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Circulation dynamics and its influence on European and Mediterranean January–April climate over the past half millennium: results and insights from instrumental data, documentary evidence and coupled climate models

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Abstract We use long instrumental temperature series together with available field reconstructions of sea-level pressure (SLP) and three-dimensional climate model simulations to analyze relations between temperature anomalies and atmospheric circulation patterns over much of Europe and the Mediterranean for the late winter/early spring (January–April, JFMA) season. A Canonical Correlation Analysis (CCA) investigates interannual to interdecadal covariability between a new gridded SLP field reconstruction and seven long instrumental temperature series covering the past 250 years. We then present and discuss prominent atmospheric circulation patterns related to anomalous warm and cold JFMA conditions within different European areas spanning the period 1760–2007. Next, using a data assimilation technique, we link gridded SLP data with a climate model (EC-Bilt-Clio) for a better dynamical understanding of the relationship between large scale circulation and European climate. We thus present an alternative approach to reconstruct

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climate for the pre-instrumental period based on the assimilated model simulations. Furthermore, we present an independent method to extend the dynamic circulation analysis for anomalously cold European JFMA conditions back to the sixteenth century. To this end, we use documentary records that are spatially representative for the long instrumental records and derive, through modern analogs, large-scale SLP, surface temperature and precipitation fields. The skill of the analog method is tested in the virtual world of two three-dimensional climate simulations (ECHO-G and HadCM3). This endeavor offers new possibilities to both constrain climate model into a reconstruction mode (through the assimilation approach) and to better assess documentary data in a quantitative way.

1 Introduction

Long and homogeneous instrumental temperature series are very important for palaeoclimatological studies, as they provide the basis for assessing the usefulness and reliability of proxy records (e.g. Jones et al. 2003). In Europe there is a wealth of generally high quality long instrumental temperature records available (e.g. Jones 2001; Camuffo and Jones 2002; Auer et al. 2007). The study of such records is one

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aspect in the rapidly developing field of 'historical climatology' (e.g. Brázdil et al. 2005; Pfister et al. 2008; Brázdil and Dobrovolný 2010). Recently, a rare opportunity for a large group of historical climatologists to engage in a collective undertaking that links with other climate research areas (e.g. dendroclimatology and other natural proxy sources) and climate modeling, has been offered in context of the EU 6th Framework Program project MILLENNIUM (Gagen et al. 2006; Brázdil et al. 2009; http://ralph.swan.ac.uk/millennium/).

The main goals of this project are to develop climate reconstructions for Europe in the last millennium and use this information to constrain simulations with climate models, which should ultimately lead to reduced uncertainty in predictions of future climate changes. To achieve the goals it is required that as much 'new' data as possible are included and integrated with 'old' data more firmly within the spatial frame of Europe. Inevitably the material upon which the MILLENNIUM project draws is wide, ranging across documentary and early instrumental sources to a variety of natural proxies.

The focus in the present paper, however, rests on analysing climate information in long instrumental temperature records, gridded SLP reconstructions, and documentary data evidence for past temperature variations in novel ways, including a variety of statistical techniques in conjunction with climate model simulations.

Fortunately much early European instrumental data have already been compiled. Many of the series go back well before the establishment of national meteorological services in the mid-nineteenth century. These series provide an important vehicle with which to link historical climatology with more well-established themes, in particular those of pressure field reconstructions and of climatic modeling, for a better

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understanding of the relationship between large scale circulation and European climate. In this context, the atmospheric circulation can be viewed as the main forcing factor for the regional interannual variability of temperature at middle and high latitudes (e.g. Trenberth 1990; Hurrell 1995; Jacobeit et al. 2001a; Slonosky et al. 2001; Xoplaki et al. 2003). Advective processes during wintertime exerted by the large-scale atmospheric circulation are crucial factors controlling regional climate changes. The relation between large-scale circulation and regional climate constitutes an important aspect for understanding variations in climate extremes, as circulation patterns are able to explain spatial distribution, regional characteristics and long-term dynamics of extremes in e.g. temperature and precipitation in a physically consistent way (Jacobeit et al. 2009).

For the present study, the basis for the selection of long temperature records used in the analysis is the requirement that co-located information from documentary evidence must exist back to the early sixteenth century. Documentary data allow us to examine, for example, trends in winter temperatures which cannot be gleaned from natural archives such as tree-rings (e.g. Brázdil et al. 2005; Pfister et al. 2008). We use seven such records. Some of the data series are new and were developed as part of the MILLENNIUM project. Of particular importance here is the Stockholm January–April (JFMA) mean temperature reconstruction and the Central Europe monthly temperature reconstruction. Both these series are discussed in detail in Dobrovolný et al. (2009b) and Leijonhufvud et al. (2009). The circumstance that the new Stockholm series is available only for the JFMA season further dictates the choice of the season for which we undertake analyses in the study. Brázdil et al. (2009) discuss various aspects of these records, including their relationships with temperatures in other parts of Europe, both as seen in gridded instrumental data and as recorded in various proxy reconstructions. Additionally, Zorita et al. (2009) compare the two new records with climate model simulations, leading to discussions related in particular to the reliability or unreliability of reconstructed and simulated low-frequency temperature variability.

In the current study, new insight on climate variability in Europe during the past few centuries is provided by arranging a set of different analyses using instrumental and documentary data in combination with coupled climate models that address various dynamical aspects of the European JFMA climate:

i) We show the interannual to interdecadal covariability between the large-scale JFMA atmospheric circulation and seven instrumental temperature series during the period 1760–2007 using Canonical Correlation Analysis (CCA).
ii) We present prominent atmospheric circulation patterns related to anomalously warm and cold JFMA conditions within different European areas spanning the period 1760–2007.
iii) We link long instrumental data series with a climate model (EC-Bilt-Clio) for a better dynamical understanding of the relationship between the large scale circulation and European climate. Applying an assimilation method, this exercise represents an alternative approach to reconstruct climate for the pre-instrumental period.
iv) We apply an analog case search method to extend the analysis of dynamic circulation for anomalously cold European JFMA conditions back to the sixteenth century combining instrumental and documentary data.

v) Finally, we test the skill of the analog case search method in the virtual world of two three-dimensional climate simulations (ECHO-G and HadCM3).

2 Data

The dataset used for this study includes temperature series based on instrumental measurements (mainly 1760–2007) and documentary data (∼1500–1759—either expressed as scaled indices on an ordinal scale or as anomalies in °C calibrated to temperatures with respect to a current reference period). The choice of 1760 (except for Warsaw and Cracow) as the starting year for the instrumental data is somewhat arbitrary but the new Central European temperature series (CEu) presented by Dobrovolný et al. (2009b) begins in 1760 and most of the instrumental temperature series used here start approximately at that time. These series are analyzed in conjunction with gridded SLP reconstructions (Küttel et al. 2009) and three GCMs. As explained in the introduction we focus our analysis on the JFMA season.

2.1 Instrumental temperature series

The analysis is based on the following long-term series:

i) **Berlin** (1760–2007): The series consists of observations from different parts of the Berlin area (Hellmann 1883; Rapp 2000 and references therein). It was homogenized from 1780 onwards using an absolute homogeneity test procedure (Abbe and Lazante) and tests for discontinuities (autocorrelation and Alexandersson tests) by Beck (2000).

ii) **Central Europe** (1760–2007): The series was calculated as an average of 11 homogenized series from the HISTALP database (Auer et al. 2007) from Austria (Kremsmünster, Vienna-Hohe Warte, Innsbruck), Switzerland (Basle, Geneva, Bern), Germany (Regensburg, Karlsruhe, Munich, Hohenpeissenberg) together with the station Prague-Klementinum (Czech Republic), all of which were corrected for insufficient radiation protection of early thermometers (see Böhm et al. 2009). The reader is referred to Dobrovolný et al. (2009b) for a detailed description of the construction of the Central European series.

iii) **De Bilt** (1760–2007): The data from the post 1760 period are better known as the Labrijn series (Labrijn 1945) and have been adjusted to De Bilt. Since 1901 the series continues on the present observation site of the Royal Netherlands Meteorological Institute. The older part of the monthly series (1706–1854) has been improved by adjusting with contemporary series at 15 locations in the Netherlands (van Engelen and Geurts 1983–1992; van Engelen and Nellestijn 1996). The series is considered to be homogeneous for DJF, JJA and annual temperatures (Shabalova and van Engelen 2003).

iv) **Northern Italy** (1760–2007): The series was calculated as an average of five series from Padua, Bologna, Milan, Florence and Vallombrosa (Camuffo et al. 2009 and references therein). The original data have been corrected for instrumental errors, observation methodology, exposure (to solar radiation) and relocation and have been homogenized.

v) **Stockholm** (1760–2007): The observations for the entire period come from the old astronomical observatory in the city the location of which has not changed.

The temperature series was homogenized with respect to changing observation hours, number of observations per day, known instrumental errors and the urban heat island effect (Moberg et al. 2002).

vi) **Tallinn** (1760–2007): The series before 1805 was created by interpolations between the long series from Stockholm and St. Petersburg and shorter series from Loviisa and Porvoo (Finland). Until 1849 it is a composite of several shorter series from different sites in the Tallinn area (Tarand 1992). In 1850 a new series of observations was started in Tallinn leading to improved data quality. The series has been homogeneity tested and adjusted by Tarand (2003).

vii) **Warsaw** (1779–2001) and **Cracow** (1792–2007): we use an average of temperature data from two Polish sites. The observations for Warsaw stem from the old astronomical observatory in the town. Non-homogenous periods appear to be the years 1790–1799, 1808–1828 and 1886–1914. In June 2002 the entire observatory was moved to another location in Warsaw. The observations for Cracow come from the old astronomical observatory in the Jagiellonian University without any change in location. The temperature records for both sites have been homogenized using Alexandersson and Craddock tests for annual data (see Trepińska 1997).

2.2 Series based on documentary data

The following reconstructions are based on a number of documentary sources which in some ways correspond to (or are continued) by the above mentioned instrumental series. It is important to note that, except for the reconstructed Stockholm and Central European temperature, the other pre-1760 temperature series represent a slightly different combination of winter/spring months than the otherwise used JFMA season. Because the various documentary series represent different definitions of seasons, it is not possible to undertake an analysis where all data represent the same defined season. However, by allowing slightly different definitions of seasons greater number of documentary data sites can be included in the analysis than would otherwise have been the case.

i) **Ice winter severity index for Western Baltic** (1500–1759): this was derived from classified values of accumulated areal ice extent along the German Baltic coast back to 1701. The series was extended beyond 1701 by the inclusion of other ice cover information from coastal locations and from indirect indices derived from tax reports of Danish harbor stations (Koslowski and Glaser 1999).

ii) **Central European temperature series—CEu** (1500–1854): this monthly index temperature series based on documentary data from Germany, Switzerland and the Czech Republic were standardized and averaged for the period 1500–1854. An overlap with the instrumental series of Central Europe (see above) for the period 1760–1854 allowed linear regression methods to be used on the quantified documentary-based indices from as early as 1500. The reconstructions before 1760 were finally re-calculated to have the same mean and variance as the measurements over the overlapping period (Dobrovolný et al. 2009a, b).

iii) **Low Countries Temperature—LCT** (1500–1759): The series (which extends back to AD 764), covering the region of the present Netherlands and neighbouring land areas near the southern part of the North Sea, include documentary based NDJFM (winter) and MJJAS (summer) indices and the derived instrumental winter (DJF) and summer (JJA) temperatures for De Bilt (e.g. van den Dool et al. 1978). The winter-indices are calibrated against the number of days that ice forming and/or frost was observed (van Engelen et al. 2001). The LCT series can be considered as homogeneous from 1300 onwards (Shabalova and van Engelen 2003).

iv) **Northern Italy** (1500–1759): Indices are derived from the analysis of 70 contemporary documentary sources. These sources mainly stem from the regions of Padua, Venice and Bologna. The series was calibrated and verified against instrumental readings from Padua and Bologna in the overlapping period 1716–1760. The series was recalculated to have the same mean and variance as the instrumental observations. For more details the reader is referred to Camuffo et al. (2009).

v) **Stockholm** (1502–1759): The start of the sailing season in the Stockholm harbour derived from custom ledgers and other documents related to port activities was abstracted for the period 1502–1892. Several, partly overlapping, time series derived from these records were standardized and averaged. The resulting composite series was calibrated and verified against Stockholm JFMA instrumental temperatures for the overlapping period (1756–1892). The reconstruction for 1502–1759 was then re-calculated to have the same mean and variance as the instrumental measurements in the overlapping period (Leijonhufvud et al. 2008, 2009).

vi) **Tallinn series** (1500–1759): The first day of ice break-up in the Tallinn port since 1500 and on the rivers in northern Estonia since 1731 were used as proxy data. A regression model has been calculated fitting the proxy information to the instrumental Tallinn temperature series and applying the statistical models to the paleo information under the assumptions of stationarity between the predictor (proxies) and predictand (instrumental data) variables (Tarand and Nordli 2001).

vii) **Poland**: (1500–1779): Information about past weather conditions is found in the collection of largely continuously written notes about atmospheric phenomena. Temperature indices were derived from different documentary sources concentrated mainly on the area of Cracow (e.g. weather diaries kept by a number of professors at Krakow University; see Limanówka 1996, 2000, 2001; Dobrovolný et al. 2009b). Temperature indices are partly available for single months, for seasons and for the entire year. An overview of existing documentary evidence from Poland is provided by Przybylak et al. (2010). In addition, Luterbacher et al. (2010) provide evidence on climate change in Poland in the Past Centuries and its Relationship to European Climate using reconstructions and coupled climate models.

