European climate dynamics and long-term variations over the past centuries

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

Marcel Küttel

von Sursee LU

Leiter der Arbeit:
Prof. Dr. H. Wanner
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Prof. Dr. U. Feller

Für meine Mutter

Summary

Testing a European winter surface temperature reconstruction in a surrogate climate

We evaluate the skill of a European winter surface air temperature reconstruction over the last 500 years using pseudoproxies obtained from the ECHO-G and HadCM3 climate models. The emphasis is thereby on the effect of the reduction of available predictors back in time, an issue that has not yet been investigated in detail at continental and seasonal scale. It is found that the key factor in determining the reconstruction skill is the number of predictors and particularly their spatial distribution. However, considering the usually insufficient spatial and temporal predictor availability in paleo-reconstructions, the quality of the predictors becomes more important further back in time. Not surprisingly, the lowest reconstruction skill is found in the early period when the predictor network is reduced. Important differences between ECHO-G and HadCM3-based pseudoproxy reconstructions are discussed and implications for future analyses are presented.

The importance of ship log data: reconstructing North Atlantic, European and Mediterranean sea level pressure fields back to 1750

Local to regional climate anomalies are to a large extent determined by the state of the atmospheric circulation. The knowledge of large-scale sea level pressure (SLP) variations in former times is therefore crucial when addressing past climate changes across Europe and the Mediterranean. However, currently available SLP reconstructions lack data from the ocean, particularly in the pre-1850 period. Here we present a new statistically-derived 5°x5° resolved gridded seasonal SLP dataset covering the eastern North Atlantic, Europe and the Mediterranean area [40°W-50°E; 20°N-70°N] back to 1750 using terrestrial instrumental pressure series and marine wind information from ship logbooks. For the period 1750-1850, the new SLP reconstruction provides a more accurate representation of the strength of the winter westerlies as well as the location and variability of the Azores High than currently avail-

able multiproxy pressure field reconstructions. These findings strongly support the potential of ship logbooks as an important source to determine past circulation variations especially for the pre-1850 period. This new dataset can be further used for dynamical studies relating large-scale atmospheric circulation to temperature and precipitation variability over the Mediterranean and Eurasia, for the comparison with outputs from GCMs as well as for detection and attribution studies.

Multidecadal changes in the circulation-climate relationship in Europe: frequency variations, within-type modifications and long-term trends

Advective processes exerted by the large-scale atmospheric circulation are known to strongly influence the spatial distribution and temporal variation of European winter climate. However, this connection is subject to important spatial and temporal variations. Applying a recently developed classification technique it is investigated in space as well as in time how the relationship between representative patterns of the European and North Atlantic atmospheric circulation and the European winter (DJF) temperature and precipitation fields has changed over the period 1750-2000. Although important changes in the frequency of the sea level pressure (SLP) clusters are found, none of them reveals any significant long-term trends. However, for most of the nine derived SLP clusters, a tendency towards overall warmer and partly also wetter conditions are found for the past 250 years, most pronounced over the last few decades. This points towards important within-type variations, i.e. the temperature and precipitation fields related to a particular SLP pattern change their characteristics over time. Using a decomposition scheme to distinguish between climate variations due to changed frequencies and due to within-type variations of the SLP clusters it is found for temperature as well as precipitation that the latter dominate over the former. Within-type variations appear to be the most important factor particularly for temperature and over Eastern Europe and Scandinavia, generally explaining more than 70% and up to 90% of the multidecadal temperature changes. This indicates that the recently observed warming over Europe cannot be explained by changed frequency of SLP patterns alone but to an important degree also to changed characteristics of the patterns themselves. So far, it can only be speculated about the specific origin of these within-type variations.

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

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.

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Abbreviations

Scientific programmes and projects

ACRE	Atmospheric Circulation Reconstructions over the Earth
CAPRICORN	Climate Anomalies and coPing stRategies of socIeties in Central eurOpe: the histoRical dimensioN
CLIWOC	CLImate variability over the World's OCeans
ESF	European Science Foundation
EXTRACT	EXtended Thousand-year Reconstruction of Alpine Climate from Tree-rings
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
LOTRED	Long Term REconstruction and Diagnostics
MEDARE	MEditerranean climate DAta REscue
MONALISA	MOdelling and reconstruction of the North Atlantic cLImate System vAriability
NCCR Climate	National Centre of Competence in Research on Climate
PALVAREX	PALeoclimate VARiability and EXtreme events
RECLAIM	RECovery of Logbooks And International Marine data
SNSF	Swiss National Science Foundation
UKMO	United Kingdom Meteorological Office
VIVALDI	Variability in Ice, Vegetation And Lake Deposits - Integrated
WP	Work Package

Variables

AD	Anno Domini
AH	Azores High
AMO	Atlantic Multidecadal Oscillation

AO	Arctic Oscillation
CCA	Canonical correlation analysis
CEu	Central European temperature
CFR	Climate field reconstruction
CPS	Composite plus scale
DJF	December, January, February
ENSO	El Niño Southern Oscillation
EOF	Empirical orthogonal function
GCM	Global circulation model
IL	Icelandic Low
JF	January, February
JFMA	January, February, March, April
JJA	June, July, August
LCT	Low Countries temperature
LMM	Late Maunder Minimum
MA	March, April
MAM	March, April, May
MJJAS	May, June, July, August, September
MLP	Multiple linear regression
MSLP	Mean sea level pressure
NAO	North Atlantic Oscillation
NDJFM	November, December, January, February, March
PC	Principal component
PCA	Principal component analysis
RE	Reduction of error
RegEM	Regularized expectation maximization
RR	Precipitation
SANDRA	Simulated annealing and diversified randomization
SLP	Sea level pressure
SON	September, October, November
SST	Sea surface temperature
SVD	Singular value decomposition
TT	Temperature

Chapter 1

Introduction

1.1 European climate dynamics

From a climatological point of view, Europe is a very fascinating place. Towards west, Europe borders on the North Atlantic Ocean while the large Eurasian landmass is situated to its east. Extending from the low- to the high-latitudes, Europe is influenced by various modes of the large-scale atmospheric circulation. Combined with the pronounced orography this leads to very distinct spatial patterns of the seasonal large-scale atmospheric circulation and the surface temperature and precipitation fields (Figure 1.1).

The ocean and the atmosphere might be considered the two most important parts of the global climate system, particularly concerning the exchange of mass and energy (e.g. Peixoto and Oort, 1992). From a simplified and temporally averaged perspective, the energy and mass transport in the world's oceans has the shape of a great conveyor belt. This ocean circulation is mainly driven by global differences in temperature and salinity, therefore also generally referred to as the thermohaline circulation (e.g. Broecker, 1991; Wunsch, 2002; Rahmstorf, 2003). The branch in the North Atlantic Ocean consists of the Gulf Stream and of its northern prolongation, the North Atlantic Drift. Connected with the warm Gulf of Mexico, this current conveys warm water bodies far up to Iceland and Scandinavia causing ice-free harbors year-round. As shown in Figure 1.1 (left panels), the sea surface temperatures (SST) in the North Atlantic Ocean show only small interseasonal changes. However, on long-term perspective, the SSTs of the North Atlantic Ocean show marked variations, as e.g. illustrated by the changes of the Atlantic Multidecadal Oscillation (AMO). The AMO, generally defined as the Atlantic Ocean SSTs averaged over 0°-70°N (Kerr, 2000) fluctuates from anomalously warm to anomalously cold temperatures with a pace of 60-80 years (e.g. Delworth and Mann, 2000; Kerr, 2000). The AMO and therefore the North Atlantic SSTs in general are known to strongly influence European climate (e.g. Bergsten, 1936; Marshall et al., 2001; Sutton and Hodson, 2005; Knight et al., 2006). Since the focus of this PhD thesis is more on the

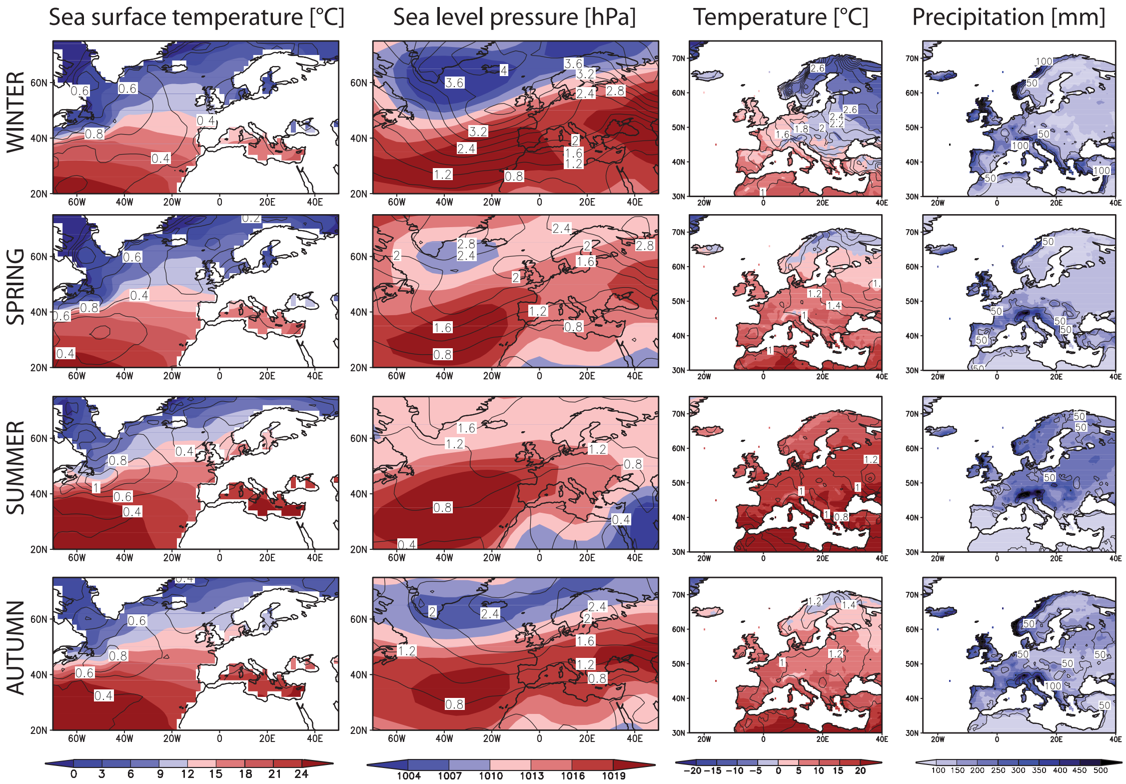

Figure 1.1: *Seasonal mean sea surface temperature (ERSST.v3; Smith et al. 2008), sea level pressure (HadSLP2r; near-real-time update of HadSLP2; Allan and Ansell 2006), air temperature and precipitation (CRU TS 3.0; P.D. Jones, pers. comm.), averaged over 1901-2006. The contour lines indicate the standard deviations over the 1901-2006 period. The seasons are the averages of three consecutive months, e.g. the mean of December, January and February for winter.*

atmosphere than the ocean, the major components of this system are introduced in more detail next.

The dominating atmospheric systems in the larger North Atlantic and European area are the subtropical Azores High (AH), the polar Icelandic Low (IL) and the continental surface highs (winter) and lows (summer). Particularly for the Eastern Mediterranean, the Indian Monsoon system is also of relevance (e.g. Raicich et al., 2003; Ziv et al., 2004), will however not be discussed here. These major centers of atmospheric action and their seasonal variations in strength and position are well detectable in Figure 1.1 (second column). The strongest pressure gradient is found for winter (DJF; Figure 1.1; top row, second column), with the AH and IL being well developed resulting in enhanced zonal winds. Furthermore, a strong Russian High reaching far into Eastern Europe is found during winter. The interannual variability of the atmospheric circulation is also largest during winter, as indicated by the contour lines in Figure 1.1. The corresponding temperature field (Figure 1.1, third column) shows the marked temperature difference between the Mediterranean region and

Northern Europe during this season. Winter precipitation (Figure 1.1, fourth column, top row) reveals highest precipitation amounts along the western coasts of Europe, reflecting the generally zonally oriented winds. During summer (JJA; Figure 1.1, third row, second column) a well developed and stable AH reaching far into the Mediterranean and continental Europe can be depicted. Accordingly, summer climate over Europe is dominated by small pressure gradients and convective processes. The temperature gradient over Europe is clearly smaller than during winter. The precipitation field during this season (Figure 1.1; fourth column, third row) reveals the convective nature with summer being the wettest season of the year over continental areas as e.g. northern Switzerland and Eastern Europe. The strong summerly anticyclone reaching well into Southern Europe is responsible for the very dry summer months in this region. The transition seasons spring (MAM; Figure 1.1, second row) and autumn (SON; Figure 1.1, bottom row) show intermediate pressure gradients with the low pressure being concentrated over Greenland and Iceland during spring but extending far into Scandinavia during autumn. The temperature gradients across Europe are larger than during summer but smaller than during winter. Precipitation amounts are largest over the western coasts of Europe, reflecting the predominantly westerly flow during these seasons.

The dipole of the pressure field over the North Atlantic with high pressure generally over the southern and low pressure over the northern North Atlantic has long been recognized, and was scientifically first described by Teisserence de Bort (1883) and Hildebrandsson (1897). This large-scale pressure vacillation is nowadays well-known as the North Atlantic Oscillation (NAO, e.g. Walker, 1924; Wanner et al., 2001; Hurrell, 2003; Luterbacher et al., 2008). Although it is a spatial pattern, the NAO is often defined as a simple time series. For example, Jones et al. (1997) defined the NAO as the station pressure difference between Reykjavík and Gibraltar. As the only low-frequency mode of the northern hemispheric large-scale atmospheric circulation, the NAO is found for every month of the year (Barnston and Livezey, 1987). However, as shown in Figure 1.2, it is strongest related to European climate during winter season, with statistically significant (p <0.01) correlations for temperature as well as precipitation over Northern and Southern Europe (Figure 1.2, green contour lines). Hardly any significant correlations are found for summer, while spring and autumn reveal some significant correlations for temperature and precipitation, however being clearly smaller than for winter. The following characterization of the relationship between the NAO and European climate therefore primarily applies for winter season.

The NAO fluctuates between a positive and a negative mode. In its positive mode, the AH and IL are well developed resulting in enhanced westerlies directed towards Northern Europe. Accordingly, Scandinavia (the Mediterranean) experiences anomalously warm (cold) and wet (dry) conditions. This is well detectable in the correlations shown in Figure 1.2 (left panels). During NAO negative, the pressure gradient over the North Atlantic Ocean is reduced and the winds point more towards the Mediterranean. The Mediterranean region experiences warmer and wetter winters than normal. Additionally, the Siberian High is well developed bringing cold and dry air primarily towards Northern Europe (Wanner et al., 2001; Hurrell, 2003).

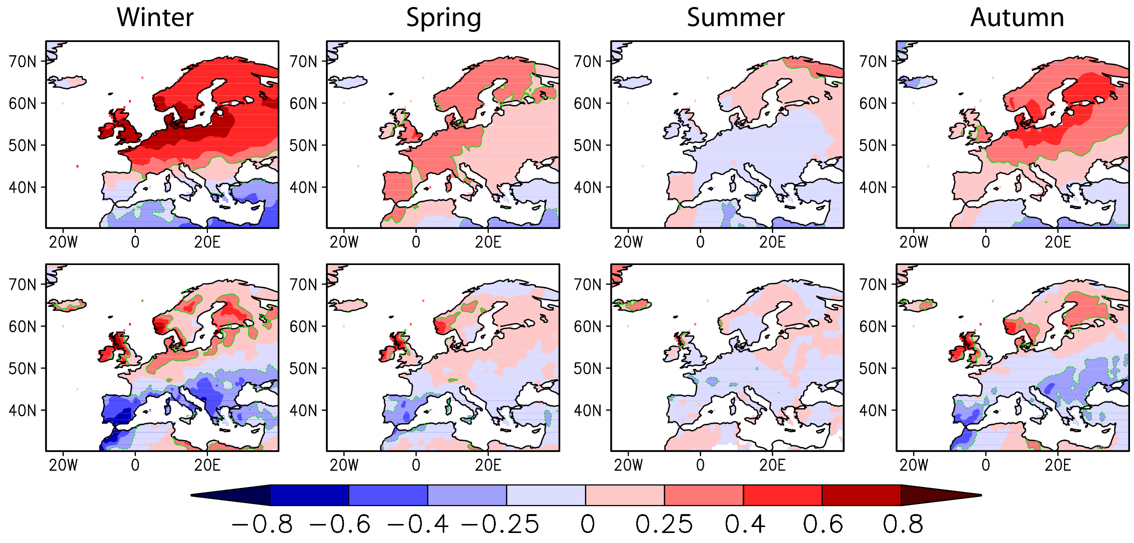

Figure 1.2: *Seasonal correlation between the North Atlantic Oscillation Index by Jones et al. (1997) and the CRU TS 3.0 reanalysis (P.D. Jones, pers. comm.) of temperature (top row) and precipitation (bottom row) 1901-2006. The green contour lines indicate the significance at* $p < 0.01$ ($|r|=0.25$)

The NAO shows important yearly to decadal variations, yet not having shown a preferred state during the past centuries (e.g. Luterbacher et al., 2002a). However, modeling studies (e.g. Paeth et al., 1999; Ulbrich and Christoph, 1999; Hu and Wu, 2004) suggest that the NAO in a future climate with increased greenhouse-gas concentrations might be forced towards the positive state. This would have tremendous effects on ecology and society of the summer-dry Mediterranean region which is strongly dependent on winter precipitation (e.g. Xoplaki et al., 2004).

