrumental data to reconstruct monthly (back to 1659) and seasonal (1500–1658) European temperature fields (25°W–40°E; 35°N–70°N at 0.5° × 0.5° resolution; for data and methods see *Luterbacher et al.* [2004]). In comparison to *Luterbacher et al.* [2004], we used only temperature indices derived from documentary evidence (before 1750) and instrumental temperature series, adding a few series from Scandinavia, central and eastern Europe [*Böhm et al.*, 2001; *Jones and Moberg*, 2003], and fitted to the gridded data by *Mitchell and Jones* [2005]. As documentary temperature indices are not available for the 20th century, normally-distributed white noise was added to the seasonally resolved indices based on instrumental measurements to ensure that the resulting documentary indices have similar quality as those derived from documentary evidence [*Mann and Rutherford*, 2002; *Pauling et al.*, 2003]. We estimated uncertainties (Standard Error, SE) for 30-yr filtered European springs and autumns using the available predictor verification residuals (from the calibration period 1901–1995) after making the residuals consistent with Gaussian white noise [*Mann et al.*, 1998; *Briffa et al.*, 2002].

[6] We define climate extremes as the return values (RVs) of anomalously European warm springs and autumns given

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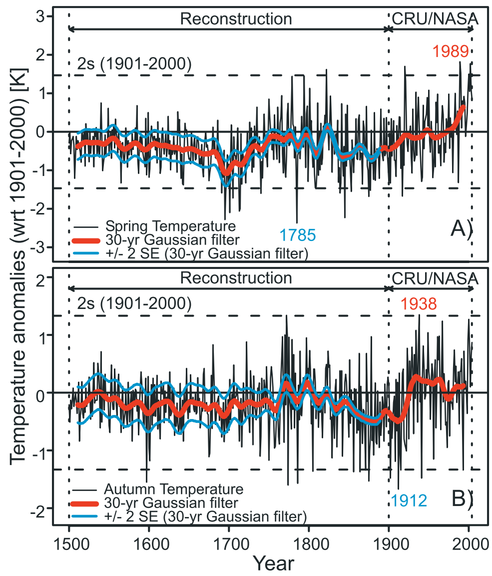

Figure 1. (a) Spring and (b) autumn European temperature anomalies (wrt 1901–2000) from 1500–2004 over the land area 25°W–40°E and 35°N–70°N (thin line). 1500–1900: reconstructions; 1901–2002: *Mitchell and Jones* [2005]; update: *Hansen et al.* [2001]. Red line: 30-yr Gaussian smooth. Blue lines: ±2SEs of 30-yr Gaussian filtered reconstructions. Dashed horizontal lines: 2SD of 1901–2000. The warmest and coldest springs and autumns are denoted.

return periods (RPs) between 5 and 50 years. The RVs are estimated from a normal distribution fitted to the modeled spring and autumn temperature time series using L-moments that are less sensitive to outliers and small sample sizes [*Hosking*, 1990]. In order to gain insight into the temporal evolution of climate extremes, the RVs are determined separately for 50-yr periods running through the period 1500–2004. The uncertainty of the RV estimate is taken into account by applying a Monte Carlo sampling approach, a tool to estimate the extreme value uncertainty and test the significance of their changes [*Paeth and Hense*, 2005]. We performed a parametric bootstrap (normal distribution, 1000 samples) in order to estimate the standard error and confidence intervals of the RV estimate, expressed by the standard deviation and the quantiles of the bootstrap samples. Given two periods in time, a change in the RVs is defined to be statistically significant at an error level of 1%, if the 90% confidence intervals of the RV estimate over 1000 bootstrap samples are not overlapping between both periods [*Kharin and Zwiers*, 2000].

3. Results and Discussion

[7] Figure 1 presents the spring and autumn averaged European land temperature variations over the last half millennium (with respect to the 1901–2000 average) and the 30-yr filtered ±2SE. The uncertainties for spring and autumn are highest prior to ca 1720 when documentary information and instrumental data is limited.