2.3 Gridded Sea Level Pressure (SLP)

A new 5×5 gridded and seasonally resolved SLP dataset, developed by Küttel et al. (2009), has been used in the analysis. This reconstruction combines instrumental pressure series and maritime wind information derived from ship logbooks to statistically reconstruct North Atlantic, European and Mediterranean SLP (40°W–50°E and 30°N–70°N) fields back to 1750. Principal component regression models were derived between pressure series and wind information and the HadSLP2r data

(Allan and Ansell 2006) over the period 1887–2001, with these models then applied to the available data 1750–1886 period. The resulting SLP dataset covers the period 1750–2007. From 1750–1849 they are reconstructed, from 1850–2007 the consist of the HadSLP2r updated reanalysis dataset (Allan and Ansell 2006). Very high skill values are obtained over large areas, except for the northwestern and southeastern corners (see Küttel et al. 2009 for details). The SLP reconstruction does not share any common predictors with reconstructed European temperature and precipitation series (Luterbacher et al. 2004; Luterbacher et al. 2007; Xoplaki et al. 2005; Pauling et al. 2006; Küttel et al. 2010); thus it can be used independently to assess the driving atmospheric patterns behind recent and past temperature and precipitation anomalies. We recalculated the SLP fields for the JFMA, JF and MA averages.

2.4 Model data

Climate model output data is used here for two purposes: In the first application a small number of data assimilation simulations have been made with the coupled ocean–atmosphere–sea ice general circulation model of intermediate complexity EC-Bilt-Clio. In the second application we use the output of two GCMs (ECHO-G and HadCM3) as a test-bed to evaluate the analog-based reconstruction method.

a) EC-Bilt-Clio

The EC-Bilt model is a coupled ocean–atmosphere–sea ice general circulation model of intermediate complexity (Opsteegh et al. 1998; Goosse and Fichefet 1999). The atmospheric component (EC-Bilt) is a T21 global model, corresponding to a resolution of ca. 5.6° × 5.6°. It has three levels in the vertical (800, 500 and 200 hPa). The dynamical part is an extended quasi-geostrophic model where the neglected ageostrophic terms are included in the vorticity and thermodynamic equations as a time dependent and spatially varying forcing. With this forcing the model simulates the Hadley circulation with qualitative precision and the strength and position of the jet stream and transient eddy activity are acceptably realistic. The model contains simple physical parameterizations, including a full (albeit simplified) hydrological cycle. The oceanic component (Clio) is a primitive equation, free-surface ocean general circulation model coupled to a thermodynamic–dynamic sea ice model and includes a relatively sophisticated parameterization of vertical mixing (Goosse and Fichefet 1999). The horizontal resolution of Clio is 3° × 3° and it has 20 unevenly spaced layers in the vertical.

b) ECHO-G

ECHO-G is a coupled atmosphere–ocean general circulation model (AOGCM), consisting of the ECHAM4 atmospheric general circulation and the Hamburg Ocean Primitive Equation models HOPE-G, which includes a dynamic–thermodynamic sea–ice model with snow cover. The atmospheric component ECHAM4 has a horizontal resolution of T30 (approx. 3.75° × 3.75° longitude X / latitude) and 19 levels along the vertical direction, five of them located above 200 hPa and with the highest being at 10 hPa. The oceanic component HOPE-G has a resolution of approx. 2.8° × 2.8° longitude X / latitude, with a decrease in meridional grid-point separation towards the equator. HOPE-G has 20 levels along the vertical direction. Due to the interactive coupling between ocean and atmosphere and the coarse model resolution, ECHO-G needs a constant mean flux adjustment to avoid a significant climate drift. Thus additional fluxes of heat and freshwater are applied to the ocean. This flux adjustment is constant in time and its global integral vanishes. In this study, the ERIK2 simulation of ECHO-G is used (González-Rouco et al. 2006; Zorita et al. 2007). It is an all-forcings simulation (without anthropogenic aerosols) for the period 1000–1990.

To drive the simulation, changes of solar irradiance, greenhouse gases and the radiative effect of volcanic eruptions were used as external forcings. The volcanic forcing was treated simply by a modulation of the solar irradiance. This implies that the model's response to volcanic forcing can lack dynamic effects that occur in the real world (Gouirand et al. 2007).

c) HadCM3

Similar to ECHO-G, HadCM3 is a state-of-the-art AOGCM. Unlike ECHO-G, however, no flux adjustment is applied in the model to prevent large climate drifts. A small long-term climate drift is present, the magnitude of which is estimated from a long control run. This drift is then corrected from the temperature data of the present simulation (Tett et al. 2007). The atmospheric component HadAM3 is a version of the United Kingdom Meteorological Office (UKMO) unified forecast and climate model with a horizontal grid spacing of 2.5° (latitude) × 3.75° (longitude) and 19 levels along the vertical direction. The ocean component has 20 levels with a spatial resolution of 1.25° × 1.25°. The resolution is higher near the ocean surface. This study utilizes a HadCM3 run including natural forcing from 1500–1749 and a natural-plus-anthropogenic forcing in the period 1750–1999. The part using natural forcings alone is driven by prescribed changes in volcanic, solar irradiance and orbital factors, while anthropogenic forcing factors were fixed at estimated pre-industrial values. The second part takes prescribed changes in volcanic forcing, solar irradiance, orbital forcing, greenhouse gases, tropospheric sulphate aerosol, stratospheric ozone and land-use/land-cover into account. Two additional forcings included in the HadCM3 are tropospheric aerosols during the twentieth century and historical changes in land use. The volcanic forcing was implemented in the HadCM3 model by modifying the stratospheric optical depth in four equal-area latitude bands according to ice-core estimations of the sulphate aerosol loads following volcanic eruptions (Tett et al. 2007). In contrast to the scheme used in ECHO-G, this scheme should in theory capture the response of the winter circulation to volcanic forcing, although this response is actually not detected in the simulations (Tett et al. 2007).

3 Methods

3.1 Canonical Correlation Analysis (CCA)

To assess the connection between the gridded large-scale SLP data of Küttel et al. (2009) and the seven instrumental JFMA mean temperature series over the 1760–2007 period we calibrated a statistical downscaling model using CCA in a Principal Component Analysis (PCA) space. CCA is a statistical technique that relates multiple predictor variables to multiple predictand variables in such a way that the correlation is maximized (e.g. Wilks 1995; von Storch and Zwiers 1999). In this study we follow the methodology presented by Della-Marta et al. (2007). The main steps are:

1. The long-term linear trend was removed from each predictor (JFMA mean SLP 1760–2007; Küttel et al. 2009) and predictand (JFMA mean temperature series from the seven instrumental sites covering the period 1760–2007). In the case of the Polish data we removed the 1793–2007 linear trend as the time series is shorter.
2. The predictor and predictand data were standardized by subtracting their long-term mean and dividing by their long-term standard deviation (1760–2007, but 1793–2007 for Polish data). This had the effect of giving equal weight to all gridpoints and station temperature series.
3. Following the Preisendorfer (1988) method of CCA the predictor and predictand were dimensionally reduced using PCA. In order to derive the significance level that determine how many PCs are to be used, 1,000 synthetic datasets were created and the significant number of PCs assessed at the 5% significance level is thereby determined by the synthetic data. Both the PCA and CCA calculations were performed using the Singular Value Decomposition (SVD) algorithm, detailed in Preisendorfer (1988).
4. The significant number of PCs set an upper limit for the number of PCs used in the CCA. However, as with Multiple Linear Regression (MLR), adding more predictors does often not necessarily result in a higher model skill. To address this problem we performed a CCA for a combination of predictor PCs and predictand PCs and performed a one time step cross-validation procedure (e.g. Michaelsen 1987), i.e. repeatedly leaving 1 year out of the CCA, and then assessed the prediction errors as the mean Spearman rank correlation skill score. The number of predictor and predictand PCs are each increased one at a time and the combination with the highest skill score is taken for further analysis.
5. In order to assess the statistical significance of the finally derived CCA patterns and the canonical correlation coefficients, we used a Monte Carlo technique similar to those adopted by Shabbar and Skinner (2004) where the PCs of the predictand were randomised 5000 times using a bootstrap with replacement technique. The CCAs of each of these synthetic series were used to build an empirical probability distribution for each statistic of the CCA.
6. The expansion coefficients of the CCA were projected onto the original (non-detrended) data in order to maintain the long-term trends in the temperature and MSLP series.
7. The significance of 30 and 20 year moving linear trend analyses is assessed by using a bootstrap technique. The partial auto-correlation coefficients of the CCA score series indicate that they are white in spectrum, hence there is no need to account for autocorrelation in the generation of 1000 synthetic timeseries of length 248 years, randomly sampled from a normal distribution. We assess the significance of the observed 30 and 20 year trends by comparing them against the distribution of the synthetic series trend values at the 5% and 10% significance levels.
8. The low pass filters applied to the CCA scores series are created using a Fourier transform method, by retaining waves with a period longer than about 20 years.

3.2 PCA based circulation patterns associated with anomalous JFMA temperatures

By using the new gridded SLP field reconstruction (Küttel et al. 2009) we present prominent atmospheric circulation patterns related to anomalous warm and cold JFMA conditions within different European areas spanning the period 1760–2007.

To derive major atmospheric circulation patterns the method described in Jacobeit et al. (1998, 2001b, 2003) was applied, which is based on rotated T-mode Principal Component Analysis (PCA) of SLP fields for a subset of years with anomalous temperatures. Only those PCs having the greatest loading among all the PCs for at least one of the original pressure fields were retained. Thus it is ensured that the extracted components represent dominant circulation patterns with sufficiently high spatial correlations with real SLP patterns (as in the present case with maximum T-mode loadings above 0.8). The temperature anomalies are determined separately for three regions in different latitudes: Central Europe (De Bilt, Berlin and CEu), Northern Europe (Stockholm and Tallinn) and Southern Europe (Padua, the only available station with data for the entire period). For every region warm and cold years are selected on the basis that at least one station exceeded the 1760–2007 climatology by one standard deviation (SD). For each of these samples, which contained 10–21% of all available SLP fields for cold/warm anomalies, the corresponding SLP grids are dimensionally reduced by T-mode PCA with varimax rotation (Jacobeit et al. 2003). The resulting major circulation patterns explained more than 95% of the SLP variance during these anomalous JFMA seasons.

3.3 Assimilation of paleoclimatic reconstructions

Because of a large degree of randomness in the time evolution of the dynamic circulation system from a certain initial state, a simulation with a climate model cannot fully replicate the observed climate trajectory even if the climate model would be perfect. One way to select the observed trajectory among all those physically possible trajectories is by the so-called data assimilation technique. The assimilation method used here has been presented in paleoclimatic studies (e.g. van der Schrier and Barkmeijer 2005, 2007; van der Schrier et al. 2007; Widmann et al. 2009; Goosse et al. 2009). In this technique, a perturbation to the forcing terms of the atmospheric equations of motion is applied to optimally nudge the atmospheric model to reproduce a specified target pattern. This tendency perturbation is recalculated every 72 h; frequent enough to allow climatic components with a long characteristic timescale, like SSTs or snow cover, to feedback on the atmosphere. Importantly, synoptic-scale variability internal to the atmospheric system, is not suppressed and can freely adjust to the changes in the large-scale atmospheric circulation. The tendency perturbations are referred to as forcing singular vectors (Barkmeijer et al. 2003) and are used to modify large-scale patterns of variability only, leaving the synoptic scale variability to evolve freely. The application of this assimilation approach gives a model-based climate reconstruction which ensures dynamical consistency between the model output and the reconstruction and provides a gridded, model-based and observations-consistent reconstruction of the physical fields in the past. The prognostic variable in the dynamic part of the EC-Bilt model is potential vorticity, which can be related, through the linear balance equation, to the stream function. We are here interested in tendency perturbations that will produce a deflection of the model atmospheric state in the direction of the target pattern. In our assimilation experiments, the JFMA SLP reconstruction (Küttel et al. 2009) is used as input to EC-Bilt-Clio where SLP anomaly patterns, as deviations from the observed climatology, are used as target pattern. We use the technique to illustrate, for two selected years (1817 and 1829; Figs. 6 and 7), anomalous patterns of simulated temperature, snow depth, albedo and precipitation.

