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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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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

J. Luterbacher[1,2,3], S.J. Koenig[4], J. Franke[5], G. van der Schrier[6], P.M. Della-Marta[7], J. Jacobeit[8], M. Küttel[2,3], F.J. Gonzalez-Rouco[9], E. Zorita[10], E. Xoplaki[2,3,11], M. Stössel[2,3], T. Rutishauser[2,3,12], H. Wanner[2,3], C. Pfister[2], R. Brázdil[13], P. Dobrovolný[13], D. Camuffo[14], C. Bertolin[14], A. Moberg[15], L. Leijonhufvud[15], J. Söderberg[16], R. Allan[17], R. Wilson[18], D. Wheeler[19], M. Barriendos[20], R. Glaser[21], D. Riemann[21], O. Nordli[22], D. Limanówka[23], A. van Engelen[6], C.S. Zerefos[24]

1 Department of Geography; Climatology, Climate Dynamics and Climate Change, University of Giessen, Giessen, Germany

2 Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

3 Institute of Geography, Climatology and Meteorology, University of Bern, Bern, Switzerland

4 Department of Geosciences, University of Massachusetts, Amherst, USA

5 Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

6 Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands

7 Federal Office of Meteorology and Climatology, MeteoSwiss, Switzerland

8 Institute of Geography, University of Augsburg, Augsburg, Germany

9 Universidad Complutense de Madrid, Spain

10 GKSS Research Centre, Geesthacht, Germany

11 The Cyprus Institute, EEWRC, Nicosia, Cyprus

12 Unitat d'Ecofisiologia CSIC-CREAF (Center for Ecological Applications and Forestry Applications), Universitat Autònoma de Barcelona, Bellaterra, Spain

13 Institute of Geography, Masaryk University, Brno, Czech Republic

14 National Research Council, Institute of Atmospheric Sciences and Climate, Padova, Italy.

15 Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden

16 Department of Economic History, Stockholm University, Sweden

17 Met Office Hadley Centre, Hadley Centre, Exeter, UK

18 School of Geography and Geosciences, The University of St Andrews, Fife, Scotland

19 Faculty of Applied Sciences, University of Sunderland, Sunderland, UK

20 Department of Modern History, University of Barcelona, Barcelona, Spain

21 Institute of Physical Geography, University of Freiburg, Freiburg, Germany

22 Norwegian Meteorological. Institute, Oslo, Norway

23 Institute of Meteorology and Water Management, Cracow, Poland

24 National and Kapodistrian University of Athens, Athens, Greece

Corresponding Author:

Prof. Dr. Jürg Luterbacher
Chair for Climatology, Climate
Dynamics and Climate Change
Department of Geography
Justus-Liebig University,
Senckenbergstrasse 1
D - 35390 Giessen
Germany
Tel.: 0049 641/99 - 3 62 45
Fax: 0049 641/99 - 3 62 09
Email: juerg.luterbacher@geogr.uni-giessen.de

Abstract

We examine the role of the atmospheric circulation dynamics in modulating European late winter/early spring (January-April, JFMA) climate both in the instrumental (post 1760) and pre-instrumental period using different data types and methods and compare results with two coupled climate models (ECHO-G and HadCM3). By using a new gridded sea level pressure (SLP) field reconstruction we present prominent atmospheric circulation patterns related to anomalous warm and cold JFMA conditions within different European areas spanning the period 1760-2007. A Canonical Correlation Analysis (CCA) investigates interannual to interdecadal covariability between the large-scale JFMA atmospheric circulation and seven long instrumental temperature series covering the past 250 years. We then link long instrumental data with a climate model (ECBilt-Clio) for a better dynamical understanding of the relationship between large scale circulation and European climate and present an alternative approach to reconstruct climate for the pre-instrumental period. Furthermore, by using evidence found in the instrumental period, we present an independent method to extend the dynamic circulation analysis for extremely cold European JFMA conditions back to the 16th century. We use high quality documentary records that are representative for the same seven 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.

***Keywords**: documentary climate evidence, circulation dynamics, analog method search, GCM, long instrumental series, Europe, CCA, sea level pressure*

Introduction

Long instrumental and homogeneous 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 good, high quality long instrumental temperature records available (e.g. Jones 2001; Jones and Moberg 2003). In this study, we will use the long Stockholm, Tallinn, Cracow, Warsaw, Berlin, De Bilt, Padova and central European time series (see data section) that are available back to the 18th century. For the same regions where long instrumental temperature data are available, there is also widespread documentary data that allow the derivation of monthly to seasonal temperature indices to the early 16th century. Documentary data allow us to examine trends in winter temperatures which cannot be gleaned from natural archives such as tree-rings (Brázdil et al. 2005; Pfister et al. 2008). Two documentary based reconstructions, one for Central Europe (Dobrovolný et al. this issue) and one for Stockholm (Leijonhufvud et al. 2008a, this issue) were developed as part of the EU-project MILLENNIUM and are discussed in detail in other papers in this special issue.

The atmospheric circulation is the main forcing factor for the regional interannual variability of temperature at middle and high latitudes (e.g. Hurrell 1995; Hurrell and van Loon 1997; Jacobeit et al. 2001a; Luterbacher et al. 2002; Slonosky et al. 2001; Trenberth 1990, 1995; Xoplaki et al. 2003, 2004).