As illustrated by Wanner et al. (2001) the NAO might not only be considered an atmospheric phenomenon, but also an oceanic. This is not surprising considering the fact that ocean and atmosphere are strongly coupled by fluxes of energy and mass, with the ocean influencing the atmosphere primarily by latent and sensible heat fluxes and the atmosphere forcing the ocean by wind stress as well as heat and mass fluxes (e.g. Bjerknes, 1964). However, these interactions work on different temporal and spatial scales (e.g. Marshall et al., 2001), making the detection of a general coupled pattern a great challenge. Nevertheless, as shown by Wanner et al. (2001), a very schematic characterization of this coupled mode is possible for winter: During the positive mode of the NAO, anomalously cold SSTs are found off the coasts of Greenland and Northwestern Africa, while positive SST anomalies prevail off the eastern coast of North America and in the English Channel. In the negative mode, the SSTs in these regions are of opposite signs. Furthermore, a relation to the Arctic sea ice distribution and continental river run-off could be detected (Wanner et al., 2001).

1.2 Reconstructing European climate

1.2.1 The data perspective

Although Europe is blessed with a wealth of long instrumental measurements, European climate prior to the late-19th century can mostly only be estimated from indirect sources. These indirect sources - commonly termed *proxies* - are either of written (documentary) origin or stem from natural sources. Documentary evidence might be considered the more precise and direct information on past climate since they either describe weather directly (e.g. personal weather diaries) or they describe processes directly related to climate (e.g. the freezing of harbors, rogation ceremonies or the flowering of trees). For an overview on documentary evidence, the reader is referred to Pfister (1999) or Brázdil et al. (2005) and references therein. By their physical, biological or chemical nature, trees, ice cores, corals, speleothems or lake sediments can record climate related phenomena. For example, the width or density of tree rings is known to depend on environmental conditions such as temperature or precipitation (e.g. Esper et al., 2002; Briffa et al., 2004). While documentary evidence can have a daily or even subdaily resolution, natural proxies are usually resolved at seasonal or longer timescale. Jones et al. (2009) give a recent overview on documentary as well as natural proxies and their relation to climate.

While there are many on-going projects to retrieve more records from documentary evidence, tree rings, speleothems, ice cores or varves from lake sediments, they all have the limitation that these proxies are only found on terrestrial ground. This might not be a substantial problem when reconstructing temperature or precipitation fields across e.g. continental Europe, but it is of relevance when assessing changes in and above the world's oceans. There exist various reconstructions of past North Atlantic SST and SLP fields prior to the widespread availability of instrumental measurements (e.g. Jones et al., 1999; Luterbacher et al., 2002b; Gray et al., 2004), but they are exclusively based on instrumental series or proxy information from terrestrial and therefore remote places. Accordingly, the SLP reconstructions usually show reduced reliability over the North Atlantic, particularly before the first instrumental pressure series from within the North Atlantic (Reykjavík; 1821) becomes available (Jones et al., 1999; Luterbacher et al., 2002b). This is relevant considering that the atmospheric centers of action driving weather and climate downstream are located over the North Atlantic (see section 1.1). However, over the last few years, marine climatic information from ship logbooks has become increasingly available (García-Herrera et al., 2005a; Worley et al., 2005; Wheeler et al., 2009). Particularly the CLIWOC (climate variability over the world's oceans) project (García-Herrera et al., 2005a) has significantly contributed to this marine database by exploring and digitizing numerous logbooks from primarily Spanish, British and Dutch sources (García-Herrera et al., 2005b; Können and Koek, 2005). CLIWOC contains information mainly back to 1750, thus extending the marine international comprehensive ocean-atmosphere data set (ICOADS, Worley et al. 2005) by a century. Besides a variety of non-climatic information (Wilkinson, 2005), this database also comprises instrumental measurements of SST, SLP and wind direction (García-Herrera et al., 2005b). Wind strength is only recorded indirectly through descriptions of the state of the sea or of the effects of wind on the sails (Koek and Können, 2005). This (descriptive) information could however be directly related to the numerical Beaufort scale (García-Herrera et al., 2005a). Therefore, the wind information contained within ship logbooks might only partly be considered instrumental but certainly not documentary in the sense of the data described earlier. Recently, Gallego et al. (2005), Jones and Salmon (2005) as well as Wheeler and Suarez-Dominguez (2006) showed that wind information from ship logbooks has great potential to assess more precisely past variations in the large-scale atmospheric circulation prior to the widespread availability of instrumental pressure series. Wind information from ship logbooks are used in this thesis to reconstruct large-scale SLP fields back to 1750 (see chapter 3).

1.2.2 Reconstruction methods

Using proxy sources, European climate can be reconstructed beyond the period of widespread availability of instrumental measurements. Composite plus scale (CPS) and climate field reconstructions (CFR) are the most commonly used reconstruction techniques. Both approaches relate the information contained within the proxy data to the instrumental target of interest (e.g. temperature or precipitation) during the overlapping period of usually the 20th century. Therefore, they both run under the assumption of linearity and stationarity in the relationship between proxy data and instrumental target. The validity of this premise is discussed later. While the aim of CPS is a reconstruction of a spatial mean, CFR assess past climate spatially explicit. In CPS, a time series representing e.g. the European mean temperature is obtained by calculating the (weighted) average of the available proxy series and subsequently scaling the average against the variance of the instrumental target in the overlapping period (e.g. Esper et al., 2002; Mann and Jones, 2003; Jones and Mann, 2004). These univariate time series therefore do not allow any spatial interpretations which, in contrast, is possible in CFR. Figure 1.3 schematically illustrates the CFR technique applied in this thesis to reconstruct SLP fields back to 1750 (see chapter 3). This is the same method used to obtain reconstructions of Alpine and European temperature (Luterbacher et al., 2004, 2007; Casty et al., 2005c; Xoplaki et al., 2005), precipitation (Casty et al., 2005c; Pauling et al., 2006) and SLP (Luterbacher et al., 2002b) fields.

In a first step, statistical regression models between the proxies and the instrumental target (e.g. gridded instrumental pressure field) are derived during the overlapping period of usually

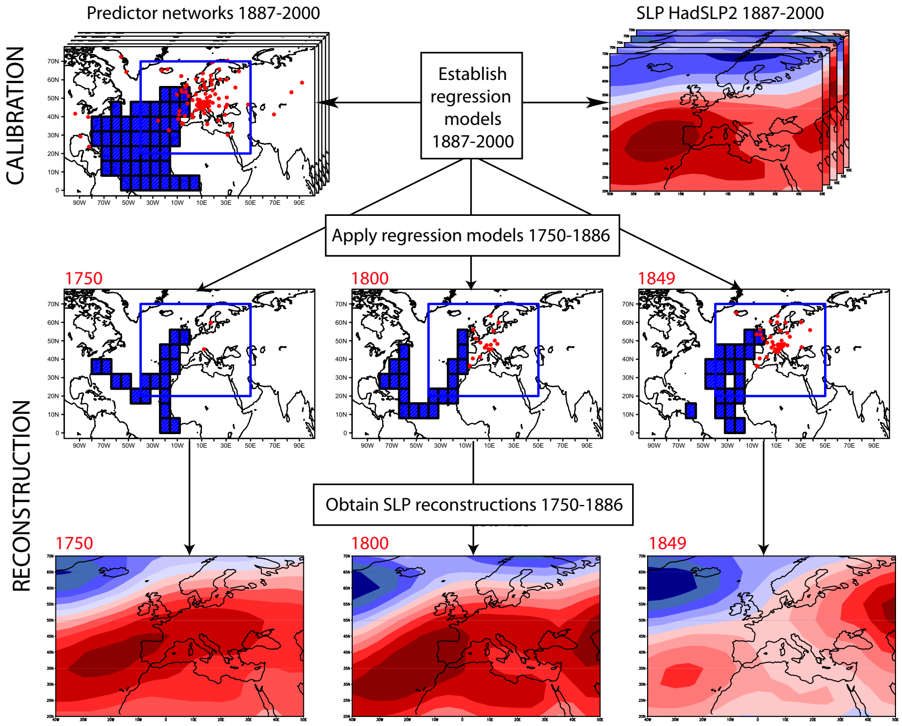

Figure 1.3: *Schematic illustration of the CFR technique used in this thesis to reconstruct SLP fields back to 1750. In a first step, regression models between the predictors and the predictand (gridded instrumental dataset, here HadSLP2 by Allan and Ansell 2006) are established during the overlapping period (here 1887-2000). Since the available predictor network changes over time, several regression models have to established. These transfer functions (here simplified illustrated for three different predictor networks) are then applied to the predictor data in the period 1750-1886 thereby obtaining reconstructed SLP fields back to 1750.*

the 20th century (=calibration; Figure 1.3). For each predictor network a separate regression model is calculated. Since this network changes over time (see Figure 1.3), several tens of such models have to be established. These regression models are thereafter applied to the proxy data in the pre-instrumental period, thereby obtaining gridded reconstructions of e.g. SLP back to 1750. In order to reduce dimensionality and separating signal from irrelevant noise but nevertheless retaining most of the variability contained in the data, principal components (PCs) of the instrumental as well as proxy data are calculated prior to the regression (Wilks, 2005). Usually, the retrieved PCs are truncated, i.e. only those containing important parts of the total variance are included in the subsequent regression (Luterbacher et al., 2002b; Wilks, 2005).

Very recently, regularized expectation maximization (RegEM) has been introduced as a new CFR technique. Based on the expectation maximization algorithm by Schneider (2001), this method iteratively models the relationship between available and missing data to estimate missing values. This approach has been used in various regional to hemispheric climate field reconstructions (Zhang et al., 2004; Mann et al., 2008; Riedwyl et al., 2008, 2009).

1.2.3 Independent climate field reconstructions: the LOTRED approach

Based on the knowledge that the four basic state variables SST, SLP, temperature and precipitation are strongly related (see section 1.1), Wanner and Luterbacher (2002) suggested to derive from instrumental and proxy data independent field reconstructions of these four variables. Independent means that the reconstructions do not share any common information, therefore allowing analyses of the dynamic processes behind past climate variations without the issue of circular reasoning (Wanner and Luterbacher, 2002). They termed this approach LOng Term REconstruction and Diagnostics (LOTRED). This technique should allow to extend dynamical analysis beyond the period covered by high-resolved gridded data sets which are exclusively based on instrumental measurements. To date, these instrumental-only datasets are globally and monthly resolved available on a 0.5° x 0.5° resolution back to 1901 for temperature and precipitation (CRU TS 3.0; P.D. Jones, *pers. comm.*), on a 2° x 2° resolution back to 1854 for SST (ERSST.v3; Smith et al., 2008) and on a 5° x 5° grid back to 1850 for SLP (HadSLP2; Allan and Ansell, 2006).

Europe with its wealth of long instrumental temperature, precipitation and pressure series as well as high-quality documentary and natural proxy data is an ideal place for the LOTRED approach. Using multivariate principal component regression (see CFR; section 1.2.2), Casty et al. (2005b) reconstructed fully independent fields of European temperature, precipitation and 500 hPa geopotential heights on a monthly resolution back to 1766 and detected recurrent climate regimes. Using the same fields, Casty et al. (2005a) assessed the temporal and spatial evolution of the three climatic variables and their leading combined patterns over the period 1766-2000. The SLP field reconstruction back to 1750 presented in this thesis (chapter 3) is completely independent from existing temperature and precipitation reconstructions, being in accordance with the concept of LOTRED.

1.2.4 Uncertainties

All reconstructions of past climate are only estimations of the true climate and therefore have important uncertainties and noise components. Their origin might either be from the data used, the method applied or the data network being available.

Data uncertainties

Considering the data, uncertainties are found in both, instrumental as well as proxy data. For instrumental data, errors might stem from changes in instrumentation, location or also non-climatic changes in the environment as urbanization. These sources of error are generally referred to as inhomogeneities which, however, can be significantly reduced by various homogeneity tests and correction algorithms (e.g. Ansell et al., 2006; Della-Marta and Wanner, 2006; Auer et al., 2007; Kuglitsch et al., 2009). A greater problem are the uncertainties in proxy data. For documentary evidence, noise components might stem from the subjectivity of the original author. Furthermore, due to the qualitative nature of the descriptions, the interpreting historian can only assign indexed values, i.e. estimate that a particular winter was cold, normal or warm (e.g. Pfister, 1999; Brázdil et al., 2005). Because of their very nature, natural proxies can record climate only indirectly, meaning that the climatic signal they contain is always contaminated by non-climatic noise. Furthermore, these noise components might not be stable over time, e.g. tree ring widths can also be affected by insect attacks (Esper et al., 2007). Again, the reader is referred to Jones et al. (2009) for an overview of the limitations of documentary and natural proxies.

Methodological uncertainties

The second source of important reconstruction uncertainties might be entitled as methodological. As shown earlier, statistical reconstructions run under various assumptions as e.g. the premise of stationarity in the climate-proxy relationship. As shown by Rutherford et al. (2003) this premise might not be valid if the forcings during the overlapping period and the reconstruction period differ strongly. However they also conclude that using the data-rich period of the 20th century to establish this relationship should not lead to an important bias. Several Bachelor theses conducted during this PhD thesis (see appendix A) showed for Europe that the proxy-climate relationship might indeed be assumed overall stable with, however, a few proxy series showing very large nonstationarities thus violating the premise.

Further sources of methodological uncertainties might arise from the reconstruction method itself. This issue has been raised by von Storch et al. (2004), McIntyre and McKitrick (2005) as well as Bürger et al. (2006) using the surrogate climate of coupled global atmosphere general circulation models (AOGCMs). Contrary to the real world, the climate at every grid point within an AOGCM is perfectly known at all times. Therefore, AOGCMs - assumed to be a reasonable realization of the real world climate system - are a valuable testing ground for reconstructions of past climate. Taking the climate simulated at a grid box as a representative for an instrumental or proxy series, the dependence of paleoclimatic reconstructions on the quality, temporal availability and spatial distribution of proxies can be assessed. Noise (usually white or red noise; e.g. Jones et al. 2009) is thereby added to the simulated climate variable to mimic the uncertainties in real-world proxies. These obtained time series are termed *pseudoproxies* (Mann and Rutherford, 2002). Investigating the dependence of the reconstruction on primarily the quality of the proxies and the applied reconstruction technique, various authors found a strong sensitivity to both of them (Rutherford et al., 2005; Ammann and Wahl, 2007; Mann et al., 2007; Wahl and Ammann, 2007; Riedwyl et al., 2009). A commonly accepted best reconstruction method has though yet to be found. The above cited studies also clearly showed that there is a strong dependence of the results on the AOGCM used, the geographical region considered, and the way the pseudoproxies are modeled. In this thesis the surrogate climate of two AOGCMs is used to assess the reliability of an existing 500-year long temperature reconstruction (chapter 2)

Network-related uncertainties

Additional uncertainties in climate reconstruction might arise from the predictor network. While the dependence on the quality of the proxies and the applied reconstruction technique has been extensively investigated (see above), hardly any studies have focused on the importance of the spatial distribution of the instrumental and proxy data. In order to capture all modes of variability across a geographical region, it is however essential to have a well-distributed predictor network. The studies by e.g. Kutzbach and Guetter (1980), Bradley (1996), Zwiers and Shen (1997) or von Storch et al. (2009) showed that attempts to reconstruct past climate should therefore also involve strategies to determine optimally located proxy sites. Working in this direction, Stössel (2008) used the currently available network of proxy information to determine the sites as well as proxy series which, when combined optimally, yield the best reconstruction of past European precipitation. Focusing on summer and winter season only, he found that the proxy location is of greater importance than the quality of the proxy series during winter, while the proxy quality is of greater relevance during summer. He suggested that this might be related to the more advective (convective) state of the atmosphere during winter (summer).