3.4 Analog case search for large scale SLP fields related to anomalous European temperatures

The strong relationship between European winter climate conditions and atmospheric circulation allows for the identification of SLP patterns based on observed JFMA temperatures in anomalous years. Analog SLP fields are chosen from the period of instrumental SLP data (1760–2007) to independently reconstruct corresponding large-scale SLP fields for periods when widespread direct pressure information is not available (see Jones et al. 1999; Luterbacher et al. 2002; Küttel et al. 2009, 2010). Here, we present anomalous SLP maps related to cold JFMA together with corresponding anomalous European land temperature and precipitation patterns.

3.4.1 Spatial representation

The approach of an analog case search and the subsequent reconstruction of large-scale SLP fields relies on the degree to which they represent (in a spatial context) the underlying temperature records as the predictors. It is therefore essential that proxy-based temperature reconstructions are indeed spatially representative. As described above the temperature records used consist of documentary derived data before 1760, and instrumental series representative for the same areas after 1760. We tested all seven instrumental records for their ability to represent European anomalous temperature conditions. Although such an examination was made only on the instrumental records, various studies have also referred to the ability of purely documentary records to represent likewise the spatial structure of climate elements (e.g. Glaser et al. 1999; Brázdil et al. 2005; Dobrovolný et al. 2009a, b). In our representation analyses, the instrumental temperature series are correlated with an instrumental gridded temperature data set (Mitchell and Jones 2005) over the period 1901–2000 for the JFMA season by using the grid point squared Spearman correlation. All records were tested for spatial representation both independently as well as in different combinations (not shown) with the aim of reducing the number of records (optimal combination) needed to best reflect the temperature signal over the whole European region. Based on this test of spatial representation we found that only two of the seven temperature series, namely Stockholm and Central Europe, were sufficient to capture the integrated European temperature anomaly field (Fig. 8). Both records are very significantly correlated to the European JFMA temperature field as a whole, according to a test of significance that takes into account the spatial autocorrelation of temperature (Livezey and Chen 1983). The number of land grid cells that locally surpass the local one-tailed 5% significance level is 91% (Central Europe) and 81% (Stockholm) of all land grid cells, whereas the 5% field-significance level lies by 27% of all land grid cells. These records/locations will be used, therefore, to identify the best analogs.

3.4.2 Analog search procedure

In order to find potential analogues the search is based on an algorithm (Koenig 2007) that identifies cold temperature anomalies in the pre-instrumental (i.e. pre-1760) and the instrumental periods (1760–2007) for those intervals when we have overlap with the SLP data (Küttel et al. 2009). To define the temperature anomalies, an overall threshold was set to 1 SD above/below the 1961–1990 climatology. After having identified the anomalous years in the pre-instrumental and instrumental part of the temperature series, the corresponding instrumental SLP fields for the anomalous years, found in the instrumental period, are taken as analogues. Anomaly composites (with respect to the 1961–1990 reference period) of these analog SLP fields suggest characteristic large-scale circulation patterns for mean JFMA SLP in anomalously cold winters. Additionally, we present the corresponding anomalous temperature and precipitation composites.

3.4.3 Application of the analog method on model data

The analog method is assessed by applying the reconstruction procedures to two independent model simulations (Franke et al. 2009). We use the ECHO-G Erik 2 simulation (González Rouco et al. 2006, 2009) and the HadCM3 simulation (Tett et al. 2007) for the periods 1000–1990 and 1500–2000, respectively. In comparison to the temperature reconstruction based on documentary data, temperature time series of the models exhibit more low frequency variations. A more detailed discussion about potential low-frequency bias in documentary data is discussed in Dobrovolný et al. (2009a, b) and Zorita et al. (2009). Thus, regardless of the effective causes of the model/data differences in the representation of the low frequency variability it is necessary to place both in a comparable framework. This has been done by filtering out the low frequency signal in the model simulations so that certain extreme periods in a long term context (e.g. Late Maunder Minimum) would not lead to a biased detection of extreme values. Therefore, a 30-year high-pass filter is applied to the series to preserve only the high frequency component. As a result only those extreme years (based on the above mentioned 1 SD criterion) which occur simultaneously in the time series of the chosen locations are selected.

4 Results and discussions

First, we show the coupled CCA patterns which optimally relate JFMA SLP to the seven selected temperature series covering the same period. Second, we present the most prominent atmospheric circulation patterns related to anomalous warm and cold JFMA conditions within three European areas spanning the instrumental period 1760–2007. Third, we present results of a climate simulation into which the reconstructed JFMA SLP has been assimilated with the EC-Bilt-Clio model. Fourth, we use the combined information in the documentary (i.e. pre-instrumental) and instrumental records and analog search algorithms to define cold anomaly cases for the JFMA season. The cold anomalies that are thereby identified within the instrumental period are used to define anomaly fields in the selected gridded SLP, temperature and precipitation reconstructions. Finally, the skill of this analog case method is evaluated in the test-bed provided by the climate models ECHO-G and HadCM3.

4.1 CCA between JFMA large-scale atmospheric circulation and seven European local to regional temperature series 1760–2007

We investigate the interannual to interdecadal covariability between the large-scale JFMA atmospheric circulation and the seven instrumental temperature series during the period 1760–2007 using CCA. The results focus on the first CCA mode, which captures 35% of the temperature and 23% of the SLP variability. Spatial patterns and expansion coefficients of the mode are presented in Fig. 1. This pair exhibits a canonical correlation of 0.76 (significant at the 1% level). The number of predictor and predictand PCs used is six and four, respectively. The first canonical map of SLP shows the well-known dipole pattern with positive correlation values south of approximately 50°N and negative correlation values over the subpolar region (Fig. 1. right top). An anomalous strong westerly flow is responsible for the significant positive temperature anomalies at six of seven stations. The scores in Fig. 1 (bottom, red line) indicate a positive significant long-term trend in the temperature, but not in the circulation score series. There are also significant trends in the predictor and

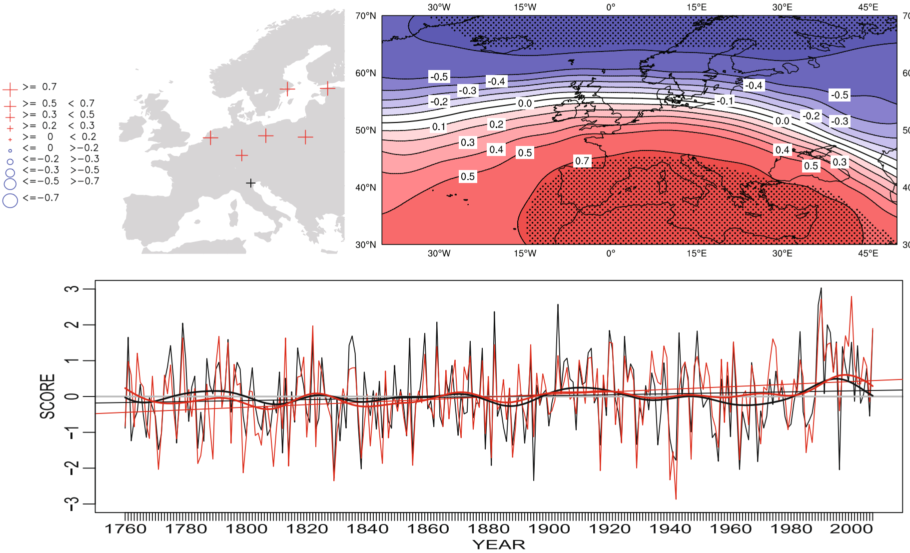


Fig. 1 The first CCA between JFMA averaged SLP and the seven station series which accounts for approximately 35% of JFMA temperature variability. (*top left*) The temperature canonical pattern, (*top right*) the SLP canonical pattern and in the lower panel the canonical score series from 1760 to 2007. In *top left* the sizes of the *crosses* ('+') and *open circles* ('*o*'), respectively, show the magnitude of canonical loadings according to the legend on the left of the figure. *Red* (*blue*) areas in *top right* indicate positive (negative) correlations above (below) 0.1. *Stippled areas* in *top right* show statistically significant correlations at the 5% level. Both CCA loadings in *top left* and *top right* panels are expressed as a correlation coefficient between each grid point (or station) data (standardized and de-trended according to the "Methods" section) and the canonical score series for each grid point (station). *Symbols* that are colored *red* (*blue*) indicate statistically significant positive (negative) correlations at the 5% level, whereas *black symbol* indicate lower than the 5% significance level correlations. In the *bottom panel* the *black* and *red lines* are the SLP and temperature canonical score series, respectively, which have a significant (5% level) correlation coefficient of 0.76. The *smoothed lines* are low pass multi-decadal filtered series

predictand CCA1 scores during four multi-decadal periods. The first, a negative trend from ~1789–1808, the second a positive trend from around 1803–1822, the third a negative trend from around 1913–1942 and the fourth, the well documented positive trend from approximately 1970 to the late 1990s. Recent years indicate a slight downward trend in the circulation and temperature relationship, however, using our methodology this decline is not statistically significant.

The CCA analyses reveal consistency in identifying the most important driving patterns of atmospheric circulation accounting for JFMA temperature variability over the seven European stations. The simple mechanism behind this link highlights: a) the advection of moist mild air masses from the Atlantic that favour warmer temperatures over most of the stations in the positive mode of CCA1 and b) the advection of cold continental air inducing negative temperature anomalies in the negative mode of the CCA, this mechanism being in winter strengthened by night time clear sky radiative loss.

We also performed CCA experiments for January–February and March–April and found that the differences were small (not shown).

4.2 PCA-derived circulation patterns associated with warm and cold JFMA anomalies

Based on the large-scale SLP grid fields covering the 1760–2007 period major circulation patterns associated with warm and cold anomalies (with reference to the 1760–2007 climatology) of the JFMA season are presented.

The number of these patterns (together explaining 95% of the variance) was four in the cold anomaly cases, but only two or three in the warm anomaly cases. For the sake of brevity, we only present the first two most important PCs that account for a significant amount of SLP variance (Figs. 2 and 3). Further, the major circulation patterns and variances explained are similar for Padua and Central Europe, therefore we only present the maps for Central and Northern Europe.

Warm anomalies in Central Europe (Fig. 2 left) are connected with a northeastward extension of the Azores High. In the case of Northern Europe (Fig. 2 right) the anticyclonic centre is shifted up to southwest England thus inducing a mixed circulation pattern (between zonal and meridional configurations).

The second important pattern for warm anomalies in all three regions (second PC) involves a strong Atlantic cyclone and a Russian high in a rather easterly position. This allows southerly advection in the western half of Europe. The main difference between the regional variants relates to the longitudinal position of the transitional area between cyclonic and anticyclonic predominance which is most eastward for Padua (not shown) and distinctly shifted westward for Northern Europe (Fig. 2). The explained variance for the two central European (northern Europe) PCs is 61.3% and 34.1% (39.2% and 35.6%), respectively.

The third PC (not shown) with a strong cyclonic centre west of Scandinavia leads to warm anomalies only in the northern region since northwesterly components prevail in more southern latitudes. In the cold-anomaly cases, the first PC (Fig. 3) reflects again a zonal circulation pattern.