Advective processes during wintertime exerted by the large-scale atmospheric circulation are a crucial factor controlling regional climate changes. Relationships between the large-scale circulation and regional climate constitute 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 a physical consistent way (Jacobeit et al. 2009).

Using long instrumental, documentary proxy and three-dimensional climate simulations back to the 16th century (see data section and also e.g. Glaser 2008; Glaser and Riemann 2009), we analyze relations between temperature extremes and atmospheric circulation patterns for a much broader time period.

In the first part of this contribution, we will present prominent atmospheric circulation patterns related to anomalously warm and cold JFMA (related to the properties of the available Stockholm temperature reconstructions based on documentary sources before the instrumental period) conditions within different European areas spanning the period 1760-2007. A prominent factor in the relationships between atmospheric circulation and temperature anomalies will also be addressed: within-type variations which modulate weather and climate characteristics of circulation patterns. We then expand on those results by showing 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 next application is linking long instrumental data with a climate model (ECBilt-Clio) for a better dynamical understanding of the relationship between large scale circulation and European climate. Applying an assimilation method, this exercise will also represent an alternative approach to reconstruct climate for the pre-instrumental period. Finally, in conjunction to the analysis conducted for the instrumental time period, we apply an independent methodological approach and thereby extend the analysis of dynamic circulation for extremely cold European JFMA conditions back to the 16th century by using documentary proxy records that are temperature sensitive and located and representative for the seven instrumental records. The skill of this method is tested in the virtual world of two three-dimensional climate simulations (ECHO-G and HadCM3).

Data

The dataset used for this study includes temperature series based on instrumental measurements (mainly 1760-2007) and documentary data (pre-1760 period – either expressed as ordinary scaled indices or as absolute 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, however, most of the instrumental temperature series used here start approximately at that time and the new Central European temperature (CEu) presented by Dobrovolny et al. (2008, this issue) begins in 1760. These series are further related to the gridded SLP reconstructions and three GCMs. As mentioned in the introduction we focus our analysis on the of January-April (JFMA) season.

Instrumental temperature series

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

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

Φιγυρε 9 **Central Europe** (1760-2007): The series was calculated as an average of 11 homogenized series of the HISTALP database (Auer et al. 2007) from Austria (Kremsmünster, Vienna-Hohe Warte, Innsbruck), Switzerland (Basle, Geneva, Bern), Germany (Regensburg, Karlsruhe, Munich, Hohenpeissenberg and the station Prague-Klementinum (Czech Republic), which were corrected for unsufficient radiation protection of early thermometers (see Böhm et al. this issue) and the growth heat urban island (Dobrovolný et al. this issue).

iii) **De Bilt** (1760-2007): The data from the post 1760 period is called the Labrijn series (Labrijn, 1945), 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 et al 1983-1992, 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 Padova, Bologna, Milan (Brunetti et al., 2001; Camuffo 1984, 2002a,b,c; Cocheo and Camuffo 2002; Maugeri et al., 2002a,b, 2004), Florence and Vallombrosa (Camuffo et al. this issue). The original data have been corrected for instrumental errors, observations methodology, exposition and relocation and have been homogenized.

v) **Stockholm** (1760-2007): The observations come from the old astronomical observatory in the town without change of the place. The temperature series was homogenized with respect to changing observation hours, number of observations per day, known instrumental errors and the urban heat island trend (Moberg et al.

2002, 2003).

vi) **Tallinn** (1760-2007): The series before 1805 was created by interpolations of the long series Stockholm and St. Petersburg and shorter series Loviisa and Porvoo (Finland). Afterwards up to 1849 it is a composite of several shorter series from different sites in the Tallinn area. 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): The observations stem from the old astronomical observatory in the town. The temperature record has been homogenized using Alexandersson and Craddock tests for annual data. As non-homogenous periods has been established the years 1790-1799, 1808-1828 and 1886-1914. In June 2002 the observatory was moved to another place in Warsaw.

viii) **Cracow** (1792-2007): The observations come from the old astronomical observatory in the Jagellonian University without change of the place. The temperature record has been homogenized using Alexandersson and Craddock tests for annual data.

Series based on documentary data

We use the following reconstructions that are based on different documentary data and which in some way 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.

Figure 9 **Ice winter severity index for Western Baltic** (1500–1759): It was derived from classified values of accumulated areal ice volume along the German Baltic coast back to 1701. Prior 1701 the series was extended by other ice cover related information from different coastal locations and from indirect indices derived from tax reports of Danish harbor stations (Koslowski and Glaser 1999).

ii) **Central European series – CEu** (1500-1759): Monthly national index temperature series based on documentary data from Germany, Switzerland and the Czech Republic were standardized and averaged for the period 1500–1854. Overlapping with instrumental series of Central Europe (see above) in the period 1760–1854 allowed use of linear regression for quantification documentary-based indices since 1500. Reconstructions before 1760 were finally re-calculated to have the same mean and variance as the measurements over the overlapping period (Dobrovolný et al. this issue).