1.3 Synoptic climatology

It is well-known that variations in surface climate are strongly related to the large-scale atmospheric circulation (section 1.1; see also Walker and Bliss, 1932; Namias, 1948; Van Loon and Rogers, 1978; Trenberth, 1995). Research within this broad field might be summarized under the term *synoptic climatology.* Yarnal (1993) simply defines synoptic climatology as follows: "synoptic climatology relates the atmospheric circulation to the surface environment" (Yarnal, 1993, p.5). Based on the starting point, Yarnal (1993) distinguishes between "circulation-to environment" and "environment-to-circulation" type of studies. Only the former type is subsequently considered, i.e. it is investigated how surface climate has changed due to variations in the large-scale circulation. As illustrated in Figure 1.4, the field of synoptic climatology contains different areas, including traditional synoptic climatology and empirical as well as dynamical downscaling (e.g. Yarnal, 1993; Yarnal et al., 2001). Here, only the traditional synoptic climatology is introduced.

Following Yarnal et al. (2001), the traditional field of synoptic climatology may be separated into three areas (Figure 1.4): (1) manual classification, (2) correlation-based analyses and (3) clustering-based analyses. All techniques have in common that they attempt to identify a small number of representative patterns of the atmospheric circulation, to which all cases (e.g. monthly SLP fields) can be allocated. These dominating patterns should be synoptically meaningful and well-separated (e.g. Wanner, 1980).

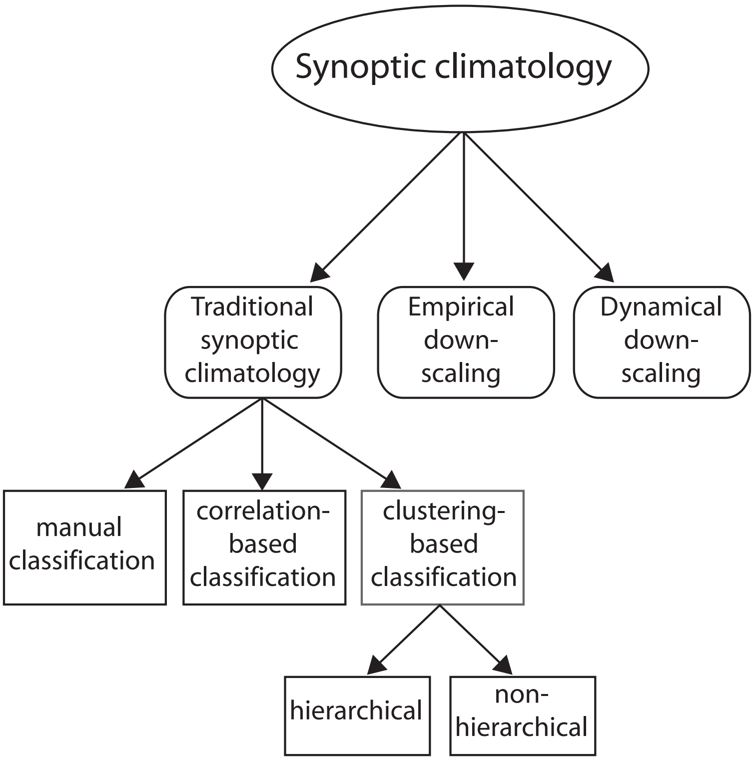

Figure 1.4: *Simplified overview of the research field of synoptic climatology. For details on the methods, the reader is referred to the text.*

Manual (or subjective) classifications are based on the expert knowledge of meteorologists and are therefore labour-intensive and and not easily replicable due to the subjective nature of the classification. Examples are the well-known catalog of Grosswetterlagen by Hess and Brezowsky (1952) or the Lamb weather types (Lamb, 1972). Correlation- and clustering-based techniques are computer-based and can be replicated if the (statistical) settings are kept. **Correlation-based** methods have been introduced by Lund (1963) and have been widely used in synoptic studies (e.g. Schmutz and Wanner, 1998; Brinkmann, 1999). As described in Huth (1996) or Philipp et al. (2007), classifications based on **cluster analysis** may be separated into hierarchical and non-hierarchical approaches. In *hierarchical* algorithms each case (e.g. daily SLP pattern) starts in its own cluster, with all cases in a nested approach being eventually assigned into a pre-determined number of final clusters. In a *non-hierarchical* approach, the cluster centroids (so-called seeds) must be chosen a priori with all cases in an iterative process subsequently being clustered around these centers. Huth (1996) tested various correlation- and clustering-based methods, concluding that all methods prove to yield meaningful classifications. He also stated that the best method to be used mainly depends on the aim of the classification. In this thesis, a non-hierarchical (Figure 1.4) clustering algorithm based on simulated annealing (Philipp et al., 2007) is used to classify winter SLP fields 1750-2000 (chapter 4). This particular method is introduced in chapter 4. Therein, it is also presented how the obtained SLP clusters are related to the independent reconstructions of temperature and precipitation.

Following the "environment-to-circulation" type of approach, i.e. changes in surface climate are related to the state of the atmosphere, variations in January-April (JFMA) European climate over the past centuries are related to the state of the atmosphere in chapter 5. The different methods applied in this approach are further illustrated there.

1.4 Framework of the PhD thesis: the PALVAREX 2 project

In 2001, the Swiss National Science Foundation (SNSF) established the National Centre of Competence in Research on Climate (NCCR Climate). NCCR Climate is a scientific network of thirteen Swiss institutions with the aim to increase our knowledge of the climate system by supporting interdisciplinary research on various aspects of past, current and future climate and its impact on society, ecology and economy (Wanner et al., 2006). NCCR Climate is currently in its second phase (2005-2009) and is organized in four work packages (WP): WP1 focuses on long-term climate variability and change, WP2 on climate predictability, forecasts and projections, WP3 on climate impacts on ecosystems and land cover, and WP4 on climate risks for economy and society (Wanner et al., 2006).

This thesis is embedded in the WP1 project PALeoclimate VARiability and EXtreme events 2 (PALVAREX 2), being the continuation of the successful PALVAREX project of the first NCCR Climate phase. The key objectives of PALVAREX 2 might be summarized as follows:

- to collect and compile spatio-temporally highly resolved paleoclimate proxy data from documentary evidence and natural archives covering the last 1000 years from the European continent and the adjacent North Atlantic Ocean.
- to reconstruct gridded climate fields for Europe using sophisticated statistical methods and multiproxy datasets.
- to understand how and why climate in the North Atlantic-European area varied over the past centuries.
- to address the statistical and dynamical behavior of extreme events, such as flooding, heat waves/summer dryness and cold spells.
- to find optimal proxy locations for the reconstruction of past European climate fields.

A key objective of NCCR Climate is to enhance collaborations within the University of Bern but also with other universities and institutions in Switzerland working on the various aspects of climate. PALVAREX 2 strongly depends on data from other projects of NCCR Climate, particularly tree ring data from the project EXTRACT (EXtended Thousand-year Reconstruction of Alpine Climate from Tree-rings), ice core- and lake sediment-based climatic series from VIVALDI (Variability in Ice, Vegetation And Lake Deposits - Integrated) and documentary information from CAPRICORN (Climate Anomalies and coPing stRategies of socIeties in Central eurOpe: the histoRical dimensioN). Furthermore, strong collaborations exist with the MONALISA project (MOdelling and reconstruction of the North Atlantic cLImate System vAriability) whose focus in on numerical simulations of past climate. Besides NCCR Climate, PALVAREX 2 is also well-connected with international partners.

1.5 Aims of the PhD thesis

Within the general objectives of PALVAREX 2, the main aims of this PhD thesis are:

1. To assess how well the past European temperature field can be reconstructed with the currently available network of instrumental and proxy data.
2. To reconstruct North Atlantic and European pressure fields using ship logbooks as a new and direct source on the large-scale atmospheric circulation.
3. To investigate how changes in past European temperature and precipitation are related to the state of the large-scale atmospheric circulation.

These three main aims contribute to several of the key objectives of PALVAREX 2 by (1) addressing the importance of the proxy location and the proxy quality, by (2) collecting and compiling new datasets on paleoclimate, by (3) reconstructing past pressure fields which are independent from existing temperature and precipitation reconstructions and finally by (4) assessing dynamically how and why European climate has changed over the past centuries.

1.6 Outline of the PhD thesis

This thesis is structured as follows: Chapter 1 gave a general introduction to the scientific background and framework of this thesis. In chapter 2 the winter temperature reconstruction by Luterbacher et al. (2004) is tested for its general reliability and its dependence on the proxy network using the temperature simulations of two AOGCMs as a surrogate climate. This gives a first impression on the importance of a spatially well-distributed proxy network. Combining terrestrial pressure series and marine wind information from ship logbooks, chapter 3 shows in a real world setting that an improved spatial network can significantly increase the skill of a SLP reconstruction. It is shown that particularly the position and strength of the Azores High can be reconstructed with more reliability. This is of great relevance for the stability of dynamical analyses. Since the SLP reconstruction obtained in chapter 3 is fully independent from existing European temperature and precipitation reconstructions, the changes in the relationship between the large-scale circulation and European winter climate can be assessed in chapter 4. Following the LOTRED approach (section 1.2.3), this analysis is done spatially explicit, i.e. not only the changes in the European mean temperature and precipitation can be related to the variations in the large-scale atmospheric circulation, but changes in the entire field. In chapter 5 the SLP reconstructions obtained in this thesis is used in various methodological approaches to investigate the dynamics behind changes in European January-April climate of the past centuries. The key results obtained in this PhD thesis are summarized and overall conclusions are drawn in chapter 6. Finally, an outlook on potential future fields of research within the wide field of past European climate dynamics is given in chapter 7.

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Chapter 2

Testing a European winter surface temperature reconstruction in a surrogate climate

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Abstract

We evaluate the skill of a European winter surface air temperature reconstruction over the last 500 years using pseudoproxies obtained from the ECHO-G and HadCM3 climate models. The emphasis is thereby on the effect of the reduction of available predictors back in time, an issue that has not yet been investigated in detail at continental and seasonal scale. It is found that the key factor in determining the reconstruction skill is the number of predictors and particularly their spatial distribution. However, considering the usually insufficient spatial and temporal predictor availability in paleo-reconstructions, the quality of the predictors becomes more important further back in time. Not surprisingly, the lowest reconstruction skill is found in the early period when the predictor network is reduced. Important differences between ECHO-G and HadCM3-based pseudoproxy reconstructions are discussed and implications for future analyses are presented.

2.1 Introduction

Reconstructions of past climate have recently been subject to investigative studies centering on their ability to appropriately reproduce low-frequency temperature variability (von Storch et al., 2004; Mann et al., 2005; Rutherford et al., 2005; Bürger et al., 2006; Wahl et al., 2006; Mann et al., 2007; Wahl and Ammann, 2007). These studies were performed using AOGCMs as a numerical laboratory in which reconstruction methods as well as their potential limitations can be tested and assessed by deriving proxy records from the model climate, so-called “pseudoproxies”. This approach thereby proved to be a valuable tool to determine the dependence of the reconstruction skill on the temporal availability and spatial distribution of predictors, their quality as well as the statistical model applied. This is a crucial contribution to identify and possibly quantify reconstruction uncertainties and thus to improve our knowledge of past climate variability.

This study tests the winter reconstruction of European land surface air temperature over the last 500 years by Luterbacher et al. (2004, hereinafter referred to as L04) using pseudoproxies (see Figure 2.1) obtained from the AOGCMs ECHO-G (von Storch et al., 2004) and HadCM3 (Tett et al., 2007). The L04 reconstruction appears particularly qualified since it allows testing the influence of various factors on the reconstruction skill: First, the regression method used by L04 is a nested approach, i.e. separate regression models were calculated for each different proxy network available over the 500 years. Around 100 models had to be calibrated/verified and reconstructed to obtain a European winter temperature reconstruction. This method thus allows the testing of the impact of a spatially and temporally reduced predictor network within a single predictor set. Previous studies also tested the influence of an increasingly sparse network by using different models, however each one with a constant number of predictors over the reconstruction period (Mann and Rutherford, 2002; Rutherford et al., 2003; Zorita et al., 2003, von Storch et al., 2004 supplementary online material; Mann et al., 2007). Secondly, the L04 reconstruction is suitable for testing the impact of the quality of the predictors on the reconstruction skill since it is based on a large number of instrumental data primarily after 1750 (Figure 2.1, bottom) and proxy information (temperature indices based on documentary evidence, ice core based temperature reconstructions, sea ice conditions, etc.) before. Finally, the L04 reconstruction covers European land areas at seasonal resolution, in contrast to previous pseudoproxy based studies which addressed annually resolved reconstructions on hemispheric or even global scale. It is therefore reasonable to perform a pseudoproxy based study on a smaller temporal (sub-annual) and spatial scale with a generally larger temperature amplitude. This serves as a test for scale dependencies that might possibly help explaining the loss of amplitude in low-frequency temperature variability in some regression-based reconstructions of past climate (von Storch et al., 2004; Bürger et al., 2006, also discussed in Mann et al., 2005, 2007; Wahl et al., 2006; Wahl and Ammann, 2007). The main focus of this study is on the effect of the reduction in the predictors' number back in time. Additional emphasis is put on the impact of a spatially less uniformly distributed predictor network in early centuries, following earlier studies (Bradley, 1996; Mann and Rutherford, 2002; Rutherford et al., 2003; Zorita et al., 2003; von Storch et al., 2004). Since the quality of the predictors also generally decreases backwards in time, the combined effect of a spatio-temporally reduced predictor network with additionally increased uncertainties in the predictors themselves can be highlighted. To determine the model-dependence of the results, this study is simultaneously performed with two AOGCMs (ECHO-G and HadCM3). By using the same code of the reconstruction algorithm (nested PCA-multiple regression) as L04 discussions about the proper methodological replication of the reconstruction can be excluded (von Storch et al., 2006; Wahl et al., 2006; Mann et al., 2007). It is important to state that this study solely tests the skill of the L04 reconstruction and does not discuss possible methodological limitations of the applied regression model as, e.g., in Bürger et al. (2006) and Mann et al. (2007).

2.2 Data and methods

The pseudoproxies were produced following the approach by e.g. Mann and Rutherford (2002) and von Storch et al. (2004). The pseudoproxy $P = T_g + \epsilon$ with T_g being the simulated surface air temperature at the grid box collocated to the L04 proxy network and ϵ being the added realization of white noise. To represent uncertainty in the proxy records and to test its influence, three uniform levels of white noise were added to T_g with the resulting pseudoproxies describing the locally simulated gridded temperature variability by 25, 50 and 75% (corresponding to correlation coefficients of 0.5, 0.7 and 0.87), respectively. Additionally, one pseudoproxy set was constructed where the noise in each individual series was scaled to values encountered in the real world proxies of L04 from the local correlation of each of the 166 proxies used (see Tables S1 and S2 in the supplementary online material of L04) with the gridded instrumental data set by New et al. (2000) in the overlapping period 1901-2000. This latter predictor set is designed to represent best the L04 proxy set in terms of their quality. Synthetic examples in the AOGCMs have revealed that the correlation coefficients obtained over the entire 500 year period do not significantly differ from those derived within the calibration period (not shown).