[8] Except for a short period around 1800, the smoothed European spring and autumn curves reveal cooler conditions than the 20th century. Our estimates indicate that the 17th and 19th centuries were the coldest for Europe with around 0.5 K (spring) and 0.25 K (autumn) lower temperatures compared with the 20th century average. The last approximately 100 years have experienced the greatest spring (autumn) temperature change within the last half millennium with approximately +0.1 K/decade (+0.07 K/decade) warming. All spring months contributed to that warming, whereby March revealed the strongest upward trend. *Klein Tank et al.* [2005] concluded that signals of anthropogenic warming very likely explain the strong spring upward trend over the last decades. Further, observational and experimental studies show the impact of climate change on European ecosystems including the lengthening of the growing season for the second part of the 20th century, largely attributed to the advancement of spring [*Menzel and Fabian*, 1999]. The most striking feature in the spring curve is the extended coldness during the second part of the Maunder Minimum (MM; 1687–1716, $\Delta T = -1$ K). The widely reported European cold during the MM is thus mainly a winter and spring phenomenon as summers and autumns do not present strong departures from the European 20th century average [*Luterbacher et al.*, 2004]. *Pfister* [1999] reported the most severe springs from 1687–1717 in central and eastern Europe as well as the British Isles over past centuries. We confirm these results for the whole European continent. The strong increase in European spring temperature at the end of the 17th/beginning of the 18th century shows a similar spatial trend pattern as for winter [*Luterbacher et al.*, 2004] and goes along with a trend towards earlier ice break up dates at the Torne River at the Swedish/Finnish border [*Kajander*, 1993; *Klingbjer and Moberg*, 2003] and an upward temperature trend in central Europe [*Brázdil*, 1996]. Thus, there is regional independent climate information, although limited, at seasonal resolution supporting our findings. Model simulations by *Shindell et al.* [2003] indicate that increased solar irradiance at the end of the MM might have induced a shift towards positive AO/NAO during November–April, leading to continental warming. Similar findings were suggested for European winters [*Luterbacher et al.*, 2004]. Thus, the solar irradiance changes might be a major trigger to explain the increasing trend in European spring temperature at decadal time scale.

[9] The European spring temperature variability amplitude over the past half millennium is quite large. The warmest and coldest 30-yr averages (1975–2004 minus 1687–1716) present a difference of 1.5 K. The autumn temperature amplitude at multi-decadal time scale (1934–1963 minus 1864–1893) accounts for 0.75 K. Spatial temperature difference maps between the warmest and coldest 30-yr springs and autumns show a monopole pattern with strongest departures over northeastern Europe and Scandinavia (Figure 2). The warmest decade was 1995–2004 with around 0.9 K (spring) and 0.45 K (autumn) higher values compared to 1901–2000.

[10] Have the RVs of anomalously warm springs and autumns increased? Figure 3 shows the temporal evolution of the RVs given RPs of 5, 10, 20 and 50 years. The displayed RVs represent mean estimates over 1000 bootstrap samples, taking into account the inaccuracy of the data. Computing the RVs for continuous 50-yr periods

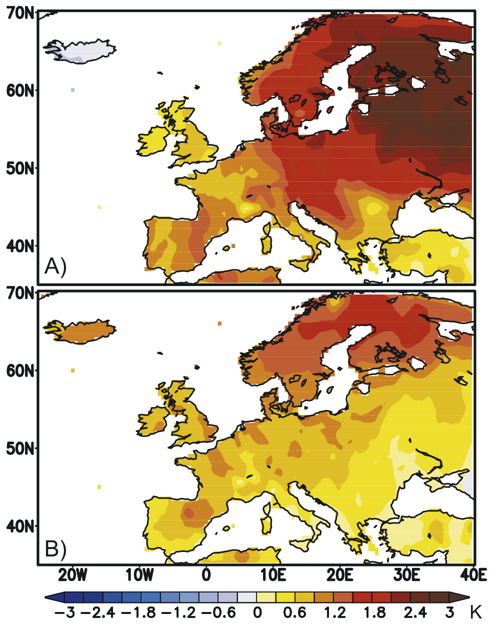

Figure 2. Difference maps between the warmest and coldest multi-decadal (a) springs (1975–2004 minus 1687–1716) and (b) autumns (1934–1963 minus 1864–1893).

reveals that extremely warm European springs (Figure 3a) have generally become more intense during the last 500 years, particularly from 1500 to 1800. This holds for various RPs but is overlaid by pronounced decadal variations. The cold period at the end of the 17th century (Figure 1) is clearly visible. The beginning of the 20th century shows a substantial increase of anomalously high spring temperature. However, since 1970 there is a trend towards reduced warm extremes, which seems contradictory to the ongoing positive trend in the mean time series (Figure 1a). It is obviously inconsistent with a continuous greenhouse forcing since the pre-industrial time and may arise from other factors such as cooling due to volcanism, anthropogenic aerosols or climate variability. In autumn, the RVs of warm temperature anomalies are subject to remarkable interdecadal variability, which largely blurs out the underlying positive trend (Figure 3b). Particularly weak