Figure 9 **Low Countries Temperature – LCT series** (764-1759): The series, covering area of the present Netherlands and neighbouring areas of the southern part of the North Sea, includes 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 with the number of days that ice forming and/or frost was observed. By comparing the summer indices with grape harvest data of the Beane and Dijon series revealed good agreement (van Engelen et al. 2001). The LCT series can be considered as homogeneous from 1300 onwards (Shabalova and van Engelen 2003).

vi) **Tallinn series** (1500-1759): The first day of ice-break up in the Tallin port since 1500 and on the rivers in northern Estonia since 1731 were used as proxy data. A statistical regression model has been calculated fitting the proxy informa-

tion to instrumental data and applying the statistical models to the paleo information under the assumptions of stationarity between the predictor (proxies) and predictand (instrumental) (Tarand and Nordli 2001).
iv) **Northern Italy**: (1500-1759) Indices are derived from the analysis of 70 contemporary documentary sources. The concerned area is Northern Italy with particular reference to its northern part (e.g. Padua, Venice and Bologna). The series was calibrated and verified against instrumental readings in 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. (this issue).
v) **Stockholm series** (1502-1759): The start of the sailing season in the Stockholm harbour derived from custom ledgers and other documents related to port activities was elaborated for the period 1502-1892. The several, partly overlapping, time series derived from these records were standardized and averaged. The resulting composite series was robustly calibrated and verified against Stockholm JFMA instrumental temperatures over the overlapping period (1756-1892). The reconstruction for 1502-1759 was then re-calculated to have the same mean and variance as the measurements in the overlapping period (Leijonhufvud et al. this issue).
vii) **Poland**: (1500-1779): Information about past weather conditions is found in the collection of more or less systematically and 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; Limanówka 1996 and references therein). Temperature indices are available for single months (with some gaps), seasons and for the entire year.

Gridded SLP

We used the new 5°x5° gridded seasonally resolved SLP dataset produced by Küttel et al. (2009). 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 SLP dataset covers the period 1750-2007, with 1750-1849 being the reconstruction and 1850-2007 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; thus it can be used independently to asses the driving atmospheric patterns behind recent and past climate anomalies. We recalculated the SLP fields for JFMA, JF and MA averages.

Model data

Climate model output data is used here for two purposes: In the first application, a small ensemble of simulations have been made with the coupled ocean-atmosphere-sea ice general circulation model of intermediate complexity ECBilt-

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) ECBilt-Clio

The EC-Bilt model is a coupled ocean-atmosphere-sea ice general circulation model of intermediate complexity (Goosse and Fichefet 1999; Opsteegh et al. 1998). The atmospheric component (EC-Bilt) resolves 21 wavelengths around the globe. 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 qualitatively correctly, and the strength and position of the jet stream and transient eddy activity become fairly 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 3º×3º 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 model and the Hamburg Ocean Primitive Equation model 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°x 3.75° longitude / latitude) and 19 levels along the vertical direction, five of them located above 200hPa and with the highest being at 10hPa. The oceanic component HOPE-G has a resolution of approx. 2.8°x2.8° longitude / 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 (Gonzalez-Rouco et al. 2006; Zorita et al. 2007). It is an all-forcings simulation 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.

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) x 3.75° (longitude) and 19 levels along the vertical direction. The ocean component has 20 levels with a spatial resolution of 1.25° x 1.25°. The resolution is higher near the ocean surface. In this study, two HadCM3 runs were merged: A natural forcings run from 1500-1749 and a natural-plus-anthropogenic run spanning the period 1750-1999. The run using natural forcings alone is driven by prescribed changes in volcanic forcing, solar irradiance and orbital forcing, while anthropogenic forcing factors were fixed at estimated pre-industrial values. The other run 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, but not in the ECHO-G simulation are tropospheric aerosols during the 20th century and historical changes in land use.

Methods

PCA based Circulation patterns associated with extreme JFMA anomalies

In the first step, we will derive major atmospheric circulation patterns associated with warm and cold JFMA anomalies covering the period 1760-2007. We will apply the method described in Jacobeit et al. (1998) where the circulation patterns result from algebraic transformations that can be seen as a reflection of reality if at least one of the original SLP fields gives a sufficiently high spatial correlation (as in the present case with maximum T-mode loadings above 0.8). The temperature anomalies will be determined separately for three regions in different latitudes: Central Europe (De Bilt, Berlin and CEuT), Northern Europe (Stockholm and Tallinn) and Southern Europe (Padova). For every region warm and cold years will be selected that exceed at least for one station one standard deviation from the 1760-2007 climatology. For each of these samples which contain between 10% and 21% of all available SLP fields, the corresponding SLP grids will be dimensionally reduced using a T-mode principal component analyses with varimax rotation (Jacobeit et al. 1998) resulting in the major circulation patterns explaining more than 95% of the SLP variance during these anomalous JFMA seasons.