Figure 2.1 summarizes the data used in L04. The bottom panel identifies the contribution of instrumental records to the full predictor set. In order to clearly contrast the influence from the instrumental series on the reconstruction performance, we regard them here as "perfect", i.e. unperturbed samples directly from the model grid. In reality, this might be overly optimistic (see Brohan et al., 2006) despite the fact that they have been homogenized or at least quality checked (L04 supplementary online material). To determine the impact of the reduction in the number of available predictors back in time, a common feature in paleo-reconstructions, continuous pseudoproxy sets over the entire reconstruction period (1500-

1900) and sets with a reduction back in time (Figure 2.1, bottom) according to L04 were designed. The limited network prior to 1750 (Figure 2.1) cannot properly resolve some of the high-amplitude variations at the European periphery, in particular Scandinavia. Therefore, an artificially augmented proxy network is tested, where a single predictor over eastern Scandinavia is added during the pre-1750 period. The goal is to evaluate how strongly a single point can affect European average reconstruction skill. Because only the last 500 years of the ECHO-G run were used, the critical influence from the climate drift visible in the first few centuries of the 1000 year simulation has mostly vanished (Osborn et al., 2006). The HadCM3 simulation does not appear to suffer from such issues. Nevertheless, the two climate models used in this study differ considerably in their climate sensitivity, the forcings included and their historical changes and amplitudes. Most importantly, ECHO-G does not contain any representation of the anthropogenic tropospheric aerosol as well as land-use change forcing,

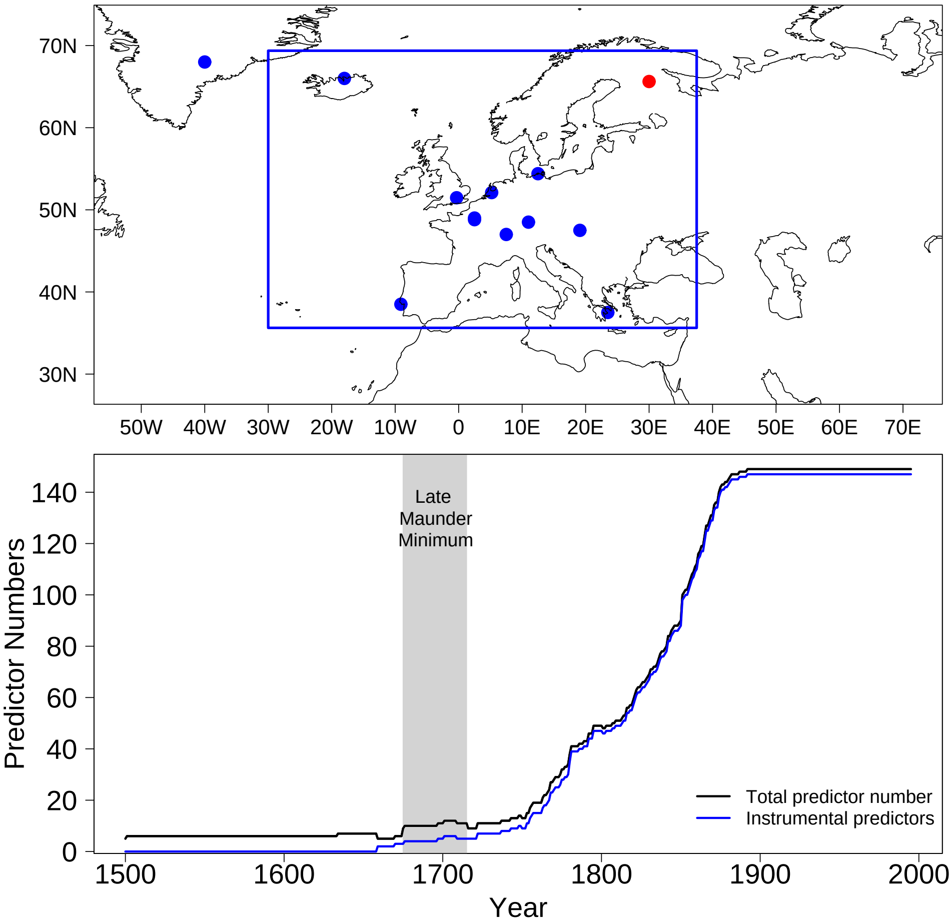

Figure 2.1: *Top: Locations of the proxies used by L04 during the Maunder Minimum (1645-1715, blue points) and of one additional pseudoproxy (red point) added in order to improve the spatial coverage. The blue frame covers the area of temperature reconstruction. Bottom: Total number of available predictors over time in the L04 reconstruction and number of instrumental predictors.*

both implemented in HadCM3. Along with influences from different climate sensitivities, this may causes the noticeably larger European temperature variability and the 20th century trend simulated by ECHO-G (Figure 2.2, upper panel). The significantly different temporal temperature evolution in the two models points to a large internal variability on the regional scale, as e.g. found by Wagner and Zorita (2005).

For the reconstruction, we used the same code as described in L04. It is a multivariate principal component regression designed to reconstruct climate fields (see Luterbacher et al., 2002, 2004 for a detailed description). Unlike some recent studies (von Storch et al., 2004, and partially Bürger et al., 2006) no detrending of the data was applied prior to the calibration. The reconstruction produced in this study represents the winter season (December-February average) covering the European land areas 30°W-37.5°E and 35.625°N-69.375°N with a 3.75° x 3.75° resolution, according to the climate models' resolution.

2.3 Results and discussion

Figure 2.2 presents the averaged European winter surface air temperature anomalies (with respect to the 1901-1995 average) over the last 500 years, smoothed with a 30-year gaussian low-pass filter. The upper panel is based on ECHO-G and the lower one on HadCM3. The black curve shows the simulated temperature while the colored lines are the pseudoproxy-based reconstructions with different qualities of the predictors. Here, all predictors are continuous throughout the entire reconstruction period and all of the 166 predictors were degraded, i.e. independent of the quality of the proxy used by L04 that they represent. For the degraded series the median of 100 Monte Carlo iterations is shown along with the 5% and 95% quantiles.

The reconstructions capture the shape of the simulated temperature history generally very well, largely independent of the noise level. This is in agreement with recent studies investigating hemispheric data (e.g. Mann et al., 2005, 2007; Rutherford et al., 2005; Wahl et al., 2006; Wahl and Ammann, 2007). The reconstructions based on perfect pseudoproxies apparently overestimate the cold spells throughout the pre-calibration period in both models. Tests revealed (not shown) that this might be related to an overfitting due to a large number of predictors relative to the number of predictands during the calibration period (caused by the coarse model resolution) as well as the length of the calibration period itself. This important issue should however be investigated in more detail.

Figure 2.3 shows reconstructions that more closely mimic the real world conditions of L04 with their quickly deteriorating number of predictors before 1750 (Figure 2.1, bottom). Additionally, it is important to note that only non-instrumental predictors were degraded, leading to a maximum impact prior to 1750 when the number of instrumental predictors decreases to zero before 1659 (Figure 2.1, bottom). The generally good visual skill of the pseudoproxy-based reconstructions during the calibration (1901-1960) and verification period (1961-1995)

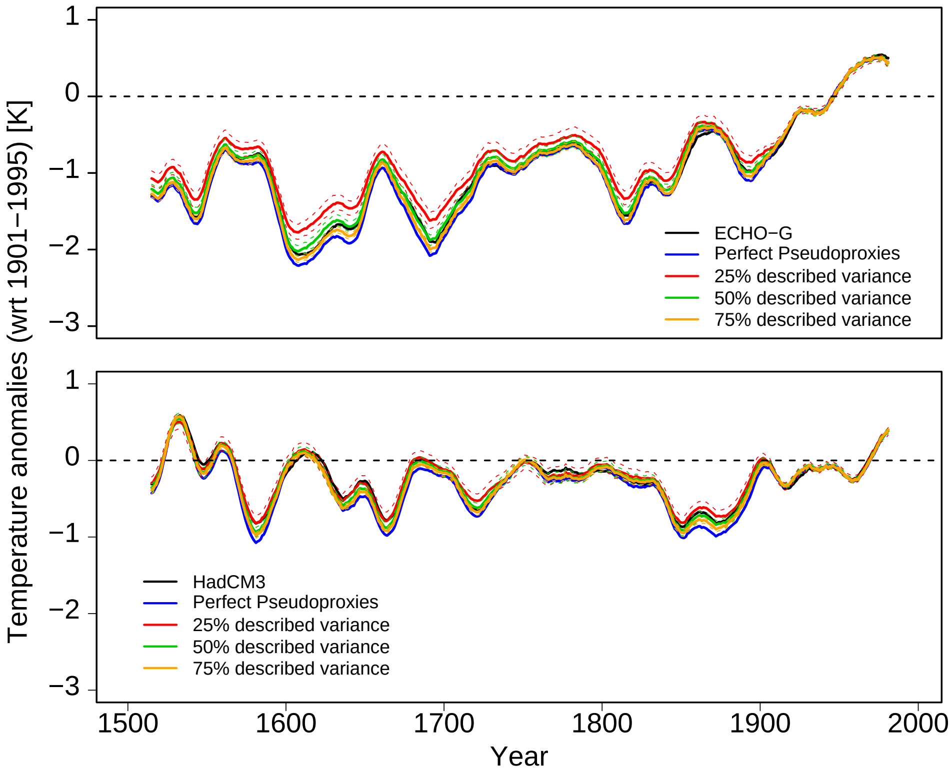

Figure 2.2: *Average European winter surface air temperature anomalies (wrt 1901-1995) over the last 500 years based on ECHO-G (von Storch et al., 2004; top) and HadCM3 (Tett et al., 2007; bottom), smoothed with a 30-year gaussian low-pass filter. The black line represents the simulated mean temperature while the differently colored lines are reconstructions based on pseudoproxies with different levels of described temperature variance. All predictors are continuous over the entire reconstruction period and all are degraded, independent from the proxy they represent. One hundred Monte Carlo realizations of noise were used to estimate the median and the 5% and 95% range (dashed lines).*

confirms that the L04 reconstruction is properly implemented in this study and has climatological meaning (Wahl and Ammann, 2007). Prior to the twentieth century the reconstructions present lower skill and show an increased underestimation towards earlier centuries. The underestimation is however strongly model-dependent. The ECHO-G shows a larger amplitude than the HadCM3 and also a stronger dependence on the noise level (Figure 2.3). Both models indicate significant loss in skill primarily prior to the late eighteenth century with the cold spells being significantly underestimated. Interestingly, ECHO-G indicates a significant underestimation of the cold Maunder Minimum (1645-1715, e.g. Luterbacher et al., 2001) largely insensitive to the quality of the predictors, while the preceding cold spell also shows an underestimation, however with a strong dependence on the noise level: the higher the signal-to-noise ratio the smaller is the underestimation. This difference in performance between Maunder Minimum and earlier, equally severe cold spells can be explained by the presence of "perfect" instrumental predictors during the Maunder Minimum and their absence before. These results suggest that under real world conditions L04 should be capable of capturing the true temperature variations over Europe after ∼1750 as the spatial coverage, the total number, and in particular the number of instrumental series increases. However, from our model based exercises one has to conclude that loss of amplitude and significant underestimation of cold periods might exist.

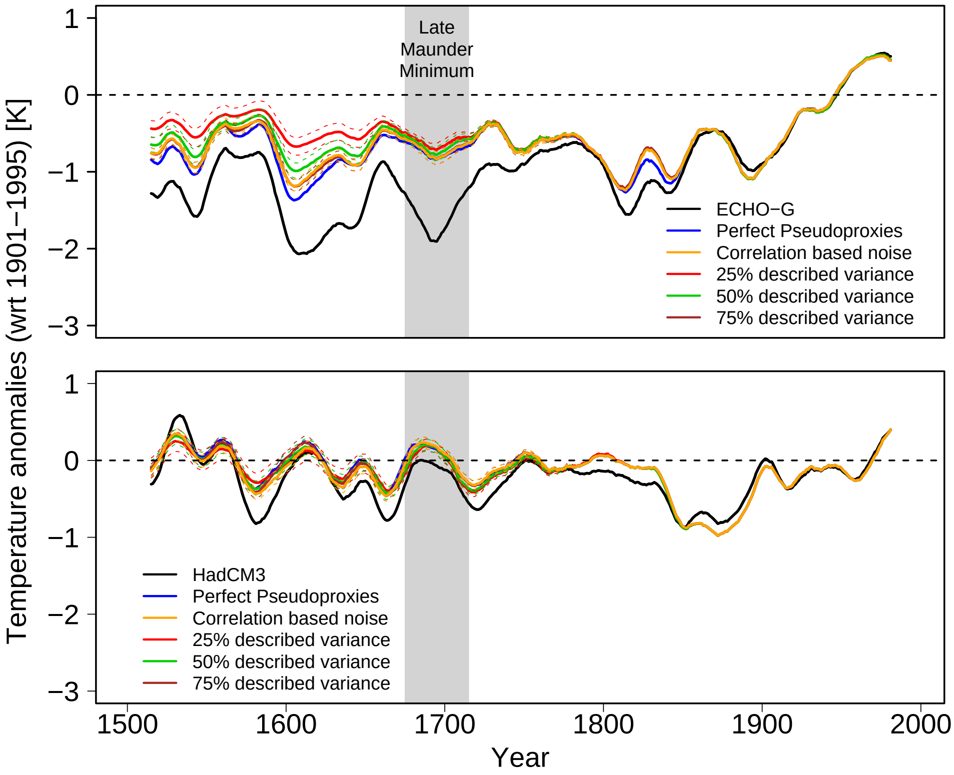

Figure 2.3: *Reconstructions based on predictors with the same availability over time as in L04 (Figure 2.1, bottom). Only non-instrumental predictors are degraded.*

The underestimation of the larger temperature anomalies in the early period shown in Figure 2.3 may partly be explained by a spatially insufficient predictor network. The spatial plots of the reconstructions produced in this study (not shown) have indicated that the underestimation of particularly the cold spells is largest over Scandinavia. This is not surprising since no proxy data are available in this region during the early centuries. As a test to evaluate the impact of an artificially improved spatial network, we have added one predictor in this region (Figure 2.1, red dot). For the results shown in Figure 2.4 this predictor is made available in the period 1500-1750. Its data were degraded with white noise to mimic documentary data (Pauling et al., 2003; Xoplaki et al., 2005). The red line in Figure 2.4 demonstrates the significant improvement of the reconstruction if the additional predictor is present over Scandinavia compared to the L04 network (blue line). While the improved spatial network leads to an almost perfect overlap of the reconstruction and the model mean in HadCM3 during some periods, ECHO-G still shows some general underestimations, however clearly smaller than with the original proxy network. Thus the addition of a single predictor leads in this case to a significant decrease in the reconstruction uncertainties.

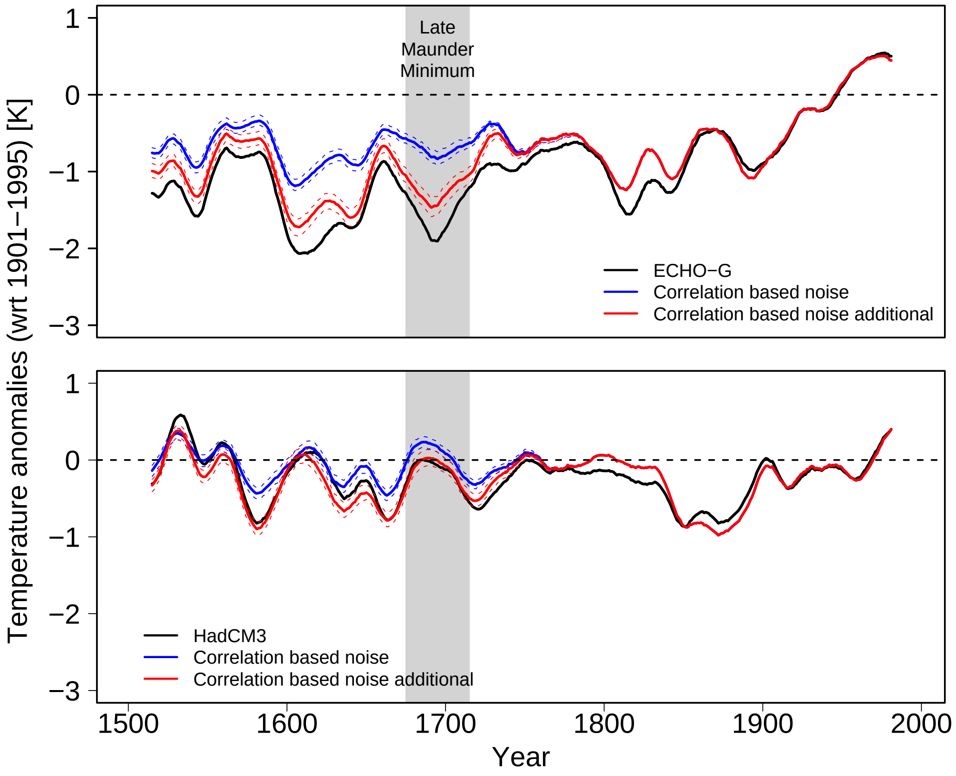

Figure 2.4: *As Figure 2.3 but showing only the reconstructions based on degraded pseudoproxies according to the correlation of the proxies used by L04 and the instrumental data by New et al. (2000) in the 20th century. The red line is based on the same predictor set as the blue line but with one additional predictor over the period 1500-1750 in Scandinavia (region with the largest uncertainties during the early centuries).*

2.4 Conclusions

The test of the European winter surface air temperature reconstruction of L04 in the surrogate climate of the two AOGCMs ECHO-G and HadCM3 has indicated that the real world reconstruction skill over Europe could be influenced by the quality of the predictors as well as their availability over time and space. The results appear to be partly dependent on the amplitudes of the simulated temperature variability, thereby emphasizing the need to perform such studies with more than one climate model.

The reconstruction performs well when a predictor set with a continuous availability over time and space is assumed. In this specific case, the quality of the predictors is of rather lower importance. This is in agreement with recent evidence at larger spatial scales (e.g. Mann et al., 2005, 2007; Wahl et al., 2006; Wahl and Ammann, 2007). In reality, paleo-reconstructions however have to deal with predictor networks that decrease significantly backwards in time. Our surrogate climate exercises point to a danger that this can lead to spatially insufficient coverage and non-reliable reconstructions. In this context significant underestimations of the true grid mean appear, with the influence from the quality of the predictors to become much more important. Artificially improving the spatial coverage by an additional predictor clearly improves the reconstruction skill.

The availability of predictors over time and mainly space has thus proven to be the key factor in determining the reconstruction skill. It is the factor significantly controlling the importance of the quality of the predictors. However as 'real world' paleo-reconstructions are over most periods based on spatially and temporally insufficient networks, the predictor quality is the key factor for improvements of reconstruction skill.

It is recommended that systematic pseudoproxy-based testing should become part of every reconstruction, being an important contribution to methodological improvements and understanding of causes of past climate variability in the 'real world'.