However, the SLP composite pattern from cold JFMA seasons being associated with this first PC differs from the corresponding composite pattern from the warm seasons (not shown). The latter reflects a mid-latitude westerly flow with advection

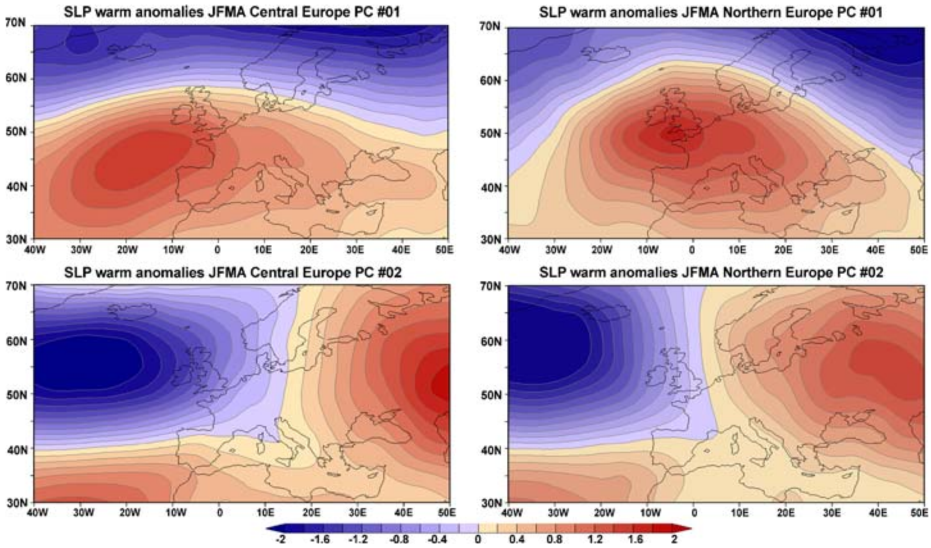


Fig. 2 Major circulation patterns associated with warm JFMA seasons in Central Europe (*left*) and Northern Europe (*right*) over the 1760–2007 period, derived from objectively reconstructed SLP fields (developed in Jacobeit et al. 1998; normalized T-mode PCA scores). The regions in *blue* (*red*) colours show low (high) pressure systems. The explained variance for the two PCs for Central Europe is 61.3% and 34.1%; for Northern Europe it is 39.2% and 35.6%

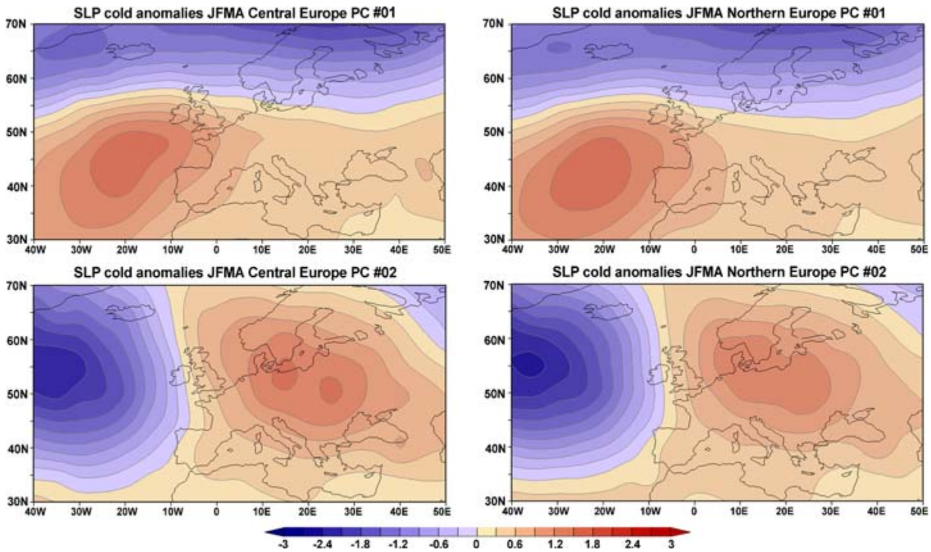


Fig. 3 As Fig. 2, but for cold JFMA seasons in Central Europe (*left*) and Northern Europe (*right*). The explained variance for the two PCs for Central Europe is 32.9% and 32.1%, in the case of Northern Europe it is 41.0% and 33.2%

of warm Atlantic air masses towards the European continent, whereas the former indicates a more northerly position of the westerlies over Europe in connection with relatively high pressure in the mid-latitudes (favouring radiative cooling during this season) and lower pressure in the northern Mediterranean (supporting even a cold easterly component to the north). Thus, important temperature variations within the same circulation pattern (Jacobeit et al. 2001a, 2003; Beck et al. 2007) have to be considered. The second PC for all three regions depicts a blocking European high anomaly that prevents relatively warm Atlantic air from influencing the continent and leads to cold conditions in large parts of Europe (Fig. 3). The explained variance for the two central European PCs (northern Europe) is 32.9% and 32.1% (41.0% and 33.2%), respectively.

Further patterns associated with cold anomalies (not shown) include an anticyclonic centre in a more easterly position (Russian high) with cold air advection towards the west and a trough-like pattern (probably in deep cold air) with different amplitudes for the various regions.

In general, the JFMA circulation patterns within the 1760–2007 period associated with warm and cold anomalies are quite similar for the different regions. Slight differences relate to the amounts of explained variance and in some cases to particular positions of pressure centres or domains of influence. The fact that zonal circulation patterns occur in both warm and cold winter sub-samples indicates important within-type variations which modulate weather and climate characteristics of circulation patterns. Variations within the advection of warm Atlantic air masses and radiative cooling by anticyclonic subtypes are examples in this regard. Furthermore, particular circulation patterns linked with cold anomalies but persisting only for considerably shorter periods than 4 months might not be represented in seasonal mean values.

Earlier studies relating circulation to the sixteenth century temperature anomalies used subjectively derived monthly or seasonal mean SLP patterns for outstanding warm and cold winters in Europe (Jacobeit et al. 1999). Subsequently, analyses were based on earlier objective SLP reconstructions back to 1780 (Jones et al. 1999), including studies on both long-term variability of circulation and climate (Beck et al. 2001) as well as investigations on SLP patterns associated with Central European temperature anomalies (Jacobeit et al. 1998). In general, there is good correspondence with the results found here for cold anomalies. However, Jacobeit et al. (1998) identify six different circulation patterns, mainly the result of the higher temporal resolution (monthly versus seasonal in the present study). Circulation patterns derived by a cluster analysis of reconstructed daily SLP fields back to 1850 have also been characterized by corresponding temperature anomalies (Philipp et al. 2007; Jacobeit et al. 2009). The studies also included all patterns presented here for warm and cold anomalies, though reflecting more regional differences than those being captured by a seasonal mean analysis presented herein.

Analyses were also performed for 2-month seasons (JF; MA, not shown): no westerly circulation patterns were found for cold anomalies in March/April, instead the first PC patterns (Central and Northern European areas) depict a Mediterranean low pressure system with easterly components to the north. For cold anomalies in January/February the westerly pattern is combined with a Russian high further to the east, thus Central Europe is situated in a transitional area between westerly and easterly components.

Only the 4-month analyses provide basic westerly patterns for cold anomalies (Figs. 2 and 3). However they represent fewer cases compared to warm anomalies (roughly 1:4) and account for considerably less SLP variance (e.g. 33% versus 61% in the Central European analysis). They refer to SLP fields whose composites differ from those for warm anomalies (see paragraph above).

4.3 Assimilation of the SLP reconstruction in a simplified GCM

The assimilation method described above is used here to simulate a climatic trajectory for which the JFMA atmospheric circulation is close to the present SLP reconstruction (Küttel et al. 2009). The time span analyzed is from 1750 to 2005. SLP is, however, not a prognostic variable in the model. Therefore, to be able to apply the data-assimilation technique, we computed the geopotential height field at 800 hPa which is associated with the SLP reconstruction, and transformed this into the stream function. By starting from different initial conditions, a three-member ensemble is produced. Based on the ensemble mean, the year-to-year JFMA-averaged stream function on the lowest model level is calculated and compared to the reconstruction of the stream function. In the remainder of this section, only those years that have a pattern correlation between the simulated and the reconstructed stream function fields above 0.8 will be considered. This reflects 30% of the years in this time span. Conditional on this requirement, the simulation with data-assimilation captures much of the observed year-to-year variability in early instrumental temperature records in the sense that correlations with early instrumental temperature records, averaged over the JFMA season, are higher than would be expected from chance alone. Figure 4 shows the correlations between each of the seven early instrumental temperature records and the simulated 2 m temperature field for the same season (correlations of 0.33 and higher are significant at the 5% level). The correspondence in year-to-year variability can only be related to the similarity of the simulations to the assimilated SLP reconstruction since observed changes in external forcings such as solar activity or volcanic aerosol loadings are not parameterized in these simulations. The correlations reach values up to about 0.7, but the location of the maxima, which should be at the location of the particular instrumental station series, is generally too far north. This is related to the fact that the centres of action of the model's variability are offset to the north.

Next, we provide evidence that the simulated surface temperature fields recover the same signal as early instrumental temperature measurements averaged over the selected period 1790–1820. This period is sometimes referred to as the 'Dalton Minimum' and is the last cold period within the European 'Little Ice Age'. Averaged over the 1790–1820 period, 2 m temperature anomalies (with respect to the 1961–1990 climatology) of the data-assimilation simulation are shown in Fig. 5. A tongue of cold temperatures that extends from northern Scandinavia over western Europe and into Spain is evident. A similar pattern was retrieved in an earlier simulation for this period (van der Schrier and Barkmeijer 2005) and was shown to be very similar to reconstructions of surface temperature (Luterbacher et al. 2004).

To analyse the data assimilated simulation in more detail, two particular extreme JFMA years are selected. The first example (1817, Fig. 6) is one of the warm winters following the Tambora eruption in April 1815. The second example (1829, Fig. 7) had a cold JFMA season in the CEu, Low Countries, Stockholm and Tallinn series. In both cases, the pattern correlation between the simulated stream function of the ensemble mean and the SLP-based reconstruction of the stream function is higher

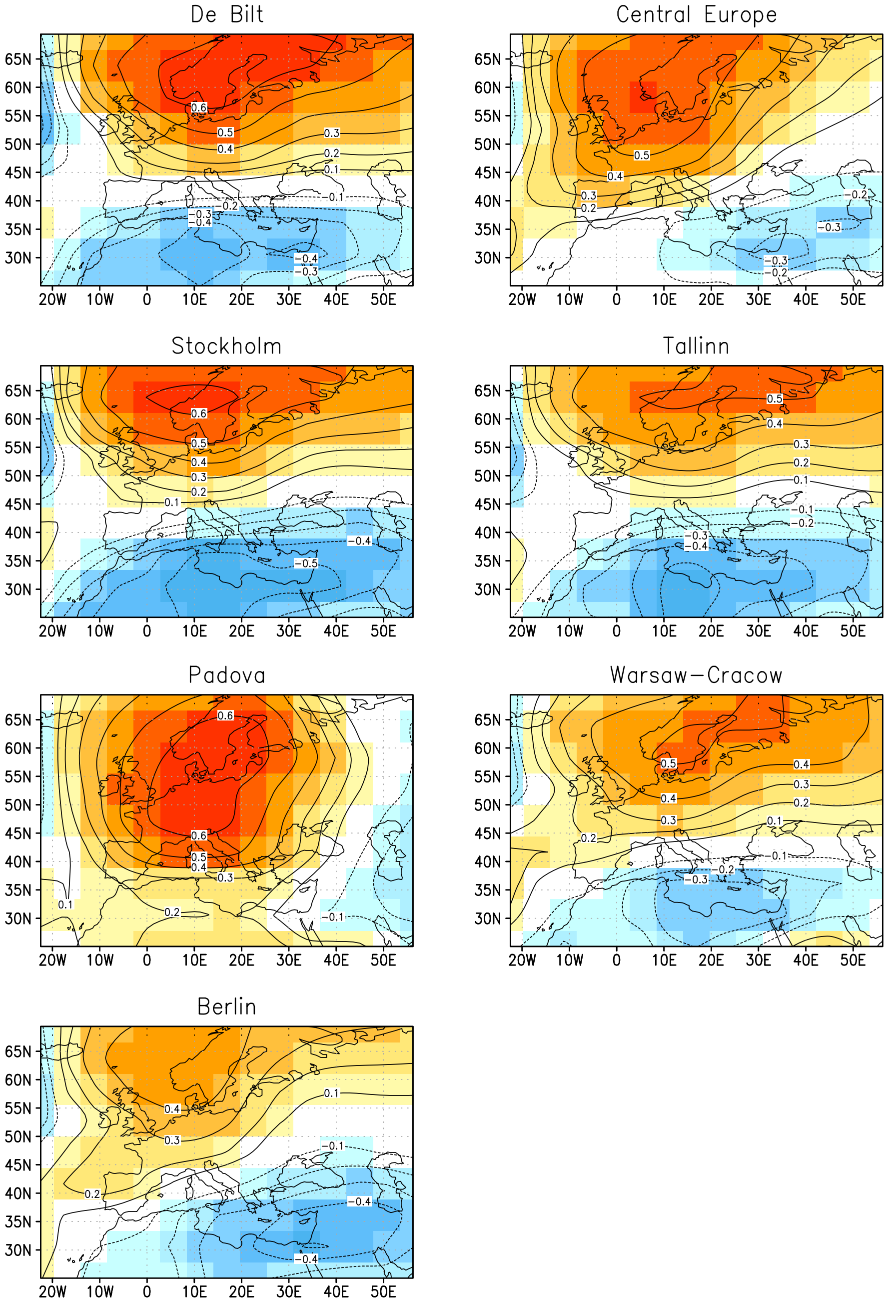


Fig. 4 Temporal correlations between the assimilated simulation of 2 m temperature, averaged over JFMA, and the instrumental temperature records from De Bilt, Central Europe, Stockholm, Tallinn, Padua, Warsaw-Cracow and Berlin averaged over the same season. Correlation maps are conditional on the pattern correlation between the streamfunction defined by the model and the SLP-based reconstruction being equal or higher than 0.8 in each year