Canonical Correlation Analysis

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. von Storch and Zwiers 1999; Wilks 1995). It has been used extensively throughout the meteorological and climatological literature (e.g., Dünkeloh and Jacobeit, 2003; González-Rouco et al. 2000; Graham et al. 1987; Nicholls 1987; Xoplaki et al. 2003; Zorita et al. 1992). In this study we mainly follow the methodology presented by Della-Marta et al. (2007):

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 at 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). 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, retaining a number of selected Principal Components (PCs) using the rule N criterium. In order to derive the significance level that determine how many PCs to be used, one thousand synthetic datasets were created and the significant number of PCs assessed at the 5% significance level 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 not often result in a higher model skill. To address this problem we performed a CCA for every combination of predictor PCs and predictand PCs and performed a one time step cross-validation procedure (e.g. Michaelsen 1987), i.e. repeatedly leaving one year out of the CCA, and then assessed the prediction errors as the mean Spearman rank correlation skill score.
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 Shabbar and Skinner (2004) where the PCs of the predictand were 9omogenizi 5000 times using a bootstrap with replacement technique (Efron and Gong 1983). 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 data (non-detrended) data in order to infer to reflect the long-term trends in the temperature and MSLP series.

Assimilation of paleoclimatic reconstructions

A simulation with a climate model cannot fully replicate the observed climate trajectory even if the climate model would be perfect, essentially because of a large degree of randomness in the time evolution of the dynamic circulation system from a certain initial state. One way to select the observed trajectory among all physically possible trajectories is the so-called data assimilation techniques. 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). 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. Importantly, synoptic-scale variability internal to the atmospheric system are not suppressed and can freely adjust to the changes in the large-scale atmospheric circulation. These 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 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 ECBilt-Clio. 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.

Analog case search for large scale SLP fields based on anomalous European temperature

The strong relationship between European winter climate conditions and atmospheric circulation, allows the use of observed spatial patterns of extreme JFMA temperature years occurring during the time window when instrumental SLP data (1760-2007) is available, as modern analogs, to independently reconstruct corresponding large-scale SLP fields for periods when widespread direct pressure information is not available (see Jones et al. 1999; Küttel et al. 2009; Luterbacher et al. 2002). Here, we present anomalous SLP maps related to cold JFMA together with corresponding anomalous European land temperature and precipitation patterns. Analogs for warm anomalies have also been calculated but for the sake of brevity they are not shown here.

Spatial Representativity

The approach of an analog case search and the subsequent reconstruction of large-scale SLP field rely on the spatial representativity of the underlying temperature records as the predictors. It is therefore essential that proxy-based temperature reconstructions are spatially representative. As described above the underlying temperature records consist of purely documentary derived data, and selected instrumental series representative for the area the documentaries were collected from. We test all seven records for their ability to represent European anomalous temperature conditions. However, a direct assessment of the spatial representativity can only cover parts of the records that overlap with independent gridded datasets. Although we test the spatial representativity on the instrumental parts of the records, in support, various studies have also referred to the ability of purely documentary records to represent a broader spatial extent (e.g. Brázdil et al. 2005; Dobrovolný et al. 2008; Dobrovolný et al. this issue; Glaser 1999). In this regard, all instrumental parts of temperature series are correlated with the instrumental gridded data set (Mitchell and Jones 2005) over the period 1901–2000 for the JFMA season by using the grid point squared Spearman correlation. We carefully tested all records for spatial representativity both independently as well as in differing combinations (not shown) with the aim of reducing the number of records (optimal combination) needed to best spatially represent the temperature signal over the whole European region. The results will present the optimal selection of predictor records that are able to represent extended parts over Europe (Figure 8).

Analog Search Procedure

We start the analog case search by looking for cold temperature anomalies in the pre-instrumental part of the seven temperature reconstructions (i.e. pre-1760). Then, we search for cold anomalies in the period 1760-2007, when we have overlap with the SLP data (Küttel et al. 2009), to find the potential analogues. The search is based on an algorithm (Koenig, 2007) that takes all possible combinations of all seven temperature reconstructions into account and searches for temperature extremes occurring at specific locations at specific times. Although the search algorithm is applied to the full set of (seven) temperature series, we strive to minimize the number of records needed to reasonably well represent an integrated European temperature anomaly situation. Based on the test of spatial representativity (see above), we solely use this minimized number of representative series to calculate the SLP patterns for cold anomalies. In this regard, we found that only two of the seven temperature series, namely Stockholm and Central Europe, were sufficient to capture the integrated European anomaly situations (Figure 8). To define the anomalies, an overall threshold was set to 1 SD above/below the 1961–1990 climatology. After having identified the appropriate extremes (i.e. the particular years) in the instrumental part of the temperature series, i.e. the analogues to the temperature anomaly situations in the pre-instrumental part, the corresponding instrumental SLP fields for the same extreme years are taken as analogues for the SLP fields associated with the temperature anomalies in the pre-instrumental period. Anomaly composites (with respect to the 1961-1990 climatology) are presented to define large-scale circulation patterns for mean JFMA SLP based on outstanding anomalies of the available temperature series. Additionally, we present the corresponding anomalous temperature and precipitation fields.

Application of analogue method on model data

As for documentary time series, the analog method is applied to model simulations. We used the ECHO-G Erik 2 simulation (Gonzalez-Rouco et al. 2006, 2008) and the HadCM3 simulation (Tett et al. 2007) for the periods from 1000-1990 and 1500-2000, respectively. In contrast to the temperature reconstructions based on documentary data, temperature time series of the models exhibit more low frequency variations. The most likely reason for an underestimation of low frequency variability within the documentary data may be the specific nature of the historical records as a source of information that operates within the limited framework of the memory of individuals of a certain society, tied to a location and to an specific moment of time. From this perspective, the unique character of an extreme event that can lead to a documentary recording may change with time according to the subjective perception of the environmental conditions by those who lived at the dates of the event taking place (e.g. Pfister et al. 2008). Thus, regardless of the effective causes of the model/data differences in the representation of the low frequency it is necessary to place both in a comparable framework. This has been done in the present study 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 systematic detection of extreme values. Therefore, a 30-year high-pass filter is applied to the series to preserve only the high frequency component. Then, extreme years (based on the above mentioned 1 SD criterion) which occur simultaneously in the time series of the chosen locations are selected.