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Chapter 3

The importance of ship log data: reconstructing North Atlantic, European and Mediterranean sea level pressure fields back to 1750

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Abstract

Local to regional climate anomalies are to a large extent determined by the state of the atmospheric circulation. The knowledge of large-scale sea level pressure (SLP) variations in former times is therefore crucial when addressing past climate changes across Europe and the Mediterranean. However, currently available SLP reconstructions lack data from the ocean, particularly in the pre-1850 period. Here we present a new statistically-derived 5°x5° resolved gridded seasonal SLP dataset covering the eastern North Atlantic, Europe and the Mediterranean area [40°W-50°E; 20°N-70°N] back to 1750 using terrestrial instrumental pressure series and marine wind information from ship logbooks. For the period 1750-1850, the new SLP reconstruction provides a more accurate representation of the strength of the winter westerlies as well as the location and variability of the Azores High than currently available multiproxy pressure field reconstructions. These findings strongly support the potential of ship logbooks as an important source to determine past circulation variations especially for the pre-1850 period. This new dataset can be further used for dynamical studies relating large-scale atmospheric circulation to temperature and precipitation variability over the Mediterranean and Eurasia, for the comparison with outputs from GCMs as well as for detection and attribution studies.

3.1 Introduction

Climate variability at local to regional scales is to a large extent driven by advective and convective processes exerted by the atmospheric circulation (e.g. Namias, 1948; Trenberth, 1990, 1995; Xu, 1993; Hurrell, 1995; Jacobeit et al., 2001; Slonosky et al., 2001; Slonosky and Yiou, 2002; Xoplaki et al., 2004; Matti et al., 2009). These atmospheric processes are connected with quasi-stationary patterns of climate variability such as the North Atlantic Oscillation (NAO) related to typical temperature and precipitation patterns in Europe (e.g. Hurrell, 1995; Hurrell and Van Loon, 1997; Wanner et al., 2001). However, these modes explain only parts of the climate variability over a defined region because they are also affected by spatial and temporal non-stationary behaviour (e.g. Casty et al., 2005a; Raible et al., 2006). For example, the pronounced European cold period of the Late Maunder Minimum (LMM, 1675-1715) coincided with a strong and persistent negative NAO phase (e.g. Luterbacher et al., 1999, 2001; Raible et al., 2006) as well as recurrent blocking conditions over Europe (e.g. Luterbacher et al., 2001; Shindell et al., 2001; Xoplaki et al., 2001). More recently, the prolonged winter drought in the Mediterranean region since the early 1960s has been attributed to different circulation states and can only partly be explained by single teleconnection patterns (e.g. Dünkeloh and Jacobeit, 2003; Xoplaki et al., 2004; Paredes et al., 2006).

Gridded data sets of the atmospheric circulation over larger geographical areas provide more internally consistent and spatially coherent insights into climatic variability than (univariate) circulation indices (e.g. the NAO). Moreover, these spatial reconstructions can be compared with model-generated sea level pressure (SLP) fields of forced (external and internal) and natural variability over the last centuries. Additionally, large-scale gridded SLP fields are necessary to study both, low- and high-frequency variability of the atmospheric circulation (Jones et al., 1999; Luterbacher et al., 2002). Efforts to explore, digitize, and homogenize instrumental pressure records covering the last few centuries (e.g. Jones et al., 1999; Slonosky et al., 1999; Rodriguez et al., 2001; Barriendos et al., 2002, 2009; Bergström and Moberg, 2002; Maugeri et al., 2002a,b, 2004; Moberg et al., 2002; Allan and Ansell, 2006; Ansell et al., 2006) have recently culminated in two papers producing 5°x5° gridded SLP reanalyses of daily resolution for Europe (Ansell et al., 2006) and on a monthly basis for the entire globe (Allan and Ansell, 2006), going back to 1850 using both terrestrial and marine observations. Other gridded data sets of atmospheric circulation covering the North Atlantic, Europe and the Mediterranean are generally based on terrestrial pressure observations (e.g. Jones et al., 1999; Luterbacher et al., 2002; Casty et al., 2007). Only a small number of stations from islands in the North Atlantic have been included such as Ponta Delgada and Funchal, both starting in the mid-nineteenth century and Reykjavík, starting in 1821 (Jones et al., 1999). Although, and particularly for Europe, some very long terrestrial pressure series reaching back to the early eighteenth century have recently become available, indirect information from proxy data are mostly used to obtain gridded data sets of the large-scale atmospheric circulation further back in time (e.g. Gordon et al., 1985; Briffa et al., 1986, 1987; Villalba et al., 1997; Luterbacher et al., 2000, 2002). However, circulation variability can only be estimated indirectly from proxy data by parameters influenced by climate. For example, the commonly used documentary data either describe a weather phenomenon (e.g. the freezing of lakes), impacts of climate on societies (e.g. famines, rogation ceremonies) or the environment (e.g. historical harvest dates, phenological records; Brázdil et al., 2005, and references therein). Other proxy information stem from natural sources such as tree rings, whose growth is determined primarily by temperature and/or precipitation. Since the climate signal of interest (commonly temperature or precipitation) is therefore only recorded indirectly in the various proxies, and the available proxy networks rapidly reduce back in time, there are major noise and reduced variance problems, adding uncertainty to reconstructions of past climate (e.g. von Storch and Zorita, 2005; Ammann and Wahl, 2007; Küttel et al., 2007; Mann et al., 2007; Riedwyl et al., 2009; von Storch et al., 2009).

Currently available SLP reconstructions covering the last few centuries suffer from either, or both, of two major limitations: First, they represent the marine regions poorly, as they miss information from the open ocean, particularly in the pre-1850 period. Therefore, the ability to adequately represent the position and strength of the Azores High and the Icelandic Low and, by interference, to interpret their control over the weather and climate downstream is rather limited. Second, they usually share common predictors with temperature and precipitation reconstructions from the same areas. This leads to circular reasoning in dynamical studies relating past and current changes in temperature and precipitation to the state of the atmosphere (e.g. Casty et al., 2007). Thus, there is a necessity to construct longer gridded data sets combining (instrumental) data from the continent and the ocean to better understand the interannual-to-multidecadal circulation variability over the Northern Atlantic and Eurasia.

Recently, the CLIWOC project (e.g. García-Herrera et al., 2005a) made significant efforts to improve the available database over the ocean by exploring and digitizing a large number of ship logbooks from the colonial powers of Europe. This new marine database draws almost exclusively on non-instrumental observations and contains the wind direction as well as written descriptions of the wind force concentrated mostly along the trading routes of the European colonial powers. Apart from pressure series, wind information provides the most direct information of large-scale atmospheric circulation and is therefore superior to indirect information from other proxy data described above. Wind information derived from CLIWOC has demonstrated its potential to improve the reconstruction skill over the open sea, overcoming one of the major limitations of existing SLP reconstructions (e.g. Gallego et al., 2005; Jones and Salmon, 2005). In addition, CLIWOC wind data have not been used in any temperature or precipitation reconstructions, therefore also overcoming the issue of circular reasoning in dynamical studies.

For the first time this study uses terrestrial, instrumental pressure series and maritime wind information derived from ship logbook data to reconstruct 5°x5° resolved seasonal large-scale atmospheric circulation fields over the North Atlantic, European and Mediterranean region for the period 1750-2002. These two complementary predictor datasets provide the possibility of capturing more adequately than previously the SLP variability over the North Atlantic during the period before the instrumental pressure measurements in Iceland (Reykjavík, 1821) and Madeira (Funchal, 1850) became available. Furthermore, the independence of this new SLP reconstruction to European temperature (Luterbacher et al., 2004, 2007; Xoplaki et al., 2005) and precipitation (Pauling et al., 2006) reconstructions, allows the assessment of the driving atmospheric patterns behind recent and past European climate anomalies (Xoplaki et al., in prep.).

This study is structured as follows: Section 3.2 describes the data used with particular focus on its spatial and temporal availability. It also presents the data pre-processing and the applied reconstruction methodology. Section 3.3 highlights the importance of ship logbook data for the reconstruction of past SLP fields over the North Atlantic/European area by focusing on the SLP reconstructions obtained for three sample years with distinctively different climatic settings and data availabilities. Furthermore, the new SLP reconstruction data set is compared with an existing multiproxy dataset by Luterbacher et al. (2002) and single instrumental pressure series not included in the reconstruction. Finally, section 3.4 summarizes the major points and provides an outlook on the potential value of the data preserved within the many thousands of yet-to-be-digitised log and remark books.

3.2 Data and methods

Combined information from long terrestrial instrumental pressure series with wind direction and wind strength derived from ship logbook data were used to statistically reconstruct seasonal SLP fields covering the North Atlantic, Europe and the Mediterranean area back to 1750.

3.2.1 Data

Instrumental pressure series from continental Europe, Iceland, the Faroe Islands, the Azores, Madeira, Greenland and North America were used and averaged to seasonal mean values. These are basically those used by Jones et al. (1999) and Luterbacher et al. (2002) with a few additional records (see Table 3.1 in the appendix for a detailed overview). Terrestrial instrumental pressure series from the North Atlantic only become available from 1821 (Reykjavík, Iceland), 1850 (Funchal, Madeira), 1865 (Ponta Delgada, Azores), and 1867 (Tórshavn, Faroe Islands). All records have been quality-checked and homogenized if necessary, using the methodology described in Caussinus and Mestre (2004).

The keeping of logbooks was a duty of the ship officers from the early days of naval exploration and trading. Besides the importance of having a logbook to keep track of the sailing route, the crew, and food on board, the proper maintenance of logbooks was in some nations of financial importance. For example in the UK, only when handing in these logbooks to the Admiralty were the officers usually rewarded with their earnings (Wilkinson, 2005). It is therefore of no surprise that the libraries and archives of the former colonial powers of Europe are filled with numerous logbooks containing the records of the travels to the colonies in the Indies, the Americas and Africa (e.g. García-Herrera et al., 2005a). The exploration of logbooks as a socio- as well as climate-historical source has a long tradition (e.g. Wheeler, 1987; Woodruff et al., 1987; Chenoweth, 1996; Wilkinson, 2005; Worley et al., 2005; Wheeler and Suarez-Dominguez, 2006; Wheeler and García-Herrera, 2008; Wheeler et al., 2009). However, only the CLIWOC project (http://www.knmi.nl/cliwoc/) has successfully combined the efforts of European countries (UK, Spain, Netherlands) to obtain a climatological database for the world's oceans for the period 1750-1855 with some very sparse additional data from as early as 1662 (García-Herrera et al., 2005a).

The CLIWOC records used in this study, usually taken at local noon, contain besides a variety of other information (see García-Herrera et al., 2005b and Wilkinson, 2005 for more details) the date and the ship's geographical position. The longitudes, in those days usually determined by dead-reckoning, were corrected by CLIWOC to present-day coordinates, i.e. to deviations from the Greenwich meridian (Können and Koek, 2005). Furthermore, and of most interest for climatological studies, the logbooks also contain information on the wind direction (usually measured on a 16- or 32-point compass; Wheeler 2005) as well as descriptions of the effects of wind speed on either the sails (primarily Dutch records; Koek and Können, 2005) or the sea. The descriptive wind speed terms of 99% of all records could be matched with the descriptions of the numerical Beaufort scale, which was formally adopted in the UK only in 1836 (García-Herrera et al., 2005a; Koek and Können, 2005; Prieto et al., 2005; Wheeler and Wilkinson, 2005). Therefore, the CLIWOC dataset includes numerical values for the wind direction as well as for wind speed. For more details on the data pre-processing performed within CLIWOC we refer to García-Herrera et al. (2005a) and references therein. Wheeler (2005) investigated the quality of these wind data by comparing records from vessels sailing in convoys and found them to be very reliable.

The current version 2.1 of the CLIWOC dataset contains a total of 281,920 records with a particularly high coverage in the North and South Atlantic and along the trading routes to the West Indies. The database covers the years 1662-1855 with 1750-1855 representing 99.6% of all available data. Therefore, only the latter period was considered here. Furthermore, we focused solely on the wider North Atlantic area [100°W-50°E and 0°-90°N] where the highest data density is found, since all routes to the colonies passed through this region (Fig. 3.1, left panel). A total of 161,726 records are available for this area covering the period 1750-1855. Only records providing complete information on date, location, wind direction, and wind speed were used, reducing the total to 119,118 records. Similar to Gallego et al. (2005) and Jones and Salmon (2005) the data were aggregated and averaged over seasonally resolved 8°x8° grid boxes in order to ensure a high enough data density containing meaningful wind information (see Fig. 3.1, left panel).

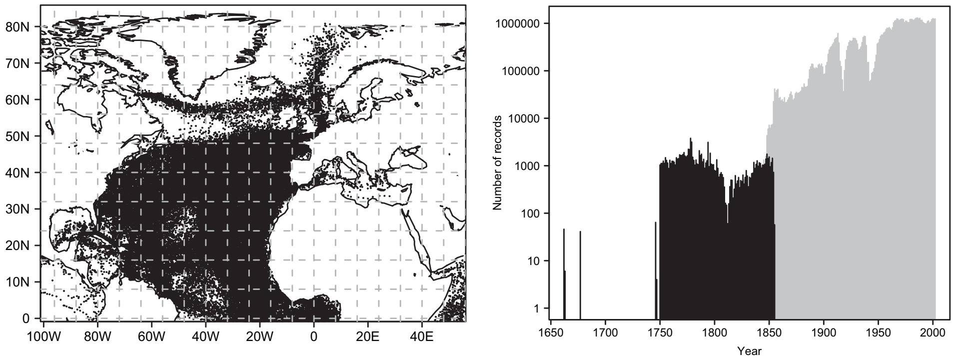

Figure 3.1: *Left: Location of CLIWOC records (black dots) for the period 1750-1855. The grey dashed grid indicates the 8° x 8° grid boxes over which the CLIWOC data were averaged. Right: Annual number of records from CLIWOC (black columns) and ICOADS (grey columns) 1662-2002 over the North Atlantic [100° W-50° E and 0°-90° N]. Note the logarithmic scale of the number of records.*

CLIWOC data are only available until 1855. To establish regression models with the gridded instrumental SLP fields by Allan and Ansell (2006), wind information up to the year 2002 is necessary (see section 3.2.3 for methodical details). For this purpose, the marine wind information from the ICOADS database version 2.4 (Worley et al., 2005) that spans the period 1784-2007, was used. As shown in Figure 3.1 (right panel), ICOADS contains a larger number of records over the greater North Atlantic area only after 1850, then however significantly by a factor of up to more than 100 (note the logarithmic scale). Therefore, CLIWOC (1750-1849) and ICOADS (1850-2002), were aggregated and averaged over 8°x8° grid boxes and transformed into the u and v vector components of the wind. These were then combined with the instrumental pressure series and used as predictor data (independent variable).

3.2.2 Data pre-processing

Using the spatially sparsely and temporally highly variable distributed wind information from CLIWOC and combining these data with the more widely available ICOADS dataset yields some methodical challenges which are addressed next.

Figure 3.1 (right panel) depicts the large inter-annual variability in the number of CLIWOC records with a minimum availability in the early nineteenth century during the Napoleonic Wars. Additionally, the number of records aggregated over 8°x8° grid boxes is spatially variable with few records north of 60°N but many records in the English Channel and along the Northwestern African and the Iberian coasts (see also Fig. 3.9 in the appendix). This means that the true wind conditions may be assumed to be well captured by the available records at a specific grid box during a particular year, while the noise component due to undersampling might be important at other locations and times. In order to address this issue, we included of each 8°x8° grid box and season only the years where at least three records were available. This somewhat subjective criterion is a compromise between including as many grid boxes as possible and increasing the signal-to-noise ratio of the wind information as much as possible. Other thresholds were also tested, however this did not improve the final results in terms of resolved variance in the reconstruction (not shown). As can be seen in Figure 3.10 in the appendix, the true temporal evolution - but not the variability - of the wind vectors can be well captured by as few as three records.

Combining CLIWOC and ICOADS data yielded another methodical challenge. As shown in Figure 3.1 (right panel), there are many more records available over the North Atlantic during the ICOADS period (1850-2002) than during the CLIWOC period (1750-1849). Therefore, the noise component at an 8°x8° grid box might be assumed to be lower during the ICOADS than the CLIWOC period, i.e. the time series of wind direction and wind speed at a particular 8°x8° grid box would probably have the same expectation value but not the same standard deviation at all time steps over the period 1750-2002, violating the stationarity assumption (e.g. Wilks, 2005). In the reconstruction methodology used in this study (multivariate principal component regression, see section 3.2.3), stationarity of the data is however required, since the regression models were derived during the 1887-2002 ICOADS period (when all instrumental pressure series are available, see section 3.2.3), and thereafter applied to the CLIWOC/ICOADS data in the 1750-1886 period. Failure to address this problem would firstly lead to a reconstruction with an increased variability during the period 1750-1886 (since the applied transfer functions are based on data with a lower variability than the pre-instrumental data on which the functions are applied to), and secondly to inflated skill values (in this case Reduction of Error; Cook et al., 1994), since they are determined within the 1887-2002 calibration period using the ICOADS data of much better coverage than CLIWOC (see section 3.2.3 for methodical details). To overcome this problem, we degraded the ICOADS data by randomly sampling the full ICOADS dataset available for each 8°x8° grid box according to the average number of records making up the seasonal mean of a particular grid box during the CLIWOC period (see Fig. 3.9 in the appendix for details). To reduce the dependence on the sampling itself, and thus preventing adding further noise to the reconstruction, the median of five sampling iterations was calculated (see Fig. 3.10 in the appendix).