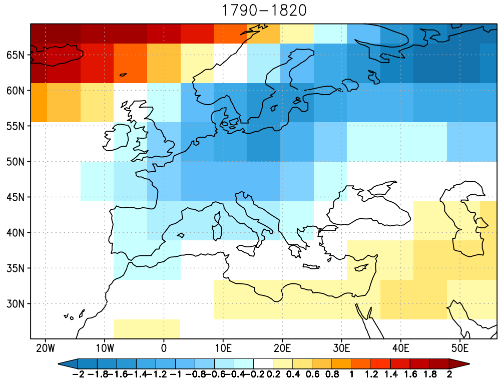


Fig. 5 Assimilated anomalous 2 m temperature for the JFMA season in °C according to the data assimilation experiment, averaged over the years 1790–1820, as a deviation from the reference period 1961–1990

than 0.9, which confirms that the average simulated circulation is consistent with the reconstruction. The aim of this exercise is to test whether the SLP reconstruction leads to the observed cold or warm winters/springs of the selected years. This allows for the identification, via the model output, of those mechanisms that might have been important, apart from simple advection, to account for the harsh or mild winters of the two selected years. In other words, the combination of the model and the data assimilation is used as a dynamical link between the pressure reconstruction and the selected extreme winters. A consistent result between observed and modeled temperatures adds to the credibility of the SLP reconstruction. Importantly, a data assimilated simulation will capture other climatic parameters in a way that is dynamically consistent with the input pressure reconstruction. Moreover, the results above show that a simulation of climate by assimilation of the reconstructed atmospheric circulation accurately recovers the observed temperature signal. This suggests that other climatic aspects are simulated with similar skill. For the 2 years we show anomalous patterns of simulated 2 m temperature, snow depth, albedo and precipitation with respect to the 1961–1990 reference period.

4.3.1 The assimilated warm anomalous JFMA season of 1817

Figure 6 shows the anomalous fields of 2 m temperature, albedo, snow depth and precipitation as simulated for the anomalously warm JFMA season of the year 1817. This winter, the second following the eruption of the Tambora in April 1815, was exceptionally warm, with anomalous warm winter temperatures reaching 2.5°C over NW Russia, southern Finland and the Baltics (Fischer et al. 2007; Zerefos et al. 2007; Trigo et al. 2009). The area with anomalous warm temperatures stretches out to Ireland, northern Spain and into Greece. In our assimilated simulation of 2 m temperature (Fig. 6) a large area with warming is found with the highest values over roughly the same area. However, the simulated amplitude of the warming is much larger. Moreover, the warming does not extent into southern Europe as far as the reconstruction suggests. The simulation suggests that JFMA 1817 was dry. This is in accordance with previous findings; the precipitation over much of Europe was reduced (Pauling et al. 2006). The reconstructed SLP field for the winter of 1817 shows a strong and extensive anomalous high with its center over Central and Eastern Europe. The area covered by the anomalous high pressure area roughly coincides with the area of anomalous negative precipitation over Europe.

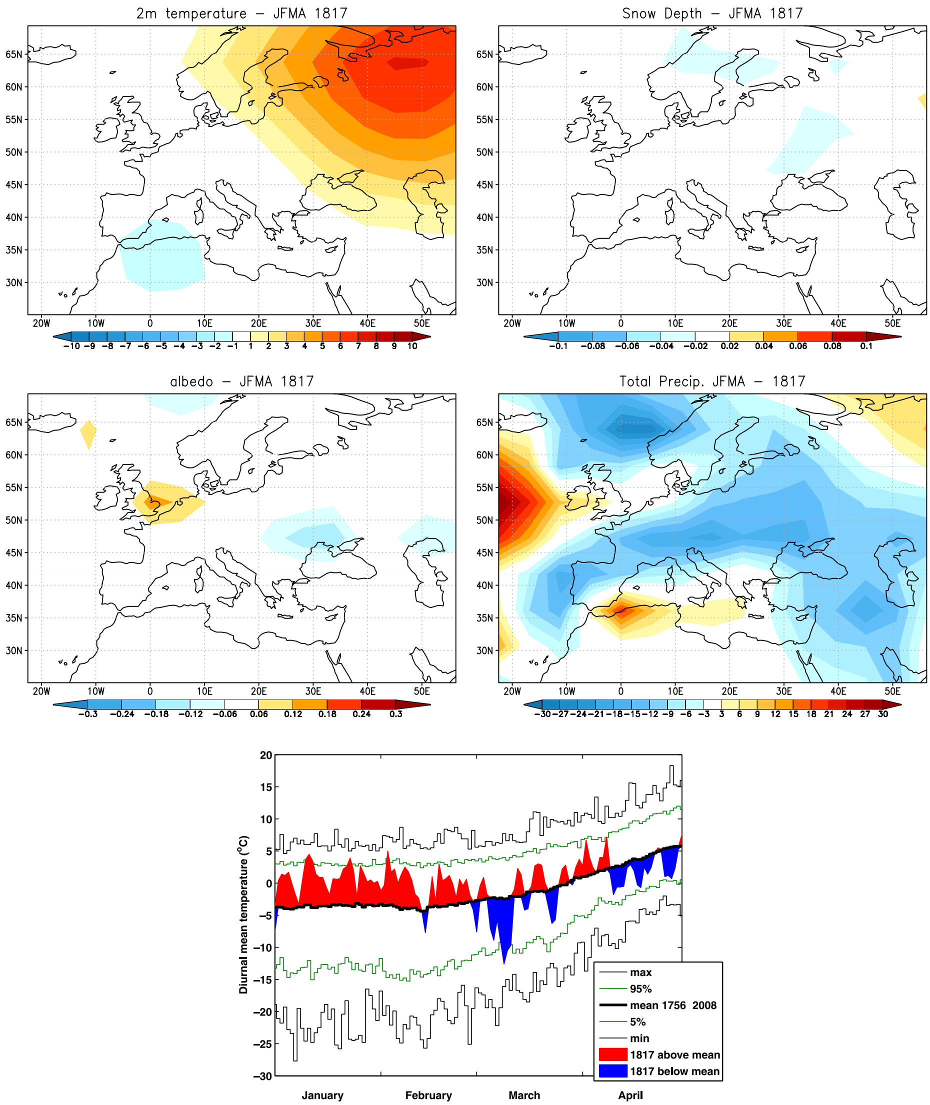


Fig. 6 Simulated anomalous (with respect to the 1961–1990 reference period) 2 m temperature (°C), snow depth (m), albedo and precipitation (mm) for the year 1817. The fields are averages over the months JFMA. For comparison, the lower plot shows the corresponding observed daily mean temperatures for Stockholm (Moberg et al. 2002), together with the climatological long-term (1756–2008) averages, the 5th/95th percentiles and max/min values of daily mean temperatures for this series

Interestingly, a more detailed level of information – daily temperature data for Stockholm (lower subplot in Fig. 6) show that nearly all days in January and February were warmer than the climatological mean annual temperature cycle, whereas March and April temperatures showed more of a mix of cold and warm days. The impact of warm anomalies on the date of plant phenological development is reflected in the three records from Switzerland, Finland and the UK (Holopainen et al. 2006; Rutishauser et al. 2009). All sites showed significantly earlier flowering and budburst for this year.

4.3.2 The assimilated cold anomalous JFMA-season of 1829

Figure 7 shows the anomalous fields of 2 m temperature, albedo, snow depth and precipitation as simulated for the anomalously cold JFMA season of the year 1829. The lowest simulated temperatures are found over northern Europe, with

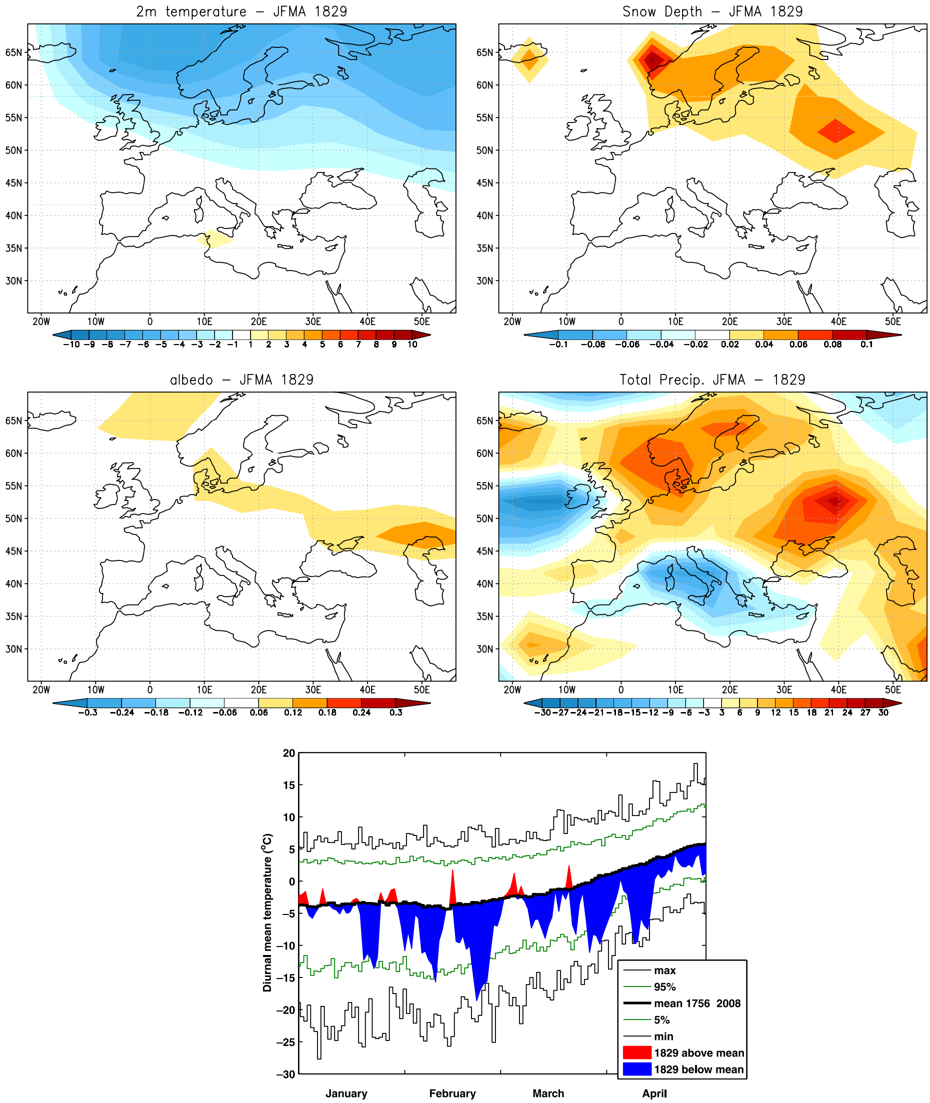


Fig. 7 As Fig. 6 but for 1829

JFMA temperatures of 5°C below normal over the Norwegian Sea and northern Russia and 1°C below normal in southern England, northern France and stretching into the Ukraine. In much of the cooler regions, a general increase in snowfall is modeled. Furthermore a southward migration of the area with snowfall is prevalent. A southward extension of the snow-covered ground is reflected by an increased simulated albedo in a band stretching from Denmark south-eastwards to the north of the Black Sea and the Caspian Sea. The increase in snow depth is at least partially related to an increase in total precipitation over much of Northern and Eastern Europe. These factors must have contributed to the simulated lower temperatures, and are thus good candidates for explaining also the observed cold temperatures. The daily temperature data for Stockholm further adds to the picture of a notably cold period throughout the JFMA season, as the large majority of days were colder than the climatological average, with several cold spells occurring. For this year, plant phenology in Finland, Switzerland and the UK suggests delayed growth with more than 1 SD in Arctic Finland and alpine Switzerland (Holopainen et al. 2006; Rutishauser et al. 2009) an indication of distinctive lower temperature in wide spread Europe.

These examples (Figs. 6 and 7) show that the deviation of European climate from the climatic normal was largely driven by the prevailing types of the atmospheric circulation patterns. It is interesting to note that a simulation which reasonably resembles the winter/spring SLP reconstruction reproduces temperature fields which can be related to observed values. Since these simulations do not explicitly include changes in volcanic aerosol loadings, any influence of explosive volcanic outbursts must be transmitted to the climate model via the assimilation of reconstructed air pressure.