Results and discussions

First, using instrumental temperature series only, we will present the most prominent atmospheric circulation patterns related to anomalous warm and cold JFMA conditions derived within three European areas spanning the instrumental period 1760-2007. Second we show the coupled CCA patterns which optimally relate JFMA SLP and the seven selected temperature series covering the same period. Third, we present results of a climate simulation into which the reconstructed JFMA SLP has been assimilated with the ECBilt-Clio model. Fourth, instrumental and documentary temperature proxy information and output of two climate simulations are combined to search for analogs of anomalous cold European JFMA. Finally, the skill of the analog method is evaluated in the test-bed provided by the climate models ECHO-G and HadCM3.

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 of the JFMA season are presented. The number of these patterns 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 (see captions of Figs. 1 and 2). Further, the major circulation patterns and variances explained are similar for Padova and Central Europe, therefore we only present the maps for Central Europe.

Warm anomalies in Central Europe (Fig 1 left) are connected with a northeastward extension of the Azores High. In the case of Northern Europe (Fig. 1 right) the anticyclonic centre is shifted up to southwest England thus inducing a mixed circulation pattern (between zonal and meridional configurations). The next 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 among the regional variants refers to the longitudinal position of the transitional area between cyclonic and anticyclonic predominance which is most eastward for Padova (not shown) and distinctly shifted westward for Northern Europe (Fig. 1). 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.

Similarly, in the cold-anomaly cases, the first PC for all regions (Figs. 2) shows a zonal circulation pattern. However, these cold anomalies cannot be linked to advection but rather to radiative cooling (especially in more southern latitudes) thus pointing to important variations within the same circulation pattern (Jacobeit et al. 2001a, 2003; Beck et al. 2007). The second PC for all three regions depicts a blocking European high anomaly that keeps away relatively warm Atlantic air from influencing the continent and leads to cold conditions in large parts of Europe. 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 modifications refer 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 between 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 four months might not be represented in seasonal mean values.

Earlier studies relating circulation to 16th century temperature anomalies derived monthly or seasonal mean SLP patterns for outstanding warm and cold winters in Europe on a subjective basis (Jacobeit et al. 1999). Subsequently, analyses were based on earlier objective SLP reconstructions back to 1780 (Jones et al. 1999), including both studies on 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) provide six different circulation patterns, mainly due to 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 (Jacobeit et al 2009; Philipp et al. 2007) including 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 two-month seasons (JF; MA, not shown). In this case the major modes are similar to the four months period, however for the different areas we found also some differences in terms of particular PCs and explained variances.

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

We extent the analysis of results from the previous chapter by investigating 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 two CCA modes, since they capture 35 and 5% of temperature variability. Spatial patterns and expansion coefficients of the modes are presented in Fig. 3. The variance that is explained by the first CCA pattern is approximately 23% for SLP and 35% for temperature. This pair exhibits a canonical correlation of 0.76 (significant at the 5% level). The first canonical map of SLP shows the well-known dipole pattern with positive correlation values south of approximately 50°N and negative SLP anomalies with centre over the subpolar region. The anomalous stronger westerly flow is responsible for the significant positive temperature anomalies at six of seven stations. The scores in Fig. 3 (bottom, dashed straight line) indicate positive significant long-term trend in the temperature, but not in the circulation score series. There are also significant positive trends in the predictor and predictand scores during two multi-decadal periods. The first from 1830s-1860s and the second from 1960s to the mid 1990s (i.e. a positive trend in westerlies over the

eastern North Atlantic and Europe and a related increase of European temperature). Recent years indicate a slight downward trend in circulation and temperature relationship. The downward trend of the NAO and Arctic Oscillation (AO) (they show much resemblance to the pattern of this first SLP CCA) has also been discussed by Overland et al. (2005).
The variance that is explained by the second CCA pattern (not shown) is 4% for SLP and 5% of temperature. The second canonical map of SLP show a large monopole pattern with positive values with centre over northwestern Europe. Anomalous northeasterly flow is connected with below normal temperature, though significant only in Padova (not shown).
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 (negative) mode of CCA1 (CCA2, not shown) and b) the advection of cold continental air inducing negative temperature anomalies in the negative (positive) mode of CCA1 (CCA2), this mechanism being in winter strengthened by night time clear sky radiative loss. This does not contradict the findings from the PCA/extreme analysis above as not all cold and warm anomalies are associated with a westerly pattern (see Fig. 1 and 2 based on PCA). In addition, not each westerly pattern in the T-mode is identical with a positive phase of the NAO, as they might also include cases with below-average SLP gradients.
We also performed CCA experiments for January-February and March-April and found that the differences were small (not shown).