Figure 3.2 presents the combined seasonal predictor network along with the ratio of the number of CLIWOC/ICOADS grid boxes and instrumental pressure series available over time. Prior to 1800, the majority of predictors stems from logbooks, while the number of instrumental series rapidly increases afterwards.

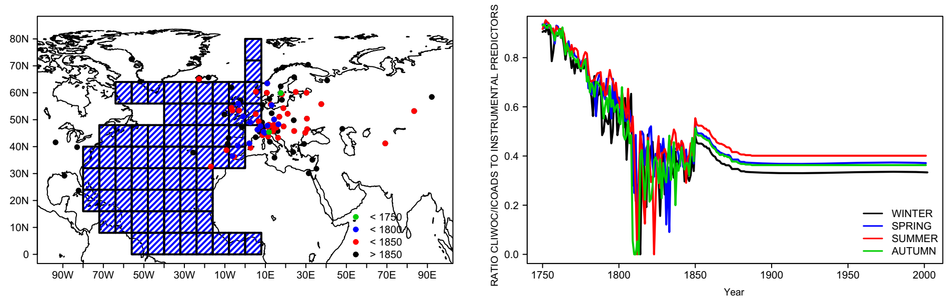

Figure 3.2: *Left: Complete predictor network used to reconstruct seasonal North Atlantic, European and Mediterranean SLP fields 1750-2002. The blue shaded grid boxes are the 8°x8° aggregated and averaged wind information derived from ship logbooks while the dots represent the terrestrial instrumental pressure series with the colours giving the starting years of the series. Right: Ratio of the seasonal number of CLIWOC/ICOADS grid boxes and instrumental predictors, 1750-2002.*

3.2.3 Reconstruction methodology

Multivariate principal component regression was used to reconstruct 5°x5° resolved seasonal mean SLP fields for the North Atlantic, European and Mediterranean area back to 1750. The same approach was used in various recent atmospheric circulation field reconstructions (e.g. Jones et al., 1999; Luterbacher et al., 2002; Gallego et al., 2005; Casty et al., 2007). For a detailed description of the reconstruction methodology we refer to Luterbacher et al. (2002). As predictand the seasonally averaged, 5°x5° gridded instrumental sea level pressure dataset HadSLP2 by Allan and Ansell (2006) was used, covering the period 1850-2004. To separate the dominant spatial patterns of variability from unnecessary details and noise, EOFs (empirical orthogonal functions) of the predictors as well as the predictands were calculated. We tested different levels of EOF truncations, finally considering the n EOFs accounting for 75% (90%) of the total variance of the predictor (predictand) data, yielding in terms of reconstructed mean, standard deviation and skill scores the best results (not shown). Compared to other SLP reconstructions (e.g. Luterbacher et al., 2002), the truncation level of 75% for the predictor data is rather low. However, the truncation level is known to depend strongly on the nature of the input data (e.g. Livezey and Smith, 1999; von Storch et al., 1999; Schmutz et al., 2001). We suggest that the truncation level is in our case strongly influenced by the noise component in the ship logbook based 8°x8° grid boxes (due to the partly low number of available records), as well as by the large number of predictors (see section 3.2.2). The calibration with the predictor data (ship logbook and instrumental records) was performed over the period 1887-2002 where all instrumental series are available. The performance of the statistical reconstruction was determined by calculating the commonly used Reduction of Error (RE) skill scores (Cook et al., 1994) using two-thirds (1887-1964) of the overlapping period 1887-2002 for calibration and the remaining one-third of the data (1965-2002) for verification. RE ranges from -∞ to +1, with 1 indicating that the reconstruction agrees perfectly with the independent SLP field of the predictand during the verification period. A value of 0 means that the reconstruction is as good as climatology, while negative RE scores denote that the reconstruction contains no meaningful information. Figure 3.3 gives an overview of the data pre-processing and reconstruction methodology applied in this study.

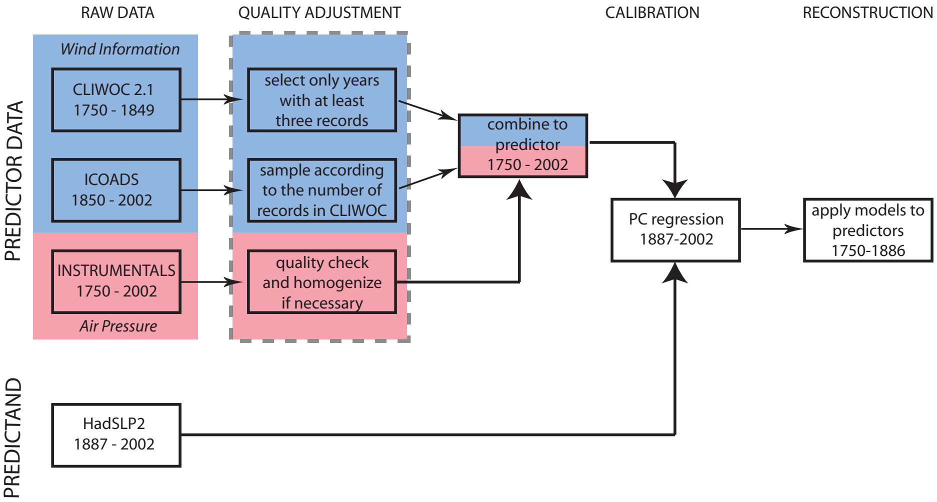

Figure 3.3: *Scheme for the data pre-processing and reconstruction methodology applied to reconstruct seasonal North Atlantic, European and Mediterranean SLP fields back to 1750. The predictor data (wind information derived from logbooks, blue and instrumental pressure series, red) were pre-processed to assure reliable reconstructions. For details on the pre-processing refer to the text. The predictor and predictand (HadSLP2; Allan and Ansell, 2006) were related to each other during the calibration period 1887-2002 using ordinary least square regression of the leading EOFs, with the derived transfer functions later applied to the predictor data in the period 1750-1886.*

3.3 Results and discussion

The overall quality of the reconstructions is first assessed by RE skill measurements. The SLP reconstructions for three selected winters are then presented and discussed. In order to detect whether the reconstructions capture the variability of the major centres of atmospheric circulation, the reconstructed time series of SLP near the Azores as well as Iceland along with the RE skill scores are shown. Finally, this reconstruction is compared to the one by Luterbacher et al. (2002) and independent pressure series.

Overall model performance

Figure 3.4 presents the performance of the seasonal reconstructions expressed as RE scores averaged over three sub-regions (northeastern and southeastern North Atlantic and continental Europe) as well as over the entire grid [40°W-50°E; 20°N-70°N] covering the full 1750-2002 period. The RE values generally increase from 1750 onwards except for the early nineteenth century which can be accounted for the low quantity of CLIWOC data abstracted from logbooks from the time of the Napoleonic Wars.

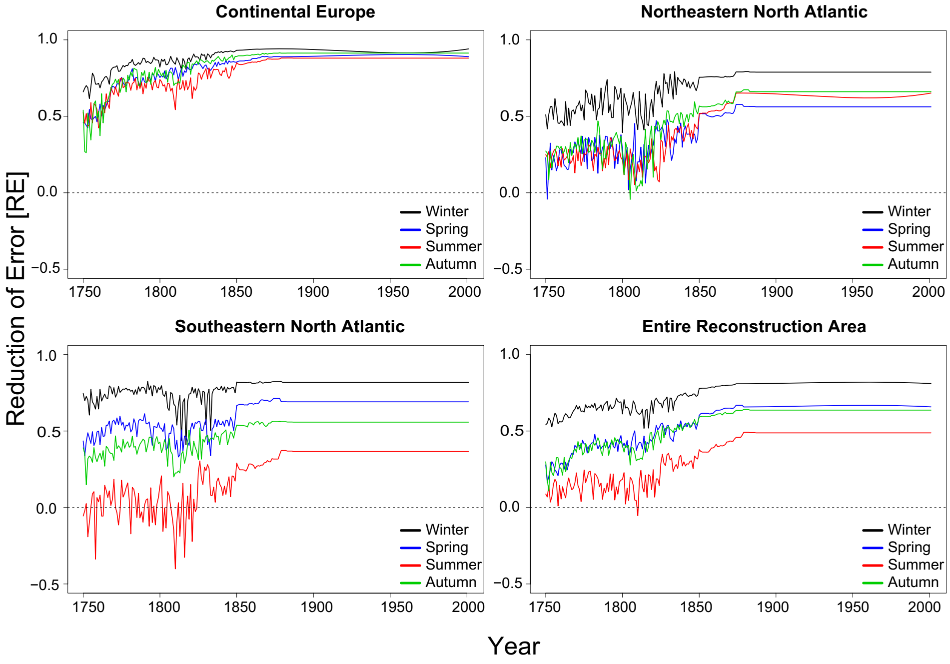

Figure 3.4: *Seasonal evolution of RE skill scores 1750-2002 averaged over continental Europe [10° W-25° E; 40° N-60° N; top left panel], the marine region of the northeastern North Atlantic [40° W-0°; 50° N-70° N; top right panel], the marine region of the southeastern North Atlantic [40° W-0°; 20° N-45° N; bottom left panel], and for the entire reconstruction area [40° W-50° E; 20° N-70° N; bottom right panel]. Positive values indicate higher skill than climatology.*

Over continental Europe and all seasons very good reconstruction skill is found. For the other regions, large interseasonal differences are prevalent. Winter (DJF) SLP is generally well captured while summer (JJA) SLP, particularly over the southeastern North Atlantic shows low skill with some negative RE values. Summer is generally the least well reconstructed season of the year (see also Jones et al., 1999; Luterbacher et al., 2002; Gallego et al., 2005). The poor spatial performance during summer could be attributed to the large-scale synoptic situation, which is characterized by a generally dispersed circulation pattern and small pressure gradients that cannot be explained by the marine wind information available from the CLIWOC/ICOADS data. In fact, the summer SLP reconstructions over the southeasternmost North Atlantic are slightly better when only terrestrial instrumental pressure series were used as predictors (not shown). For the other seasons and regions, the skill is always higher when CLIWOC data are included. The transition seasons autumn (SON) and spring (MAM) show intermediate skill, with RE skill scores well above 0 (i.e. better than climatology) for all regions. As shown in Figure 3.4, the overall highest skill is found during winter. This is mainly due to the well organized atmospheric circulation during this season, allowing a good representation of the SLP field over the reconstruction area even with a spatially and temporally limited predictor network. We subsequently focus only on winter.

Case studies: the winters 1750, 1830, and 1843

To comprehensively present the spatial performance of our reconstruction during distinctively different climatic settings and predictor networks, we focus in this subsection on the winters of 1750 (two instrumental pressure series and a good distribution of CLIWOC wind information available), 1830 (28 instrumental time series and hardly any CLIWOC data) and 1843 (a spatially well distributed predictor network from both sources).

Figure 3.5 (top row) shows the SLP reconstruction for winter 1750. Most information on the large-scale atmospheric circulation stem from CLIWOC (blue shaded boxes in Fig. 3.5, top left panel), while instrumental pressure measurements (red dots) are only available from Padua (Italy; Maugeri et al., 2004) and Uppsala (Sweden; Bergström and Moberg, 2002). The large-scale atmospheric circulation during this particular winter (Fig. 3.5, top middle panel) was characterised by large-scale high pressure stretching from the eastern North Atlantic over Europe towards western Russia and low pressure over southeastern Greenland and Iceland. During this winter above normal precipitation were found over the Scandinavian west coast and dry conditions over large parts of Europe (Pauling et al., 2006). The strong southwesterly flow was also responsible for above normal winter temperatures over Europe with strongest departures over Scandinavia (Luterbacher et al., 2007). The spatial RE map (Fig. 3.5, top right panel) for the winter of 1750 shows maximum values over areas where predictor data are available. Lower skill (though still positive RE values) is found over Eastern Europe and the periphery of the grid, away from the predictor information.

A different distribution and number of instrumental pressure time series and ship logbook information is available for the winter of 1830 (Fig. 3.5, middle row). The reconstruction for this winter mostly relies on instrumental pressure time series but hardly any information from CLIWOC (Fig. 3.5, middle left panel). It shows a strong Western Russian high (Fig. 3.5, centre). This strong blocking was also found by Luterbacher et al. (2002). On the southern flank of this continental anticyclone, cold air advection led to a widespread European cooling (Luterbacher et al., 2007). This winter is well known as one of the coldest European winters since 1500 (Luterbacher et al., 2004, 2007) and was likely the coldest alpine winter since 1500 (Casty et al., 2005b). Except for the northern part of the Mediterranean this winter was very dry (Pauling et al., 2006). The lack of information from the North Atlantic is reflected in the reduced skill values (Fig. 3.5, middle right) with RE values in the range of 0.2 to 0.6. The correct representation of the position and strength of the Azores High and Icelandic Low is therefore limited. The skill over the continent is generally very good.

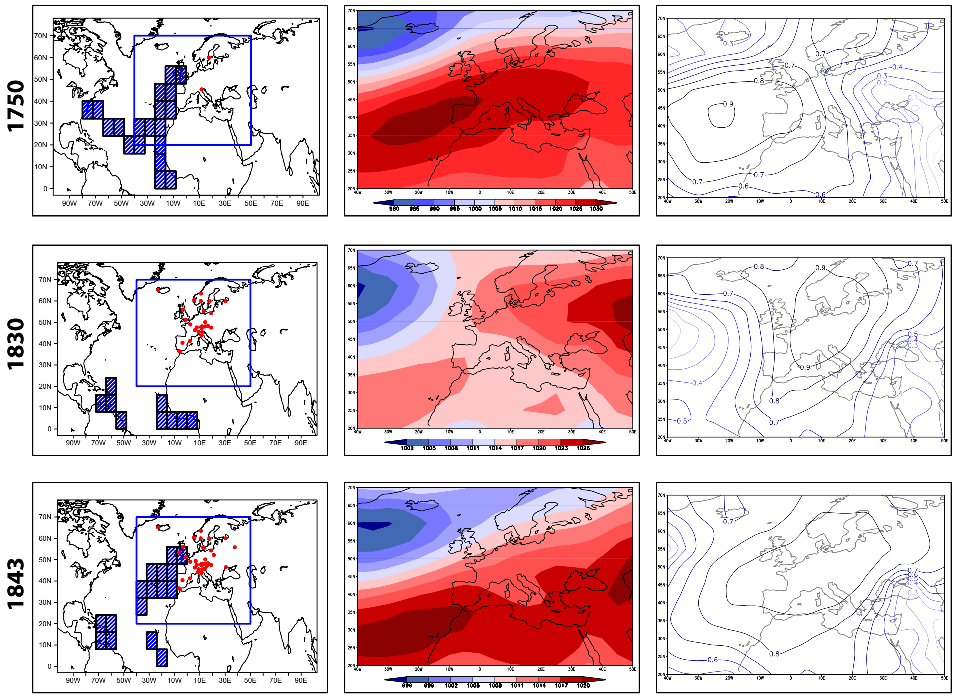

Figure 3.5: *Left: Predictor network (blue shaded boxes denote CLIWOC wind information, red dots refer to instrumental pressure series, blue frame: reconstruction area); middle: reconstructed SLP field; right: reconstruction skill expressed as RE values calculated during the verification period 1965-2002 for winter 1750 (top row), 1830 (middle row), and 1843 (bottom row).*

As an example of a spatially well-distributed predictor network over the sea and the continent, Figure 3.5 (bottom row) shows the SLP reconstruction and the spatial performance for the winter of 1843. A strong gradient between the Azores High and the Icelandic Low is found bringing warm and humid southwesterly winds towards Europe. Indeed the winter of 1843 was among the warmest European winters in the period 1500-1900 (Luterbacher et al., 2004, 2007). Interestingly, this winter was one of the coldest in the Midwest and Northeast US with a strong and persistent blocking situation (Ludlum, 1968; Rosendal, 1970). The spatially well distributed predictor network is clearly reflected in the RE values (Fig. 3.5, bottom right) with values well above 0.7 over almost the entire reconstruction area. Lower values, though still positive, are found over the southeastern part. This example, particularly in comparison with the winter of 1830 (Fig. 3.5, middle row), where few marine data are available, strongly underlines the complementary nature of the marine (quasi-instrumental) CLIWOC/ICOADS and terrestrial (instrumental) information for past large-scale atmospheric circulation.