4.4 Analog case search

The analog case search method is used to extend some aspects of the analysis back in time and address also the pre-instrumental (before 1760) period back to ~1500. By combining the independent approaches and a set of model and proxy data for both the pre- and the instrumental period, we can better assess underlying uncertainties and can subsequently more accurately point to the primary dynamic patterns for cold extremes. In conjunction with the analysis conducted above for the instrumental period (post-1760), we here apply an independent methodological approach, using additional underlying data, in an attempt to extend the analysis of circulation dynamics for extremes back to 1500. The initial search for key sites with documentary series showed that a combination of only the Stockholm and CEu temperature series has statistically significant positive correlation with temperatures over almost the entire European continent (Fig. 8). Thus they can be considered as representative regions of Europe. Only Iceland and Turkey feature insignificant and weak negative correlations and are thus not well represented by combining only the two mentioned stations.

4.4.1 Analog cases for anomalously cold temperature

Table 1 presents the years identified in the search for the anomalously (1 SD with respect to the 1961–1990 climatology) cold pre-instrumental (1500–1759) and instrumental (1760–2006) temperatures, as computed from the analog case search based on

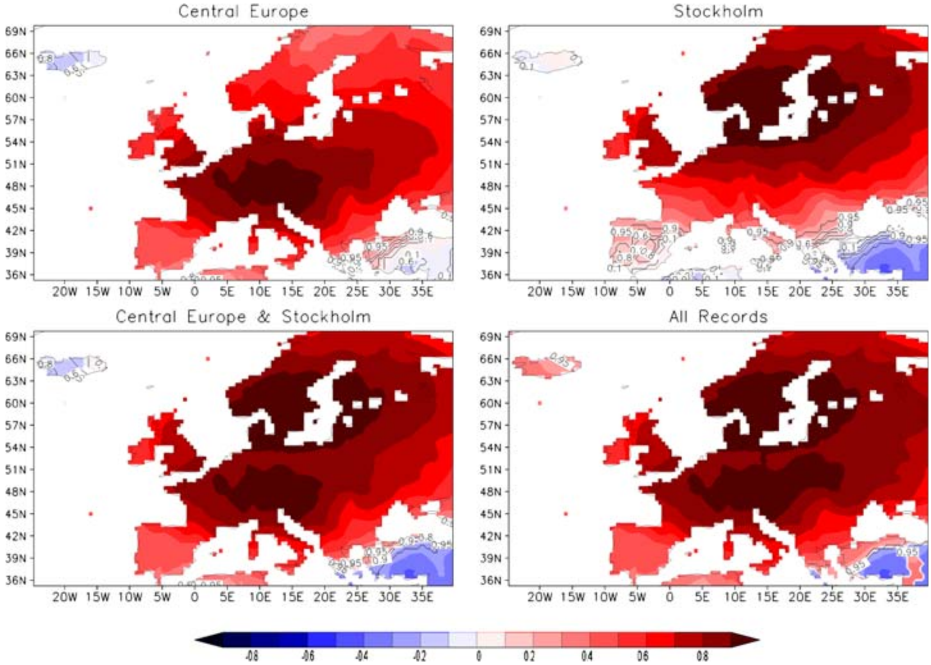


Fig. 8 Spatial representation of selected temperature records for Central Europe (*top left*) and Stockholm (*top right*), their combination (*lower left*), and a combination of all seven temperature series for JFMA (*lower right*). The values are expressed in grid point squared correlation coefficients (*contours*) between the individual (*top panels*) or the combined index records (*lower panels*) and the independent gridded datasets by Mitchell and Jones (2005) for the 1901–2000 period. Significance is tested by a Student *t*-test and is indicated with printed numbers

the Stockholm and CEu records. The search algorithm identified 13 cases in the pre-instrumental period and 14 cases in the instrumental data. The derived 14 cold cases for the post-1759 period were then subjected to the subsequent anomaly composite analysis described below. It is noteworthy that some major extreme cold winters described in the literature, such as 1709 and 1740 (e.g. Camuffo 1987; Luterbacher et al. 2004), were not identified in the analog case search herein. We do identify both these extremes in the CEu record, but not in the Stockholm reconstruction, suggesting that their geographical extent may be somewhat limited and not include the more northern parts of Europe. For the year 1740, this interpretation is corroborated by the fact that instrumental temperatures for Uppsala (near Stockholm) do not indicate it to have been a notably cold winter (e.g. Moberg and Bergström 1997; Jones and Briffa 2006).

Table 1 Anomalously cold JFMA seasons based on the analog case search. The years in the instrumental period (indicated in bold) are used to calculate the anomalous cold composites

Analog cases	Years AD
Pre-instrumental	1569, 1573, 1586, 1595, 1600, 1601, 1614, 1658, 1663, 1684, 1685, 1688, 1692
Instrumental	**1784, 1785, 1799, 1808, 1829, 1838, 1839, 1847, 1853, 1888, 1917, 1940, 1942, 1963**

4.4.2 Composite analysis of anomalous cold cases

Based on the years identified in the analog case search, Fig. 9 presents anomaly (1961–1990 average subtracted) composites of SLP (Küttel et al. 2009), temperature (Luterbacher et al. 2004; Xoplaki et al. 2005) and precipitation (Pauling et al. 2006) fields for the anomalous cold JFMA means in the post-1760 period and their corresponding standard errors (standard deviations divided by the square root of the number of cases averaged for the composite). The SLP anomaly composite depicts a dipole pattern with marked positive SLP anomalies in the higher latitudes and generally below normal pressure south of approximately 50°N. The anomaly composite thus shows a distinct pressure structure resembling a strong NAO neg-

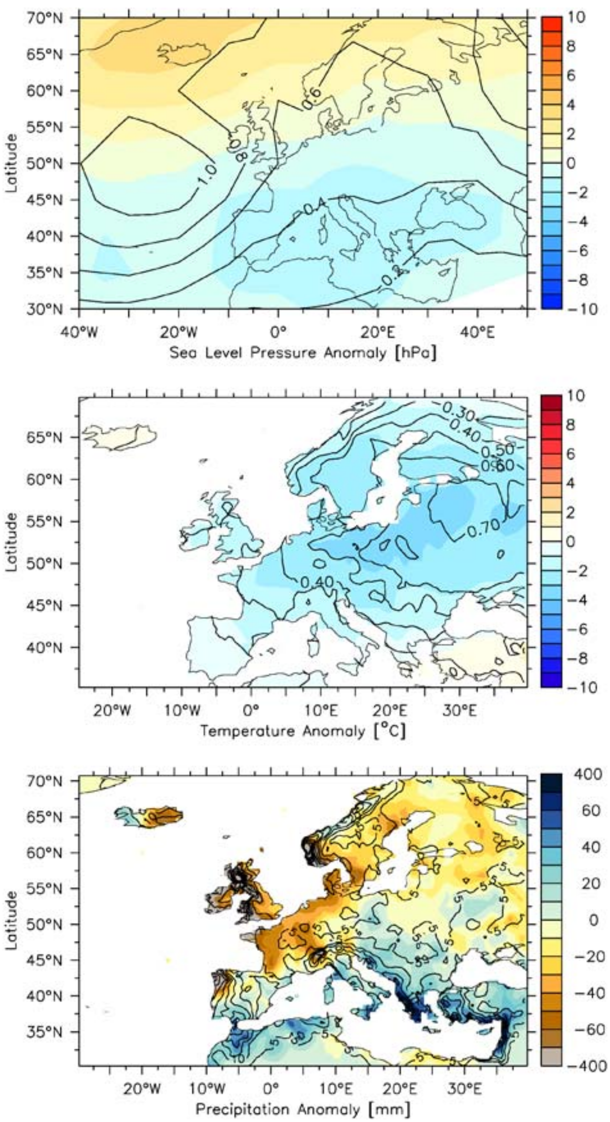


Fig. 9 Anomaly composites (with respect to the 1961–1990 reference period) of selected anomalous cold winters for the post-1759 period and their standard errors. SLP (*top*), temperature (*middle*), and precipitation (*bottom*). Colors represents the anomaly fields. *Contours* represent the standard errors

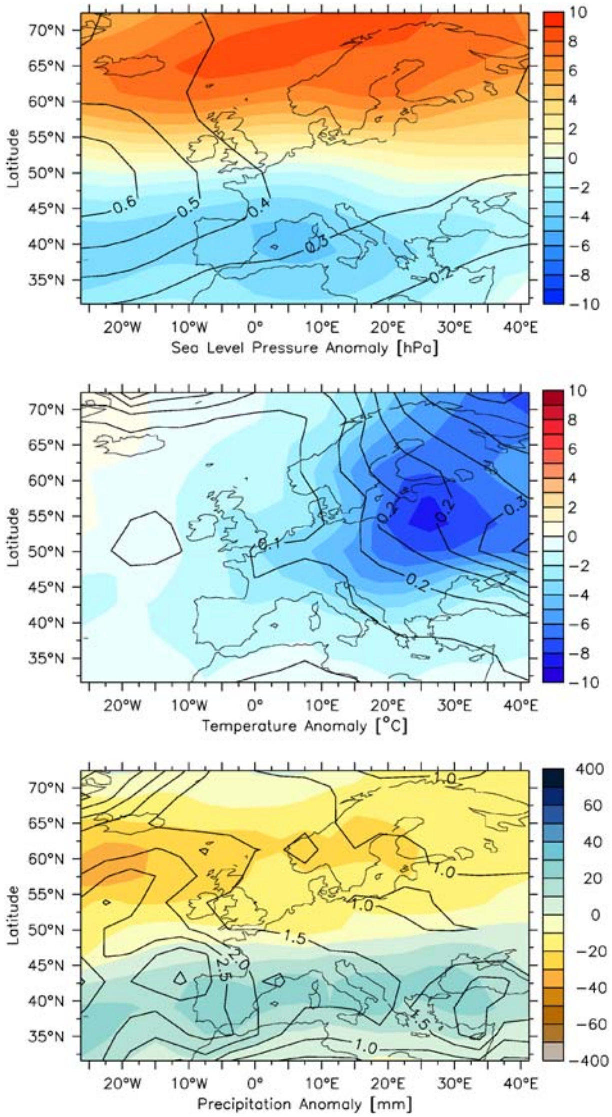
ative pattern connected with blocking situations. The temperature anomaly map indicates continental cold with the largest deviations and highest variability over northeastern Europe and a tendency to positive anomalies over Iceland and parts of Turkey. It thus shows the well-known seesaw in winter temperature between Greenland/Iceland and Europe (van Loon and Rogers 1978), associated with large-scale variations in the atmosphere–ocean–sea ice system. Consistent with the anomalous SLP distribution, negative precipitation anomalies are found over large parts of northern Europe but wetter conditions prevail over the Mediterranean area.

In comparison to the subjectively (Jacobeit et al. 1999) and objectively (Luterbacher et al. 2000, 2002) reconstructed SLP fields of single anomalously cold winters for the pre-1760 period our analogs indicate a similar distribution and location of the main pressure patterns and bear resemblance to the calculated average composite (not shown, Koenig 2007). It points to the fact that major anomalous years unequivocally exist independently of the approaches applied. With these independently reconstructed anomalous years, we have additional confirmation that the pre-instrumental years found in the analog search procedure do represent analogs of widespread surface extremes over Europe. Given this, it allows us to test and extend the analysis further back in time using documentary evidence.

4.4.3 Model results

The SLP anomaly composites for all cold years ($n = 59$ for ECHO-G and $n = 19$ for HadCM3) based on the model simulations (Figs. 10 and 11) are in good agreement with the anomaly composite presented in Fig. 9. The SLP and temperature composites derived from the HadCM3 model and from the gridded reconstructions show anomalies of similar magnitude, whereas the pressure and temperature departures within the ECHO-G model are much stronger compared to the observed composite anomalies and compared to HadCM3. This is well within the expected behavior of the ECHO-G simulations since it displays much larger variability than the HadCM3 simulation. The precipitation composites of the two models show good resemblance with each other and also with the observed wetter (drier) conditions in southern (northern) Europe. The magnitude as well as the spatial extent of the anomalies differ with the models generally underestimating the precipitation totals. This is mainly due to the coarse spatial resolution of the model and consequently the less detailed topography. A larger temperature anomaly seen in the ECHO-G composite is mainly due to a strong positive temperature trend simulated for Europe in the twentieth century. In contrast, the HadCM3 shows globally the same positive trend for this period but for Europe there is hardly any trend visible. Tett et al. (2007) invoke the effect of deforestation and aerosols in this region to explain this difference, neither factor is contained in ECHO-G. Hence the more negative temperature anomalies in HadCM3 are an artifact of the positive temperature trend in the twentieth century. This fact does not influence the choice of the extreme years as the time series used for identification of the extremes were filtered beforehand (see methods). Taking this artifact into account the instrumental based anomaly and model based composites are in good agreement. The fact that these independent methods/datasets lead to similar results is a strong indication for the skill of the method on the one hand and the skill of the models on the other hand. It also suggests that both models simulate climate states of extreme years which are consistent with reconstructions.