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 atmospheric circulation, averaged over JFMA is close to the present SLP reconstruction (Küttel et al. 2009). SLP is not a prognostic variable in the model. 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 of the simulation that have a pattern correlation for each year between the simulated and the reconstructed fields with the stream function reconstruction above 0.8 will be considered. 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 the seven early instrumental temperature records and the simulated 2m temperature for the same season. 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, like solar activity or volcanic aerosol loadings, are not parameterized in these simulations. The correlations reach values up to 0.7 (Fig. 4), 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 centers of action of the model's variability are offset to the north. Next, we provide evidence that the year-to-year variability of the simulated surface temperature fields captures the same temporal 15omogeniz as early instrumental measurements within the selected period 1790-1820 period and show that the model derived sea-level pressure reconstruction is trustworthy. Averaged over the 1790-1820 period, 2m 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 extending into Spain is visible. 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) for this period.

To analyse the data assimilated simulation in more detail, two particular extreme JFMA years are selected for closer inspection. The first example (1817, Fig. 6) is the warm winter after the Tambora eruption in April 1815. The second winter (1829, Fig. 7) was cold in CEu, the Low Countries, Stockholm and Tallinn series. In both cases, the pattern correlation between the simulated stream function of the ensemble mean and the reconstruction of the stream function is higher than 0.9, which ensures 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 cold or warm winters of the selected years. This allows for the observation, via the model output, which mechanisms might have been important, apart from simple advection, to account for the harsh or mild winters of the two selected years. With 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 15omogeni temperatures adds to the credibility of the SLP reconstruction. Moreover, a data assimilated simulation will capture other climatic parameters as well in a way which is dynamically consistent with the input pressure reconstruction. For the two years we show anomalous patterns of simulated 2m temperature, snow depth, albedo and precipitation with respect to the 1961-1990 reference period.

The JFMA season of 1817

Figure 6 shows the anomalous fields of 2m temperature, albedo, snow depth and precipitation as simulated for the anomalously warm JFMA season of the year 1817. This winter, following the eruption of the Tambora in April 1815, was exceptionally warm in parts of Europe (Fischer et al. 2007; Luterbacher et al. 2004; Trigo et al. 2009; Xoplaki et al. 2005; Zerefos et al. 2007). The simulated 2m temperature (Fig. 6) over the area 40°N-67.5°N and 0°E-27.5°E is less than 0.2°C warmer than the average of the early instrumental temperatures mentioned above. The largest warming is found in northeastern Russia and extends over Scandinavia and into Poland. Not surprisingly, simulated snow depth in that area is smaller than the model climatology (1961-1990). The simulation suggests that winter 1817 was dry – 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 anomalously negative precipitation over Europe.
The impact of warm anomalies on the date of plant 16omogenizing 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. Interestingly, in the Stockholm daily temperature series (Fig 6 bottom panel), January and February were warm (almost all days in these months were above the long-term mean), whereas daily temperature in March and April fluctuated around the normal.

The JFMA-season of 1829

Figure 7 shows the anomalous fields of 2m 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 winter-averaged temperatures of 1°C below normal in southern England, northern France and stretching into the Ukraine. In these cooler regions, a general increase in snowfall is modeled and as well as a southward migration of the area with snowfall. These factors must have contributed to the observed lower temperatures. The increase in snow depth is at least partially related to an increase in total precipitation over Northern Europe.
The Stockholm daily temperature series (Fig. 7, bottom panel) support the model results as daily temperature from January to April were almost throughout below normal. For this year, plant phenology in Finland, Switzerland and the UK was decreasingly delayed with more than 1 SD in arctic Finland and the Alpine Switzerland (Holopainen et al. 2006; Rutishauser et al. 2009) an indication of distinctive lower temperature in wide spread Europe.

These examples (Figures 6 and 7) show that the deviation of European climate from the climatic normal was largely driven by the actual types of the atmospheric circulation patterns. It is interesting to note that a simulation which reasonably resembles the winter SLP reconstruction reproduces temperature fields which can be related to observed values. In those two examples the modeled and reconstructed temperature and to some degree also the precipitation distribution are in good agreement (not shown). The simulation of the warm 1817 winter, following the Tambora eruption, is intriguing. 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.
A new approach to reanalysis is being pioneered as part of the international ACRE (Atmospheric Circulation reconstructions over the Earth, http://www.met-acre.org/) initiative, in which the only meteorological data that are assimilated by the reanalysis are surface variables – notably synoptic SLP and monthly sea surface temperature and sea-ice. The masses of historical surface terrestrial and marine weather observations recovered and digitized under ACRE will provide an important boost to the international databases to produce a series of global historical 4D reanalyses pushing back into the mid-late 18th century. These products will be tailored and downscaled for use by climate researchers, the climate applications, impacts and risk communities, the teaching and educational sector, and even the general public.
The similarity of the circulation patterns found in the instrumental period 1760-

2007 for a set of target regions points to a spatial coherence in the dynamic patterns that led to cold and warm extremes. It is therefore reasonable to assume to a certain degree stationarity in the relationship between European JFMA temperatures and the underlying large-scale SLP field. Here, we want to further extend the analysis back in time and address the pre-instrumental (before 1760) period. Using the analog case technique described earlier, the pre- and instrumental period are linked. 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 addition, the following reconstruction validates the results on model data to test the methodological approach applied on documentary records. In conjunction to the analysis conducted for the instrumental period (post-1760), we apply an independent methodological approach, use additional underlying data, and extend the analysis of dynamic circulation for extremes back into the pre-instrumental period to 1500.