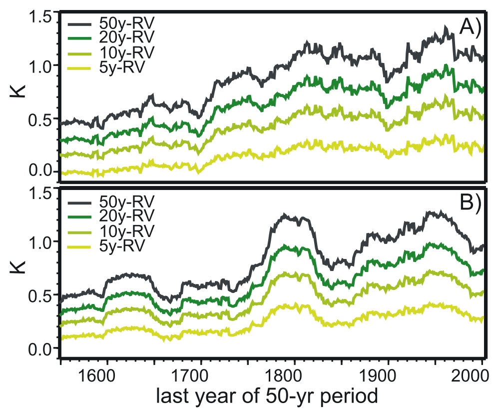

Figure 3. Estimated RVs of extremely warm European (a) spring and (b) autumn temperature for various RPs, each RV refers to a 50-yr period within 1500–2004.

warm temperature extremes in autumn prevailed during the second half of the 16th and 17th centuries, while the period with the strongest warm anomalies occurred around 1800 according to the mean values in Figure 1b. Similarly high RVs are reached in the middle of the 20th century but afterwards warm extremes become weaker (Figure 3b). The time series in Figure 3 are characterized by pronounced decadal and interdecadal variations, suggesting that the occurrence of anomalously warm spring and autumn temperatures are related to additional sources of climate variability than continuously increasing greenhouse-gas concentrations alone.

[11] This interpretation is supported by the results in Figure 4, indicating whether a change in the RVs of extremely warm spring and autumn temperatures between the last 50 years (1955–2004) and all previous 50-yr periods until 1954 is statistically significant as measured by the Monte Carlo approach. Although the RVs of positive spring temperature departures are characterized by an upward trend during the period 1500–2004 (Figure 3a), the last 50 years apparently do not stand out from the centuries before, except the first 200 years (Figure 4a). This either means that extremely warm springs were indeed significantly less pronounced during this early period, which may be physically interpreted in connection with the MM, or that the reconstruction method leads to an underestimation of climate variability and, hence, an underestimation of climate extremes until 1700 (see larger uncertainties in Figure 1). Until such a technical explanation cannot be excluded, the assessment and interpretation of changes in climate extremes remains debatable. A similar picture is drawn for anomalously high autumn temperature (Figure 4b). After 1750, there is no statistically significant change in the RVs, independent of the considered RPs. The same test has also been applied to the means of all 50-year periods, which is equivalent to testing the 2-year RVs. There are indeed highly significant changes in the climate means as inferred from the Monte Carlo sampling (not shown). This demonstrates that significant changes in the mean state are not necessarily associated with significant changes in climate extremes. This behavior, though, may change in a warmer future climate.

4. Conclusions

[12] European temperature reconstructions of spring and autumn temperature back to 1500 indicate generally cooler

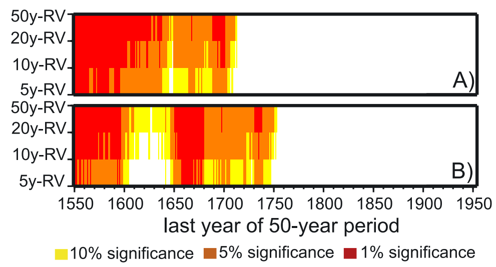

Figure 4. Statistical significance of changes in extremely warm (a) spring and (b) autumn temperature for various RPs, testing the last 50 years (1955–2004) against all previous 50-yr periods between 1500 and 1954.

conditions throughout the 16th–19th centuries. The decade 1995–2004 was very likely the warmest supporting recent findings for European winters and summers. The well-known European cold during the MM seems to be restricted to winter and spring only. Spring temperature variations at decadal and multidecadal time scales are twice as large as that of autumn, mostly expressed in NE Europe. The reconstructions can also serve for the validation of climate simulations of the last centuries. A clear signal in the European mean spring and autumn time series does not necessarily imply a significant change in the extremes. Other factors, like volcanic forcing, greenhouse gasses, anthropogenic aerosols or internal climate variability could well explain this inconsistency. The PDFs of European spring and autumn temperature do not simply respond in the form of a systematic shift towards warmer means and extremes. Rather the shape of the PDFs is also affected, which implies that a more differentiated analysis of climate change in the mean values and in the lower and upper tails of the PDFs is required.

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