The reconstruction skill over the Azores and Iceland

A key objective of this study is to improve the reconstruction skill over the eastern North Atlantic, thereby providing more reliable representations of the Azores High and the Icelandic

Low. Figure 3.5 indicated that the use of CLIWOC information does indeed improve the reconstruction skill over the entire North Atlantic. To emphasise this improvement, Figure 3.6 presents the time series of the reconstructed SLP (using instrumental pressure series only and additionally with CLIWOC data), each averaged over four 5°x5° grid boxes located south of Iceland and over the Azores, along with the associated skill scores.

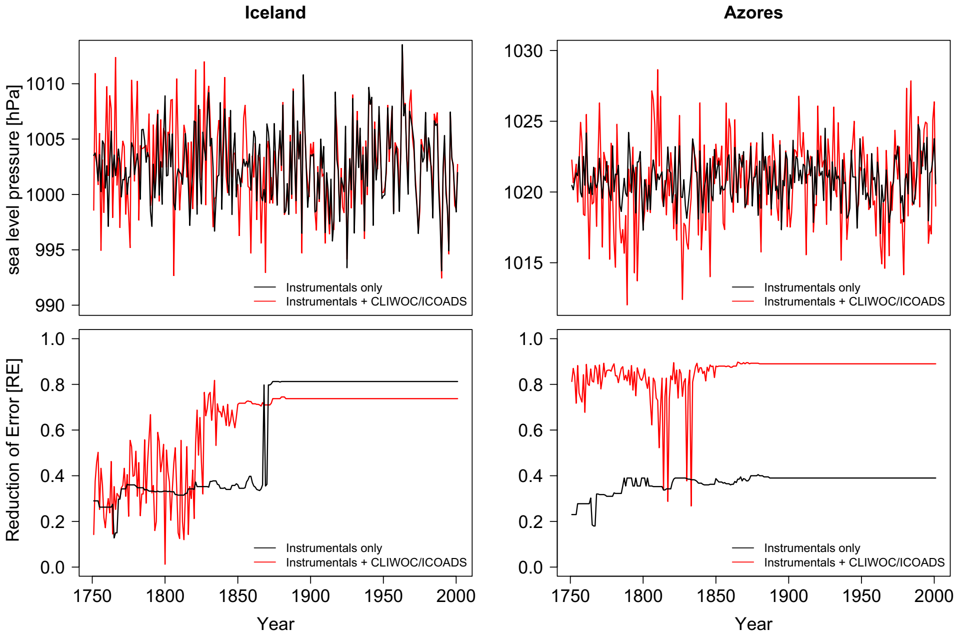

Figure 3.6: *Reconstructed winter SLP (top) and corresponding RE scores (bottom) each averaged over four grid boxes located south of Iceland (left, grid boxes centred at 17.5° W; 62.5° N) and the Azores (right, grid boxes centred at 27.5° W; 37.5° N) 1750-2002. The black line is the reconstruction based on instrumental pressure records only, the red line additionally includes ship log data.*

Figure 3.6 (upper panels) clearly demonstrates the reduced SLP variability prior to 1850 over Iceland and the Azores when only instrumental pressure series from the continent (black lines) are considered. For Iceland, the variability of the pre-1850 period is statistically significant different (p <0.01) from that of the post-1850 period as well as from the variability of the respective grid box of the HadSLP2 dataset (Allan and Ansell, 2006) used as predictand. We therefore assume that the real (but unknown) SLP variability during this period is underestimated. However, when CLIWOC based wind information are combined with instrumental pressure series (red lines), the SLP variability during the early decades resembles much more the recent decades. These findings are supported by the RE skill scores for these two regions (Fig. 3.6, bottom panels), where a significant increase in reconstruction skill, particularly for the pre-1850 period, is found in the case CLIWOC data are included. The generally lower RE values over Iceland compared to those over the Azores during the first few decades might be attributed to the general lack of currently available wind information derived from logbooks in northern latitudes but also to the stronger variations of SLP in the north. Since instrumental pressure series from Iceland are currently only available from 1821 onwards (Reykjavík), most information on the large-scale atmospheric circulation for this region stems (via teleconnections) from predictors located in remote places.

Verification: comparison with Luterbacher et al. (2002) and independent instrumental pressure series

To evaluate our SLP reconstruction, Figure 3.7 shows the correlation between this study and the SLP reconstruction by Luterbacher et al. (2002) at each 5°x5° grid box over the winters of the period 1750-1850 for the common reconstruction area [30°W-40°E; 30°N-70°N]. Additionally, the average reconstruction RE skill values over the 101 year period are presented. In the reddish (bluish) fields the RE values of this study are higher than (equal to) Luterbacher et al. (2002). White boxes indicate lower skill compared to Luterbacher et al. (2002).

Although Luterbacher et al. (2002) used the same statistical reconstruction method as this study, there are some differences that have to be mentioned: Luterbacher et al. (2002) used a different predictand (Trenberth and Paolino, 1980, updated), and fitted their regression models on monthly means instead of seasonal means as is done in this study. Further they chose 1901-1960 as calibration and 1961-1990 as verification period using the leading EOFs explaining 95% (90%) of the total variance of the predictor (predictand). Finally, Luterbacher et al. (2002) and this study are not completely independent since they share some common information from terrestrial pressure series. It might therefore not be surprising that the two reconstructions share some common signals with correlation values being mostly above 0.5, i.e. being statistically highly significant ($p < 0.01$). Focusing on the reconstruction skill (RE values in Fig. 3.7) over the period 1750-1850, clear spatial differences are found: while the skill over continental Europe is comparable, the new SLP reconstruction clearly reveals higher RE values over the southeastern North Atlantic. This improved skill over the marine region is not surprising, since Luterbacher et al. (2002) and other North Atlantic SLP reconstructions lack data from this area. Obviously, this limitation could partly be overcome with the CLIWOC data used in this study. However, the reconstruction skill of Luterbacher et al. (2002) is higher over the northeastern North Atlantic. This might be attributed to their inclusion of documentary data from continental Europe (primarily Western Baltic Sea Ice Index by Koslowski and Glaser, 1999 and the reconstructed precipitation from Andalusia by Rodrigo et al., 1999) which were found to contain very valuable information for the entire reconstruction area (Luterbacher et al., 2002).

As an additional independent verification of our results, single terrestrial instrumental pressure series that have not been used as predictors (Palermo, southern Italy: Barriendos et al., 2009; Stockholm, Sweden: Moberg et al., 2002; Liverpool, UK: Woodworth, 2006) were compared with the closest reconstructed grid box. The results generally indicate very good overall agreement with highly significant ($p < 0.01$) correlations for almost all stations and seasons

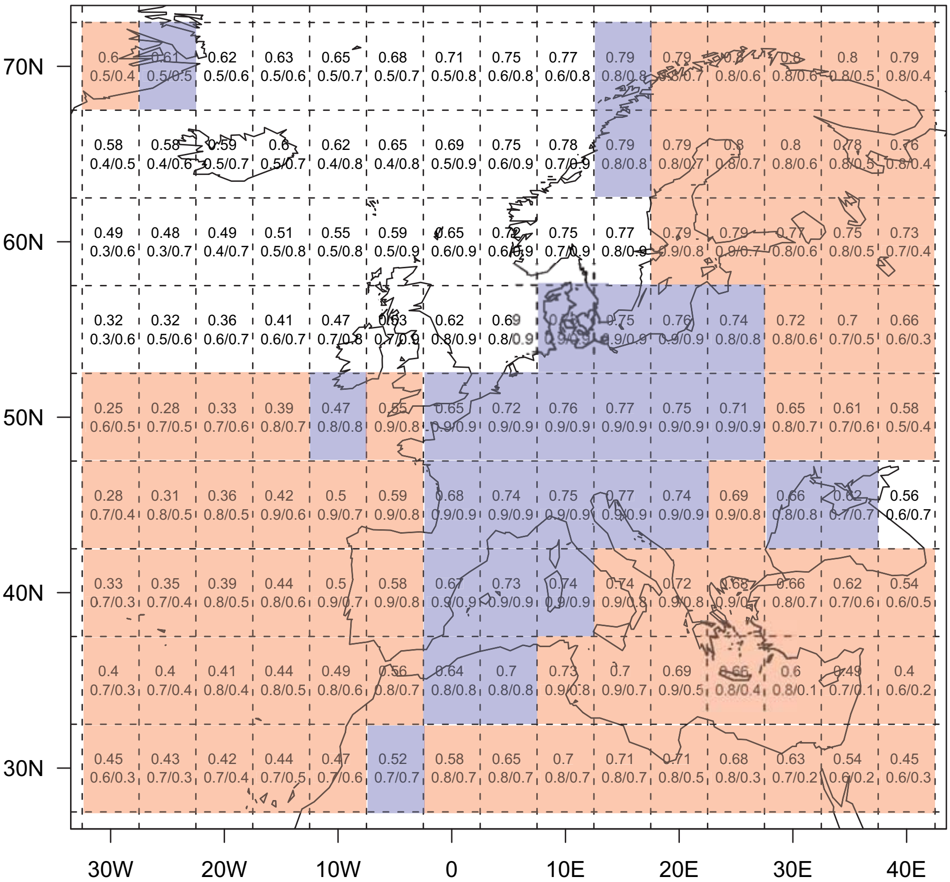

Figure 3.7: *Comparison of the spatial skill of the reconstruction from this study and Luterbacher et al. (2002) during the winters of the overlapping period 1750-1850. Each 5°x5° grid box shows at the top line the correlation values and at the bottom line the mean RE skill of this study (left) and Luterbacher et al. (2002, right). The RE skill value in the reddish (bluish) highlighted fields of this study is higher than (equal to) Luterbacher et al. (2002), the white boxes indicate lower skill.*

(Fig. 3.8 for winter; for the other seasons see Figs. 3.11-3.13 in the appendix). For summer, a correlation coefficient of 0.35 ($p < 0.1$) was found for Liverpool (Fig. 3.12 in the appendix). This rather low value might partly be due to increased uncertainties in this instrumental pressure series during the first few years (Woodworth, 2006). The reconstruction not only captures the multiannual SLP evolution but also reflects the interannual SLP variability very well. The high skill over Stockholm is to be expected as the nearby station of Uppsala (Bergström and Moberg, 2002) was included in our reconstruction. The very good agreement for Liverpool (Woodworth, 2006) and Palermo (Barriendos et al., 2009) however strongly confirms the high RE skill values obtained for these regions over the entire 250-year period (Fig. 3.4). The agreement over southern Italy is remarkable, considering the fact that terrestrial instrumental pressure measurements from this region only become available in 1852 with the series from Malta.

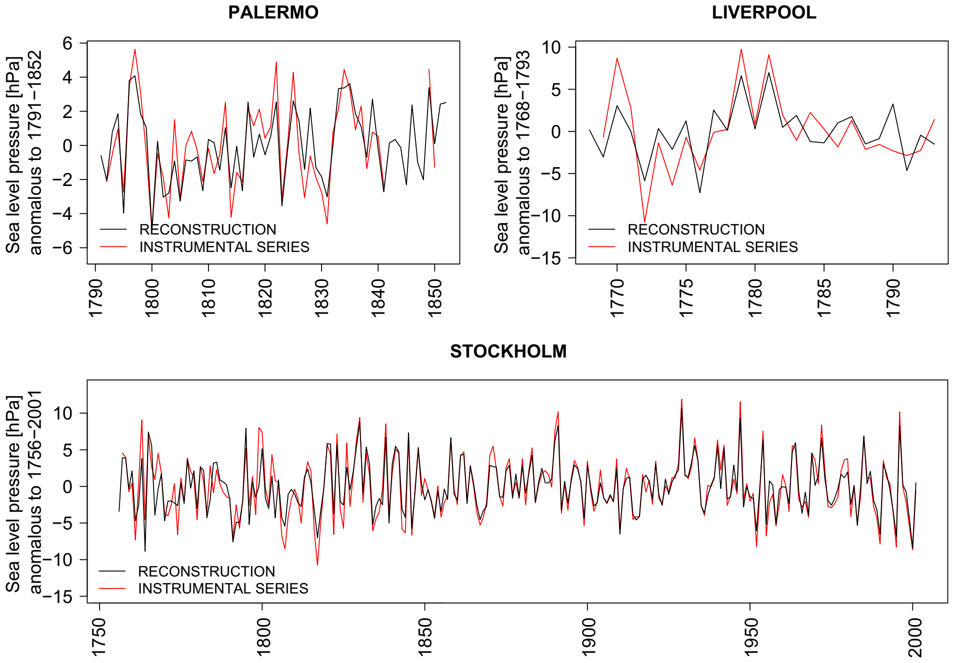

Figure 3.8: *Winter mean SLP from independent instrumental pressure series (red lines) and as reconstructed at the corresponding 5°x5° grid box (black lines) for Palermo (1791-1852; Barriendos et al., 2009), Liverpool (1768-1793; Woodworth, 2006), and Stockholm (1756-2001; Moberg et al., 2002). The correlation coefficients are 0.87 (Palermo), 0.76 (Liverpool), and 0.92 (Stockholm), all significant at the 99% significance level.*

3.4 Conclusions and outlook

Combining North Atlantic wind information derived from logbooks and instrumental pressure series from continental Europe and adjacent regions, a 5°x5° gridded seasonally resolved reconstruction of eastern North Atlantic, European and Mediterranean SLP fields back to 1750 has been developed. The combined information from marine logbooks and terrestrial instrumental pressure series is significantly improving previous SLP reconstructions, mainly in winter over the southeastern North Atlantic. This is an important finding as the location and strength of the Azores High can now be estimated with higher precision. Therefore, the influence of the Atlantic large-scale circulation on European climate can be addressed more accurately. Since this new reconstruction does not share any common predictors with existing temperature and precipitation reconstructions, dynamical studies relating changes of European and Mediterranean temperature and precipitation over the past 250 years to the state of the atmosphere can be performed without circular reasoning (Xoplaki et al., in prep.).

The major challenge of using wind information derived from logbooks as a source of past atmospheric circulation is the high variability in their spatial and temporal availability. However, it was shown, that with appropriate data pre-processing, this direct and marine source of the large-scale atmospheric circulation contains very reliable information, clearly superior to commonly used (terrestrial) proxies as e.g. tree rings or ice cores. Most of the logbooks in libraries and archives of the European colonial powers and elsewhere have yet to be fully explored and digitised. Only 5% of all British logbooks were included in the CLIWOC project (García-Herrera et al., 2005a). Recovering these data would have the potential to extend the quasi-instrumental period of knowledge on the state of the atmosphere to the early eighteenth century or even further back in time, as was recently demonstrated by Wheeler et al. (2009) for the English Channel region. Exploring Danish data from voyages to Iceland and Greenland (e.g. Frydendahl et al., 1992) has similarly great potential to improve the availability of data over the northern North Atlantic allowing a more appropriate representation of the Icelandic Low. Furthermore there are also many yet to be recovered terrestrial as well as marine instrumental pressure series which would be particularly useful for improving the SLP field reconstructions during summer and over the southeastern North Atlantic. The international ACRE (Atmospheric Circulation Reconstructions over the Earth) initiative has now taken up this challenge and is recovering global terrestrial and marine instrumental daily to sub-daily weather observations from as far back in time as possible. Within ACRE, several hundred ship log and remark books from e.g. the English East India Company containing instrumental data have been imaged by the British Library and are currently being digitised by the Climate Data Modernization Program (CDMP) in the US. Details of ACRE's activities and links to pioneering surface observations only historical reanalyses can be found on its WWW site (http://www.met-acre.org/).