Analog case search

The search for the locations of optimal spatial representativity shows that a few selected key sites with documentary series such as Stockholm (Lejonhuvud et al. 2008; Lejonhuvud et al. this issue; Moberg et al. 2002) and CEu temperature (Dobrovolný et al. this issue) can be considered as representative to cover broad regions of Europe (Figure 8; see also Zorita et al. 2009). The combination of both locations show strong positive correlation over almost the entire European continent. Only Iceland and Turkey feature insignificant and weak negative correlations and may not be represented accurately combining both stations. For the model simulations Erik 2 and HadCM3 the spatial correlations are calculated between the co-located grid cells including CEu and Stockholm and all other European grid boxes. Stockholm is representative for Scandinavia and eastern Europe while the central European data is representative for central, western and southern Europe (not shown). Hence, the test of spatial representativity in the model domain points to similar results as obtained by testing records based on documentary data.

Extreme Analogs

Table 1 presents the analogs for the extremely (1 SD with respect to the 1961-1990 climatology) cold pre-instrumental (1500-1759) and instrumental periods (1760-2006) computed from the analog case search based on the selected documentary records. As mentioned above, we limit the detailed analysis on cold anomalies. The derived 14 cold cases for the post-1759 period are then subjected to the anomaly composite analysis. It is important to note 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 record both extremes in the CEu record, but not in the Stockholm reconstruction. In addition, apart from two single years (1940, 1942) we did not find a single cold extreme that occurred at all seven locations simultaneously.
Additional to the search within the documentary series sensitivity experiments have been carried out on the model data to check the influence of the threshold for the identification of extreme years in the model simulation. The use of the same threshold of 1 SD as applied to documentary data leads to an averaging of a larger

sample of anomalous years since the pool of theoretical analogs from the model simulations is much larger. However, the averaging of more anomalous years does not influence the main pattern, but only the uncertainty in the estimation of that composite. Regarding the search for anomalous years, 59 cold events were identified for the 1000-year long Erik2 simulation and 19 cold years for the 500 - year long HadCM3 simulation.

Anomalous European cold composite analysis

Figure 9 presents anomaly (1961 to 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) and the corresponding standard errors (standard deviations divided by the square root of the number of cases averaged for the composite) for the extremely cold European JFMA means in the post-1760 period. The anomaly SLP 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 negative pattern connected with blocking situations. The anomaly temperature map indicates continental cold with the largest deviations and highest variability over northeastern Europe and tendency to positive anomalies over Iceland and parts of Turkey. It shows the well-known seesaw in winter temperature between Greenland/Iceland and Europe (van Loon and Rogers 1974), 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 over the Mediterranean.

The results of the analog case search also show that certain assimilated anomalous winters mentioned previously (e.g. winter 1829, Fig 7) are also mirrored in the results here which are independently reconstructed based on the selected documentary records. In comparison to the subjectively (Jacobeit et al. 1999) and objectively (Luterbacher et al. 2002) reconstructed extremely 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). It points to the fact that major extreme years unequivocally show up independently of the approaches applied. With this overlap of extreme years, we have additional confirmation that these pre-instrumental years found here do represent true analogs of widespread surface extremes over Europe, allowing us to extend the analysis further back in time. In summary, a strength of this method is that it can serve as an independent validation for manually and especially objective statistically reconstructed SLP patterns in the past.

The concept of a stationary relationship between temperature and SLP is generally assured in this study. However, a terrestrial pattern may result from a set of modes of atmospheric circulation. As a consequence, it is crucial that the methodological approach shows the ability to address for the variations in the response of the surface variable. That is to account for varying modes of atmospheric patterns that may be related to a similar surface signal (see Jacobeit et al. 2003). Single analogs from the instrumental period revealed small variability within the chosen group (within-group variability). This endorses the fact that the applied approach can capture these different types of SLP modes that may correspond to similar extreme patterns in the past.

The SLP anomaly composites based on the model simulations (Figs. 10 and 11) are in good agreement with the anomaly composite presented in Figure 9. The SLP and temperature composites derived from the HadCM3 model and from the documentary data 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. 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 amounts. This is mainly due to the coarse spatial resolution of the model and consequently the less detailed topography.

The smaller temperature anomaly in the ECHO-G composite is due to the strong positive temperature trend simulated for Europe in the 20th century. In contrast, the HadCM3 shows globally the same positive trend for this period but in 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, both factors are not contained in ECHO-G. Hence the more negative temperature anomalies in HadCM3 are just an artifact of the positive temperature trend in the 20th century. This fact does not influence the choice of the extreme years as the time series used for identification of the extremes were filtered before (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 the same 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.

Conclusions

This contribution deals with the connection between the January-April large-scale atmospheric circulation and European temperature covering the last centuries using instrumental data, documentary evidence and model simulations.

Based on T-mode principal component scores specific circulation patterns linked with warm and cold anomalies in different regions of Europe during winter 1760-2007 are well-known from previous analyses and are confirmed in this study using the most recent SLP reconstruction (Küttel et al. 2009). A prominent factor in the relationships between atmospheric circulation and temperature anomalies seems 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 decisive mechanisms (advection of warm Atlantic air masses versus radiative cooling by more anticyclonic subtypes).