Fig. 10 As Fig. 9, but for ECHO-G Erik 2 and selected anomalous cold winters of the entire model simulation (1000–1990 AD)



In order to assess if climate field pattern of anomalous years were similar in the pre-instrumental (mainly naturally forced) and instrumental (naturally and anthropogenically forced) period, we split the model simulations in the year 1760. Separate composites based on the pre- and post-1760 part of the model simulation do not diverge significantly (not shown). This further supports the validity of the composite build from post-1760 SLP, temperature and precipitation fields for anomalous years that were identified in the documentary series before 1760.

The anomaly SLP composite for anomalous warm winters (not shown) indicates the expected positive (negative) anomalies in the south (north) connected with above normal westerlies that bring above normal temperature conditions over much of Europe resembling a strong NAO positive mode (not shown). The anomalous

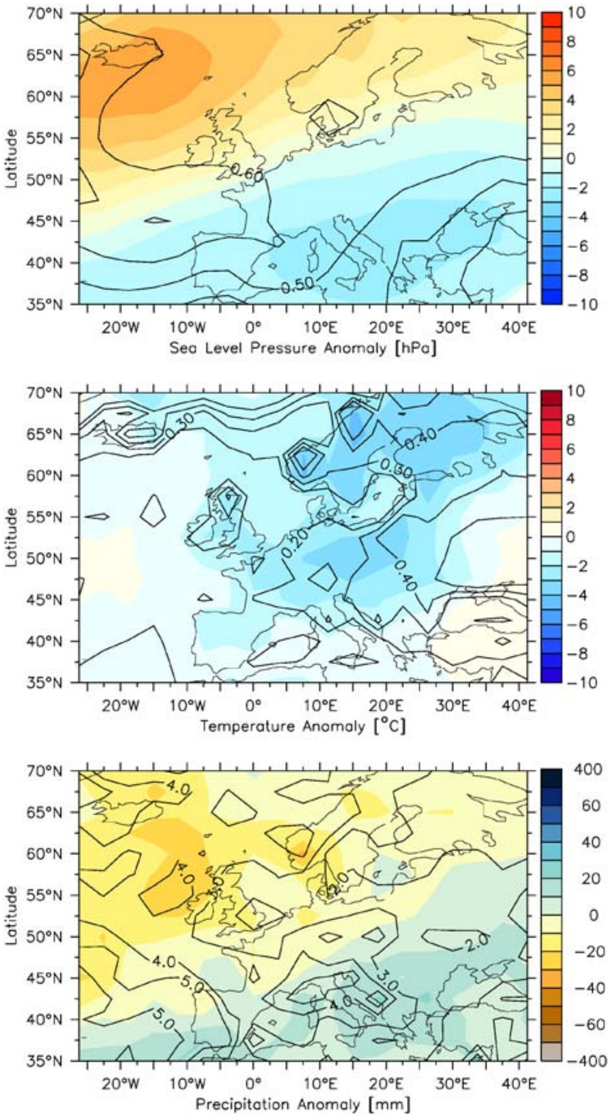


Fig. 11 As Fig. 10, but for HadCM3 and selected anomalous cold winters of the entire model simulation (1500–2000 AD)

precipitation pattern represents the NAO positive phase with positive anomalies in northern and negative anomalies over southern Europe. The model simulation based anomaly composites again show strong resemblance to the reconstructed anomaly plots.

5 Conclusions

Our study is concerned with climatological aspects but it meets two further needs; on the one hand it demonstrates the intrinsic value of documentary sources in climate studies, but also, and more generally it integrates, as the MILLENNIUM project has attempted to do throughout, this emerging field more firmly within the discipline of climatology paving the way for future and fruitful realization of the potential of material hitherto locked away in archive and document collections around Europe. We demonstrated not only the validity of early instrumental sources for climatic studies but we extended this same conclusion to non-instrumental, documentary sources. In doing so we also arrive at the significant conclusion that the two sources can be treated as one in terms of providing temporally continuous and homogeneous series.

This particular contribution deals with the atmospheric circulation dynamics in late winter/early spring within the both the instrumental (post-1760) and pre-instrumental period. A Canonical Correlation Analysis (CCA) investigates inter-annual to interdecadal covariability between SLP field reconstruction and seven long instrumental temperature series covering the past 250 years. The results indicate a clear NAO-like pattern as characterizing temperature variability accounting for approximately a third of the seasonal temperature variability at the seven stations across Europe. However a prominent factor in the relationships between atmospheric circulation and temperature anomalies would seem to be the existence of within-type variations which modulate weather and climate characteristics of circulation patterns. This is especially true for the zonal circulation pattern which occurs in both warm and cold JFMA sub-samples with different controlling mechanisms (advection of warm Atlantic air masses versus radiative cooling by more anticyclonic situations).

We then linked long instrumental data with a climate model (EC-Bilt-Clio) for a better understanding of the dynamical relationship between large scale circulation patterns and European climate. Using data assimilation to combine the empirical information from reconstructed SLP data with the physical understanding of the climate system represented by a climate model is a promising way of securing better estimates for the pre-instrumental period. Results showed that the deviation of European climate from the climatic normal was largely driven by the actual types of the atmospheric circulation patterns.

Although it was not possible to undertake a full and independent analysis for the pre-instrumental period, we made an attempt to extend the analysis back to the early sixteenth century by using a combination of instrumental and (pre-instrumental) documentary data to define anomalously cold winters using an analog case search algorithm. The analog case search applied to the combined documentary- and instrumental-based series and the subsequent compositing of (post-1759) climatological fields indicated that years with surface temperature extremes in the instrumental period can be used to reconstruct SLP fields for extreme temperature analogs in the pre-1760 period. Documentary data can act as a reliable predictor to reconstruct SLP patterns for anomalous cold winters in the past when no instrumental information is available. It is remarkable that the reconstructed patterns of the extreme years for JFMA are in very good agreement with the two coupled climate models (ECHO-G and HadCM3). This suggests that the latter can be a useful tool to assign large-scale fields to extreme regional climate variations in the absence of observational information that might otherwise provide the large-scale climate context. Also, this agreement underscores the skill of models in simulating the spatial pattern of extreme temperature and precipitation in simulations of future climate. These results suggest also that it is possible to constrain model states on the basis of the spatial structure of anomalies observed in proxy data, a feature that supports the concept of data assimilation.

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References

Allan R, Ansell T (2006) A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2):1850–2004. J Clim 19:5816–5842

Auer I, Böhm R, Jurkovic A et al (2007) HISTALP—historical instrumental climatological surface time series of the Greater Alpine Region. Int J Climatol 27:17–46

Barkmeijer J, Iversen T, Palmer TN (2003) Forcing singular vectors and other sensitive model structures. Q J R Meteorol Soc 129:2401–2423

Beck C (2000) Zirkulationsdynamische Variabilität im Bereich Nordatlantik-Europa seit 1780. Würzburger Geographische Arbeiten. Mitteilungen der Geographischen Gesellschaft Würzburg, Würzburg, Deutschland, Heft 95, 350 pp

Beck C, Jacobeit J, Philipp A (2001) Variability of North-Atlantic-European circulation patterns since 1780 and corresponding variations in Central European climate. In: Brunet India M, López Bonillo D (eds) Detecting and modelling regional climate change. Springer, Berlin, pp 321–331

Beck C, Jacobeit J, Jones PD (2007) Frequency and within-type variations of North-Atlantic European circulation types and their effects on low-frequency climatic variability in Central Europe since 1780. Int J Climatol 27:473–491

Böhm R, Jones PD, Hiebl J, Brunetti M, Frank D, Maugeri M (2009) The early instrumental warm-bias: a solution for long central European temperatures series 1760–2007. Clim Change. doi:10.1007/s10584-009-9649-4

Brázdil R, Pfister C, Wanner H, von Storch H, Luterbacher J (2005) Historical climatology in Europe—the state of the art. Clim Change 70:363–430

Brázdil R, Dobrovolný P (2010) Historical climate in central Europe during the last 500 years. In: Przybylak R et al (eds) The polish climate in the European context: an historical overview, pp 41–70. doi:10.1007/978-90-481-3167-9_2

Brázdil R, Dobrovolný P, Luterbacher J, Moberg A, Pfister C, Wheeler D, Zorita E (2009) European climate of the past 500 years: new challenges for historical climatology. Clim Change. doi:10.1007/s10584-009-9783-z

Camuffo D (1987) Freezing of the Venetian Lagoon since the 6th century AD, in comparison to the climate of Western Europe and England. Clim Change 10:43–66

Camuffo, Jones PD (eds) (2002) Improved understanding of past climatic variability from early daily European instrumental sources. Kluwer Academic, Dordrecht, 392 pp

Camuffo D, Bertolin C, Barriendos M, Dominguez-Castro F, Cocheo C, Enzi S, Sghedoni M, della Valle A, Garnier E, Alcoforado M-J, Xoplaki E, Luterbacher J, Diodato N, Maugeri M, Nunes MF, Rodriguez R (2009) 500-year temperature reconstruction in the Mediterranean Basin by means of documentary data and instrumental observations. Clim Change (revised)

Della-Marta PM, Luterbacher J, von Weissenfluh H, Xoplaki E, Brunet M, Wanner H (2007) Summer heat waves over western Europe 1880–2003, their relationship to large scale forcings and predictability. Clim Dyn 29:251–275

Dobrovolný P, Brázdil R, Valášek H, Kotyza O, Macková J, Halíèková M (2009a) A standard paleoclimatological approach to temperature reconstruction in historical climatology: an example from the Czech Republic, AD 1718–2007. Int J Climatol 29:1478–1492

Dobrovolný P, Moberg A, Brázdil R, Pfister C, Glaser R, Wilson R, van Engelen A, Limanówka D, Kiss A, Halíčková M, Macková J, Riemann D, Luterbacher J, Böhm R (2009b) Monthly and seasonal temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500. Clim Change. doi:10.1007/s10584-009-9724-x

Fischer EM, Luterbacher J, Zorita E, Tett SFB, Casty C, Wanner H (2007) European climate response to tropical volcanic eruptions over the last half millennium. Geophys Res Lett 34:L05707

Franke J, González Rouco JF, Frank D, Graham NE (2009) 200 years of European temperature variability: insights from and tests of the Proxy Surrogate Reconstruction analog method. Clim Dynam (in review)

Gagen M, McCarrol D, Hicks S (2006) The MILLENNIUM project: European climate of the last MILLENNIUM. PAGES News 14:4

Glaser R, Brázdil R, Pfister C, Dobrovolný P, Barriendos Vallvé M, Bokwa A, Camuffo D, Kotyza O, Limanówka D, Rácz L, Rodrigo FS (1999) Seasonal temperature and precipitation fluctuations in selected parts of Europe during the sixteenth century. Clim Change 43:169–200

González-Rouco JF, Beltrami H, Zorita E, von Storch H (2006) Simulation and inversion of borehole temperature profiles in surrogate climates: spatial distribution and surface coupling. Geophys Res Lett 33:L01703

González-Rouco J, Beltrami H, Zorita E, Stevens M (2009) Borehole climatology: a discussion based on contributions from climate modeling. Clim Past 5:97–127

Goosse H, Fichefet T (1999) Importance of ice-ocean interactions for the global ocean circulation: a model study. J Geophys Res (Oceans) 104:23337–23355

Goosse H, Crespin E, de Montety A, Mann ME, Renssen H, Timmermann A (2009) Reconstructing surface temperature changes over the past 600 years using climate model simulations with data assimilation. J Geophys Res. doi:10.1029/2009JD012737

Gouirand I, Moberg A, Zorita E (2007) Climate variability in Scandinavia for the past millennium simulated by an atmosphere-ocean general circulation model. Tellus 59A:30–49

Hellmann G (1883) Repertorium der Deutschen Meteorologie. Leistungen der Deutschen in Schriften, Erfindungen und Beobachtungen auf dem Gebiet der Meteorologie und des Erdmagnetismus von den ältesten Zeiten bis zum Schluss des Jahres 1881. Verlag Wilhelm Engelmann, Leipzig

Holopainen J, Helama S, Timonen M (2006) Plant phenological data and tree-rings as paleoclimate indicators in south-west Finland since AD 1750. J Biomet 51:61–72

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

Jacobeit J, Beck C, Philipp A (1998) Annual to decadal variability in climate in Europe—objectives and results of the German contribution to the European climate research project ADVICE—Würzburger Geographische Manuskripte 43

Jacobeit J, Wanner H, Koslowski G, Gudd M (1999) European surface pressure patterns for months with outstanding climatic anomalies during the sixteenth century. Clim Change 43:201–221