The CCA analyses indicate that similar large-scale relationships can be seen as in the T-mode PCA, however, the CCA is limited to uncorrelated modes of variability and hence some of the cold/warm signals may not be captured using the CCA methodology. The NAO-like pattern is clearly the most important pattern for temperature variability and explains approximately 35% of seasonal temperature variability at the seven stations across Europe covering the last 250 years. The 2nd CCA only explains 5% of temperature variability, which maybe the result of within-mode variability contained in CCA1.

A more detailed dynamical understanding of the relationship between large scale circulation and European JFMA climate was achieved by the data assimilation approach, where a consistent relation was found between modeled and observed temperatures for selected years.
We then extend the analysis back to the early 16th century and address the pre-instrumental period, when no direct SLP data is available. We presented a method to reconstruct past SLP fields using an analog method that links the pre- and instrumental period by using documentary proxy records. This approach aimed at detecting the extremes for the entire European realm by using derived temperature indices from documentary evidence that are located and representative for the same seven instrumental records. The analog case search applied on documentary-based series and the subsequent compositing 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. It is stated that documentary data can act as a reliable predictor to reconstruct SLP patterns for analog extreme seasons in the past when no instrumental information is available. In respect of a progressive reduction in the spatial and temporal availability of high resolved climate information for the pre 16th century, it is the advantage of historical sources that primarily provide information on extreme conditions (e.g. Pfister et al. 2008). The proposed analog case method allows to integrate new data that will become available from different national and international projects and thus will provide evidence on the dominant atmospheric circulation over the North Atlantic European area for the first part of the last millennium related to extreme warm and cold anomalies.

It is remarkable that the reconstructed patterns of the extreme years for JFMA are in very good agreement with the two coupled climate models. 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 can provide a large-scale climate context. Also, this agreement underscores the skill of the model 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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Figure captions

Figure 1: 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 according to the procedure developed in Jacobeit et al. 1998 (normalized T-mode PCA scores). Explained variance for the two PCs (Central Europe) is 61.3% and 34.1%, for Northern Europe it is 39.2% and 35.6%.

Figure 2: as Fig. 1, but for cold JFMA seasons in Central Europe (left) and Northern Europe (right)

Explained variance for the two PCs (Central Europe) is 32.9% and 32.1%, in the case of Northern Europe it is 41.0% and 33.2%.

Figure 3: The first CCA between JFMA mean SLP and the seven temperature stations over the period 1760-2007. Top left: the JFMA temperature canonical pattern for the seven stations. Top right: the SLP canonical pattern, bottom: the canonical score series from 1760-2007. Red (blue) areas indicate positive (negative) correlations above (below) 0.1. Both CCA loadings in the top of the figure are expressed as a correlation coefficient between each grid point (or station) data (standardized and de-trended according to method section) and the canonical score series for each grid point (station). They explain 23% (SLP) and 35% (station temperature) of the total variance in the CCA space. In top left the sizes of the crosses ('+') and open circles ('o'), respectively, show the magnitude of canonical loadings. Colored red and blue symbols indicate statistically significant positive and negative correlations at the 5% level. The lower panel presents the SLP (solid line) and station temperature (dashed line) canonical score series with a correlation coefficient of 0.76 (significant at the 5% level)

Figure 4: Temporal correlations between the simulated 2m temperature, averaged over JFMA, and the instrumental records from De Bilt, Central Europe, Stockholm, Tallinn, Padova, Warsaw-Cracow and Berlin averaged over the same season. These correlation maps are conditional on the pattern correlation between the model streamfunction and the reconstruction being equal or higher than 0.8.

Figure 5: Assimilated anomalous 2m temperature for the JFMA season in degrees Celsius according to the data assimilation experiment, averaged over the years 1790-1820, as a deviation from the reference period 1961-1990.

Figure 6: The simulated anomalous (with respect to the 1961-1990 reference period) 2m temperature (degrees C), snow depth (m), albedo and precipitation (mm) for the year 1817. The fields are averages over the months JFMA

Figure 7: as Fig. 6 but for 1829

Figure 8: Spatial representativity for selected documentary records for Central Europe (top left) and Stockholm (top right), their combination (lower left), and all seven documentary series for JFMA are considered (lower right). The values are expressed in grid point squared correlation coefficients 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 as contours.

Figure 9: Anomaly composites (with respect to the 1961-1990 reference period) of selected extreme cold winters with corresponding standard deviation for the post-1759 period. SLP (top), temperature (lower left), and precipitation (lower right). The contours represent the standard deviation divided by the square root of the number of extreme cases that are averaged in the composite.

Figure 10: as Fig. 9, but for ECHO-G Erik 2

Figure 11: as Fig. 10, but for HadCM3

Tables

Table 1: Extreme 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
Cold	1569, 1573, 1586, 1595, 1600, 1601, 1614, 1658, 1663, 1684, 1685, 1688, 1692, **1784**, **1785**, **1799**, **1808**, **1829**, **1838**, **1839**, **1847**, **1853**, **1888**, **1917**, **1940**, **1942**, **1963**