Jacobeit J, Jönsson P, Bärring L, Beck C, Ekström M (2001a) Zonal indices for Europe 1780–1995 and running correlations with temperature. Clim Change 48:219–241

Jacobeit J, Jones PD, Davies T, Beck C (2001b) Circulation changes in Europe since the 1780s. In: Jones PD, Ogilvie A, Davies T, Briffa K (eds) History and climate: memories of the future? Kluwer Academic, Plenum, pp 79–99

Jacobeit J, Wanner H, Luterbacher J, Beck C, Philipp A, Sturm K (2003) Atmospheric circulation variability in the North-Atlantic-European area since the mid-seventeenth century. Clim Dyn 20:341–352

Jacobeit J, Rathmann J, Philipp A, Jones PD (2009) Central European precipitation and temperature extremes in relation to large-scale atmospheric circulation types. Meteorol Z 18:397–410

Jones PD (2001) Early European instrumental record. In: Jones PD, Ogilvie AEJ, Davies TD, Briffa K (eds) History and climate: memories of the future? Kluwer Academic, New York, pp 55–77

Jones PD, Briffa KR (2006) Unusual climate in northwest Europe during the period 1730 to 1745 based on instrumental and documentary data. Clim Change 79:361–379

Jones PD et al (1999) Monthly mean pressure reconstruction for Europe 1780–1995. Int J Climatol 19:347–364

Jones P, Briffa K, Osborn T (2003) Changes in the Northern Hemisphere annual cycle: implications for paleoclimatology? J Geophys Res 108:4588. doi:10.1029/2003JD003695

Koenig SJ (2007) Potential of documentary based climate information for the evaluation of European temperature extremes and large scale SLP reconstructions. Master's thesis, Institute of Geography, University of Bern

Koslowski G, Glaser R (1999) Variations in reconstructed ice winter severity in the Western Baltic from 1501 to 1995, and their implications for the North Atlantic Oscillation. Clim Change 41:175–191

Küttel M, Xoplaki E, Gallego D, Luterbacher J, Garcia-Herrera R, Allan R, Barriendos M, Jones PD, Wheeler D, Wanner H (2009) The importance of ship log data: reconstructing North Atlantic, European and Mediterranean sea level pressure fields back to 1750. Clim Dyn. doi:10.1007/s00382-009-0577-9

Küttel M, Luterbacher J, Wanner H (2010) Multidecadal changes in winter circulation-climate relationship in Europe: frequency variations, within-type modifications, and long-term trends. Clim Dynam. doi:10.1007/s00382-009-0737-y

Labrijn A (1945) Het klimaat van Nederland gedurende de laatste twee en een halve eeuw, publ. MV49 KNMI

Leijonhufvud L, Moberg A, Wilson R (2008) Documentary data provide evidence of Stockholm average winter to spring temperatures in the 18th and 19th centuries. Holocene 18:333–343

Leijonhufvud L, Wilson R, Moberg A, Söderberg J, Retsö D, Söderlind U (2009) Five centuries of winter/spring temperatures in Stockholm reconstructed from documentary evidence and instrumental observations. Clim Change. doi:10.1007/s10584-009-9650-y

Limanówka D (1996) Daily weather observations in Cracow in the 16th century. Zeszyty Nauk UJ, Prace Geograficzne 102:503–508

Limanówka D (2000) The transformation of thermal descriptive characteristic in Cracow from 16th century into the quantitative evaluation. Prace Geograficzne 107:113–117

Limanówka D (2001) Rekonstrukcja warunków klimatycznych Krakowa w pierwszej polowie XVI wieku (Reconstruction of climatic conditions in Cracow in the first half of the 16th century). Instytut Meteorologii i Gospodarki Wodnej, Warszawa

Livezey RE, Chen W (1983) Statistical field significance and its determination by Monte Carlo Techniques. Mon Weather Rev 111:46–59

Luterbacher J and 33 co-authors (2000) Monthly mean pressure reconstruction for the late maunder minimum period (AD 1675–1715) based on canonical correlation analysis. Int J Climatol 20:1049–1066

Luterbacher J, Xoplaki E, Dietrich D, Rickli R, Jacobeit J, Beck C, Gyalistras D, Schmutz C, Wanner H (2002) Reconstruction of sea level pressure fields over the Eastern North Atlantic and Europe back to 1500. Clim Dyn 18:545–561

Luterbacher J, Dietrich D, Xoplaki E, Grosjean M, Wanner H (2004) European seasonal and annual temperature variability, trends and extremes since 1500. Science 303:1499–1503

Luterbacher J, Liniger MA, Menzel A, Estrella N, Della-Marta PM, Pfister C, Rutishauser T, Xoplaki E (2007) The exceptional European warmth of Autumn 2006 and Winter 2007: historical context, the underlying dynamics and its phenological impacts. Geophys Res Lett 34: L12704

Luterbacher J, Xoplaki E, Küttel M, Zorita E, González-Rouco JF, Jones PD, Stössel M, Rutishauser T, Wanner H, Wibig J, Przybylak R (2010) Climate change in Poland in the past centuries and its relationship to European climate: Evidence from reconstructions and coupled climate models. In: R. Przybylak et al. (eds) *The Polish climate in the European context: An historical overview* (pp. 3–39). doi:10.1007/978-90-481-3167-9_1

Michaelsen J (1987) Cross-validation in statistical climate forecast models. J Clim Appl Meteorol 26:1589–1600

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712

Moberg A, Bergström H (1997) Homogenization of Swedish temperature data. Part III: the long temperature records from Stockholm and Uppsala. Int J Climatol 17:667–699

Moberg A, Bergström H, Ruiz Krigsman J, Svanered O (2002) Daily air temperature and pressure series for Stockholm (1756–1998). Clim Change 53:171–212

Opsteegh JD, Haarsma RJ, Selten FM, Kattenberg A (1998) ECBILT: a dynamic alternative to mixed boundary conditions in ocean models. Tellus 50A:348–367

Pauling A, Luterbacher J, Casty C, Wanner H (2006) 500 years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Clim Dyn 26:387–405

Pfister C, Luterbacher J, Wanner H, Wheeler D, Brázdil R, Ge Q, Hao Z, Moberg A, Grab S, Rosario del Prieto M (2008) Documentary evidence as climate proxies. White paper produced from the PAGES/CLIVAR workshop, Trieste, 2008, http://www.pages-igbp.org/cgi-bin/WebObjects/products.woa/wa/product?id=331

Philipp A, Della Marta PM, Jacobeit J, Fereday D, Jones PM, Moberg A, Wanner H (2007) Long-term variability of daily North-Atlantic–European Pressure Patterns since 1850 classified by Simulated Annealing Clustering. J Climate 20:4065–4095

Preisendorfer R (1988) Principal component analysis in meteorology and oceanography. Elsevier, Amsterdam

Przybylak R, Oliński P, Chorążyczewski W, Nowosad W, Syta K (2010) Documentary evidence. In: R. Przybylak et al. (eds) The polish climate in the European context: an historical overview (pp. 167–190). doi:10.1007/978-90-481-3167-9_6

Rapp J (2000) Konzeption, Problematik und Ergebnisse klimatologischer Trendanalysen für Europa und Deutschland. DWD, Offenbach

Rutishauser T, Schleip C, Sparks T, Nordli Ø, Menzel A, Wanner H, Jeanneret F, Luterbacher J (2009) The temperature sensitivity of Swiss and British plant phenology 1753–1958. Clim Res 39:179–190

Shabalova MV, van Engelen AFV (2003) Evaluation of a reconstruction of winter and summer temperatures in the Low Countries, AD 764–1998. Clim Change 58:219–242

Shabbar A, Skinner W (2004) Summer drought patterns in Canada and the relationship to global seas surface temperatures. J Climate 17:2866–2880

Slonosky VC, Jones PD, Davies TD (2001) Atmospheric circulation and surface temperature in Europe from the 18th century to 1995. Int J Climatol 21:63–75

Tarand A (1992) Meteorological observations in Estonia before 1850 (in Estonian). Folia on science history in Estonia VIII. Tallinn, 30–50

Tarand A (2003) Tallinnas mõõdetud õhutemperatuuri aegrida (in Estonian with English summary). Time series of average monthly and annual air observed air temperature in Tallinn. Publications Instituti Geographici Universitatis Tartuensis 93:24–30

Tarand A, Nordli O (2001) The Tallinn temperature series reconstructed back half a millennium by use of proxy data. Clim Change 48:189–199

Tett S, Betts R, Crowley T, Gregory J, Johns T, Jones A, Osborn TJ, Öström E, Roberts D, Woodage M (2007) The impact of natural and anthropogenic forcings on climate and hydrology since 1550. Clim Dyn 28:3–34

Trenberth KE (1990) Recent observed interdecadal climate changes in the Northern Hemisphere. Bull Am Meteorol Soc 71:989–993

Trepińska J red (1997) Fluctuations of climate in Cracow (1792–1995). Institute of Geography of Jagiellonian University, Kraków

Trigo RM, Vaquero JM, Alcoforado MJ, Barriendos M, Taborda J, Garcia-Herrera R, Luterbacher J (2009) Iberia in 1816, the year without summer. Int J Climatol 29:99–115

van den Dool HM, Krijnen HL, Schuurmans CJE (1978) Average winter temperatures at De Bilt (the Netherlands): 1634–1977. Clim Change 1:319–330

van Engelen AFV, Nellestijn JW (1996) Monthly, seasonal and annual means of the air temperature in tenths of centigrade in De Bilt. Publ. KNMI, The Netherlands

van Engelen AFV, Geurts HAM (1983–1992) Historische Weerkundige Waarnemingen, I–V, I: Geschiedenis van weerkundige waarnemingen in het bijzonder in Nederland vóór de oprichting van het KNMI, II Vooruitstrevende ideeën over de meteorologie en klimatologie van Petrus van Musschenbroek—1692–1761 IIa: Inleidende tekst bij de meteorologische waarnemingsreeks Utrecht/Leiden 1729–1758, Petrus van Musschenbroek, III: Een rekenmodel dat het verloop van de temperatuur over een etmaal berekent uit drie termijnmetingen van de temperatuur, IV: Nicolaus Cruquius (1678–1754) and his meteorological obeservations, V: Beschrijving antieke meetreeksen, KNMI publ. 165-I, II, IIa, III, IV, V, (De Bilt. 1983–1992)

van Engelen AFV, Buisman J, IJnsen F (2001) A millennium of weather, winds and water in the Low Countries. In: Jones PD et al (ed) History and climate: memories of the future? Kluwer Academic, New York, pp 101–124

van Loon H, Rogers J (1978) The seesaw in winter temperatures between Greenland and Northern Europe. Part I: general description. Mon Weather Rev 106:296–310

van der Schrier G, Barkmeijer J (2005) Bjerknes' hypothesis on the coldness during 1790–1820 AD revisited. Clim Dyn 24:355–371

van der Schrier G, Barkmeijer J (2007) North American 1818–1824 drought and 1825–1840 pluvial and their possible relation to the atmospheric circulation. J Geophys Res 112:D13102

van der Schrier G, Drijfhout SS, Hazeleger W, Noulin L (2007) Increasing the Atlantic subtropical jet cools the circum-North Atlantic. Meteorol Z 16:675–684

von Storch H, Zwiers F (1999) Statistical analysis in climate research. Cambridge University Press, Cambridge

Widmann M, Goosse H, van der Schrier G, Schnur R, Barkmeijer J (2009) Using data assimilation to study extratropical Northern Hemisphere climate over the last millennium. Clim Past Discuss 5:2115–2156

Wilks DS (1995) Statistical methods in the atmospheric sciences. An introduction. Academic Press

Xoplaki E, Gonzalez-Rouco JF, Luterbacher J, Wanner H (2003) Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. Clim Dyn 20:723–739

Xoplaki E, Luterbacher J, Paeth H, Dietrich D, Steiner N, Grosjean M, Wanner H (2005) European spring and autumn temperature variability and change of extremes over the last half millennium. Geophys Res Lett 32:L15713

Zerefos CS, Gerogiannis VT, Balis D, Zerefos SC, Kazantzidis A (2007) Atmospheric effects of volcanic eruptions as seen by famous artists and depicted in their paintings. Atmos Chem Phys 7:4027–4042

Zorita E, González-Rouco JF, von Storch H (2007) Comment to "Testing the fidelity of methods used in proxy-based reconstructions of past climate" by Mann et al. J Climate 20:3693–3698

Zorita E, Moberg A, Leijonhufvud L, Wilson R, Brázdil R, Dobrovolný P, Pfister C, Luterbacher J, Söderberg J, Gonzalez-Rouco JF (2009) European temperature records of the past five centuries based on documentary information compared to climate simulations. Clim Change (revised, this issue)