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3.5 Appendix

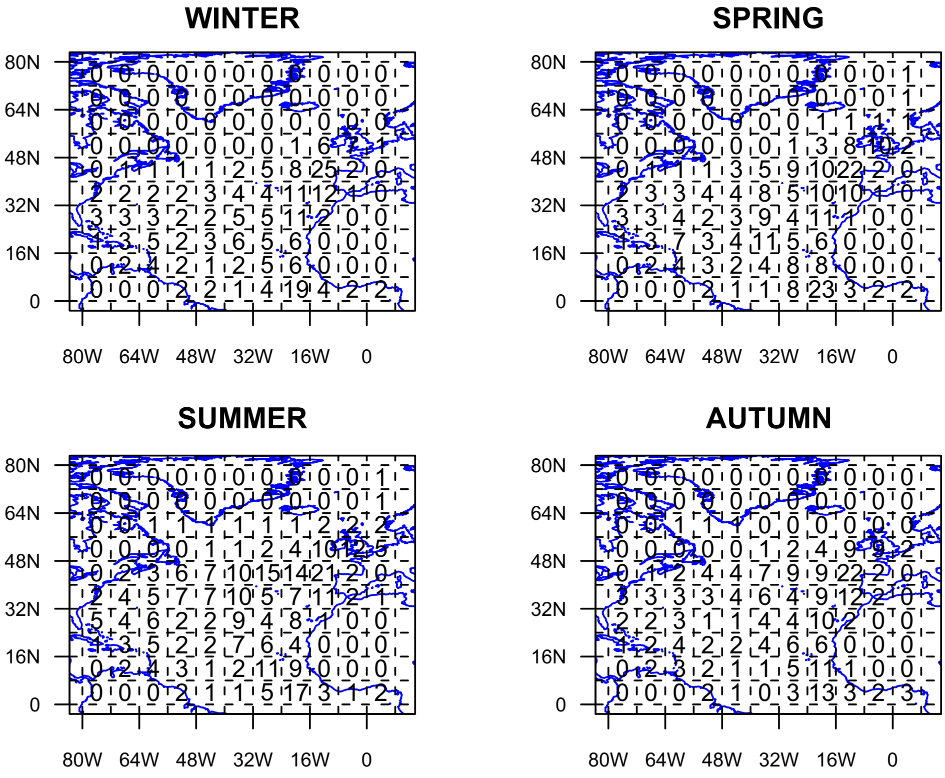

Figure 3.9: *Seasonal average number of records per 8°x8° grid box CLIWOC 2.1 1750-1850.*

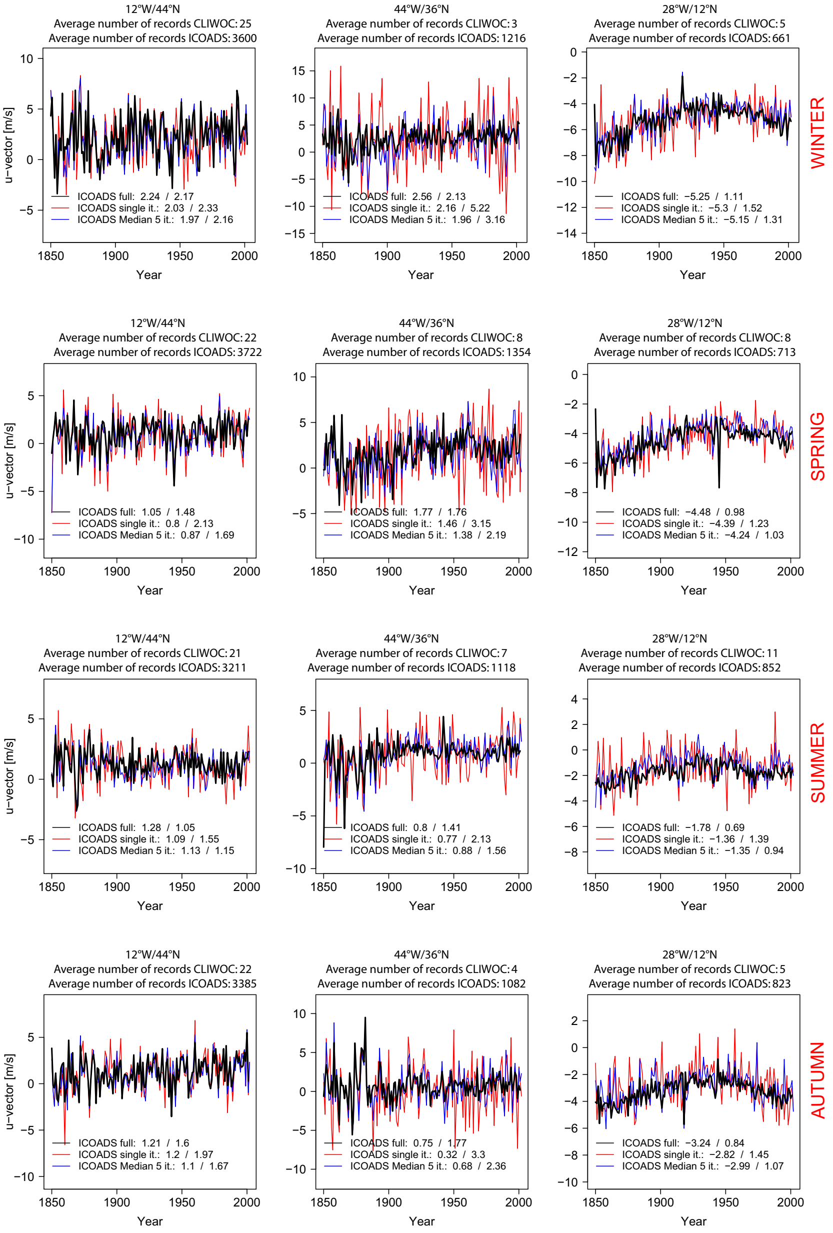

Figure 3.10: *Temporal evolution of the seasonal u-vector [m/s] 1850-2002 for different 8°x8° grid boxes spread across the North Atlantic using the full, i.e. not sampled ICOADS data set (black thick line) and sampling ICOADS according to the average number of records in a particular grid box in CLIWOC 1750-1850 (see Figure 3.9). The red line is based on one single sampling iteration, the blue line is the median of 5 iterations. The title of each box indicates the centre of the grid box and the average number of records of this particular box in CLIWOC 1750-1850 and ICOADS 1850-2002, respectively. The legend in the box refers to the mean and standard deviation of the series over the 153 year period.*

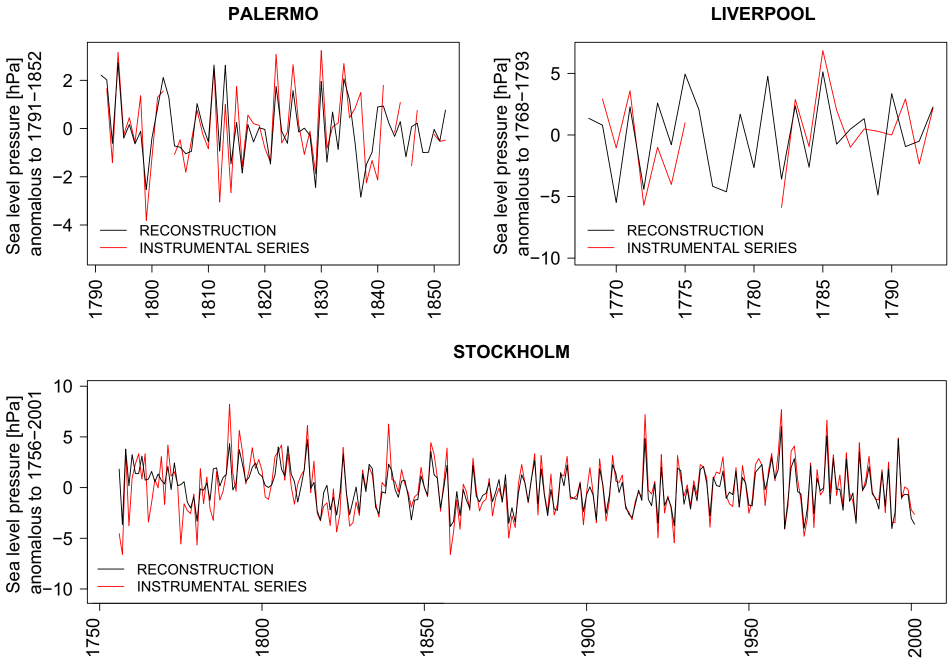

Figure 3.11: *Spring mean SLP from independent instrumental pressures series (red lines) and as reconstructed at the corresponding 5°x5° grid box (black lines) for Palermo (Barriendos et al., 2009), Liverpool (Woodworth, 2006), and Stockholm (Moberg et al., 2002). The correlation coefficients are 0.73 (Palermo), 0.64 (Liverpool), and 0.87 (Stockholm), all significant at the 99% significance level.*

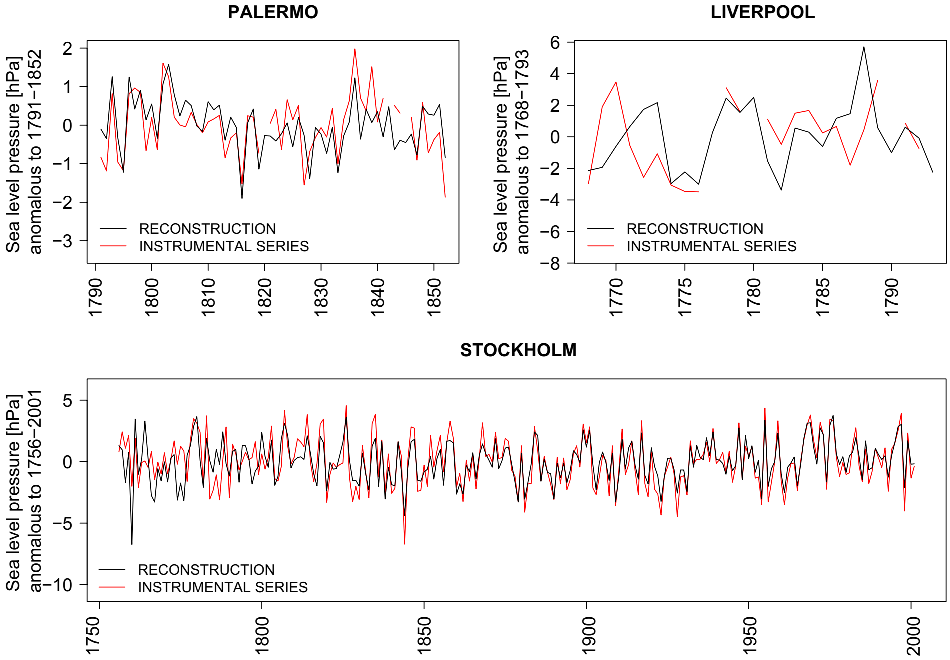

Figure 3.12: *As Figure 3.11, but for summer. The correlation coefficients are 0.68 (Palermo), 0.35 (Liverpool), and 0.82 (Stockholm), all except for Liverpool (p <0.1) being significant at the 99% significance level.*

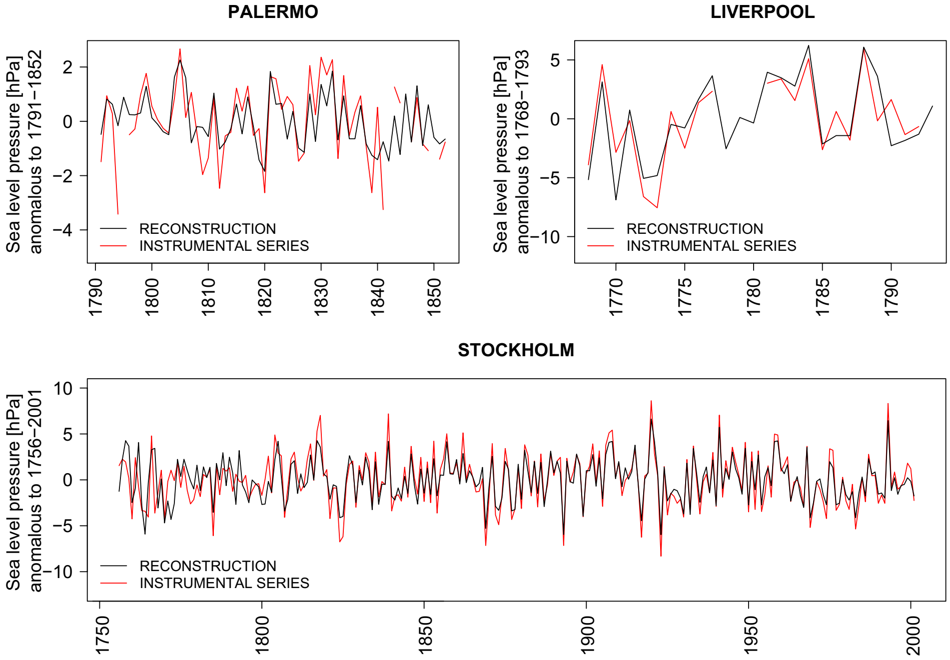

Figure 3.13: *As Figure 3.11, but for autumn. The correlation coefficients are 0.69 (Palermo), 0.87 (Liverpool), and 0.88 (Stockholm), all significant at the 99% significance level.*

Station Name	Latitude [°N]	Longitude [°E]	Start Year	End Year	Source
PP-Aberdeen	57.2	-2.22	1856	2002	Allan and Ansell (2006)
PP-Akureyri°	65.68	-18.08	1874	2002	Allan and Ansell (2006)
PP-Archangelsk	64.6	40.5	1851	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Armagh	54.4	-6.7	1850	2002	Allan and Ansell (2006)
PP-Astrakhan	46.6	48	1850	2002	Allan and Ansell (2006)
PP-Athens	38	23.7	1857	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Bad Ischl	47.72	13.63	1855	2002	Auer et al. (2007)
PP-Barcelona	41.2	2.1	1780	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Barnaul	53.21	83.45	1850	2002	Allan and Ansell (2006)
PP-Basel	47.6	7.6	1755	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Bergen	60.4	5.3	1816	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Berlin	52.4	13.1	1851	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Bidston	53.4	-3	1846	2002	Woodworth (2006)
PP-Boothville[1]	29.19	-89.23	1873	2002	Vose et al. (1992)
PP-Budapest	47.5	19	1809	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Cádiz*°	36.5	-6.3	1787	2002	Barriendos et al. (2002), updated
PP-Cairo*°	30.1	31.4	1857	2002	Allan and Ansell (2006)
PP-Casa Blanca[2]	23.7	-82.23	1858	2002	Vose et al. (1992)
PP-Copenhague	55.7	12.6	1842	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-De Bilt	52.1	5.2	1849	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Des Moines°	41.6	-93.6	1879	2002	Vose et al. (1992)
PP-Dublin	53.4	-6.3	1831	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Edinburgh	56	-3.4	1770	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Eniseisk	58.45	92.15	1871	2002	Allan and Ansell (2006)
PP-Florence	43.8	11.3	1814	2002	Maugeri et al. (2004)
PP-Funchal°	32.6	-16.9	1850	2002	Allan and Ansell (2006)
PP-Gdańsk	54.3	18.9	1807	2002	Jones et al. (1999); Slonosky et al. (1999), update from M. Mietus (U. Gdańsk, pers. comm.)
PP-Geneva	46.3	6.1	1768	2002	Auer et al. (2007)
PP-Genoa	44.24	8.55	1833	2002	Flocchini et al. (1983); Maugeri et al. (2004)
PP-Gibraltar	36.2	-5.4	1821	2002	Jones et al. (1997); Osborn (2006)
PP-Nuuk (Godthåb)	64.17	-51.75	1873	2002	Allan and Ansell (2006)
PP-Gothenburg	57.7	11.99	1860	2002	Allan and Ansell (2006)
PP-Graz	47.07	15.45	1837	2002	Auer et al. (2007)
PP-Gr. St. Bernhard	45.5	7.1	1864	2002	Auer et al. (2007)
PP-Haparanda	65.8	24.2	1860	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Harnosand	62.38	17.56	1860	2002	Allan and Ansell (2006)
PP-Helsinki	60.3	25	1850	2002	Allan and Ansell (2006)

Table 3.1: *Overview of the instrumental pressure series.*

PP-Hohenpeissenb.	47.8	11	1781	2002	Auer et al. (2007)
PP-Innsbruck	47.27	11.4	1830	2002	Auer et al. (2007)
PP-Istanbul	41	29.1	1856	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Jerusalem	31.8	35.2	1861	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Karlsruhe	49.01	8.39	1869	2002	Auer et al. (2007)
PP-Kiev	50.4	30.5	1850	2002	Allan and Ansell (2006)
PP-Klagenfurt	46.7	14.3	1844	2002	Auer et al. (2007)
PP-Kremsmünster	48.05	14.13	1822	2002	Auer et al. (2007)
PP-La Coruña	43.21	-8.24	1866	2002	Allan and Ansell (2006)
PP-Lisbon	38.7	-9.2	1850	2002	Jones et al. (1999); Slonosky et al. (1999), update from R. Trigo (U. Lisbon, pers. comm.)
PP-Lockbourne[3]	39.81	-82.97	1878	2002	Vose et al. (1992)
PP-London	51.2	-1	1774	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Lugano	46	8.6	1864	2002	Auer et al. (2007)
PP-Lund	55.4	13.1	1780	2002	Bärring et al. (1999), updated
PP-Luxembourg°	49.36	6.7	1838	2002	Allan and Ansell (2006)
PP-Lvov	49.8	24	1851	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Madrid	40.4	-3.7	1786	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Malta	35.9	14.5	1852	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Marseille	43.5	5.2	1851	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Milan	45.5	9.1	1765	2002	Maugeri et al. (2004)
PP-Moscow	55.8	37.6	1838	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Munich	48.1	11.7	1825	2002	Auer et al. (2007)
PP-Nantes	47.2	-1.6	1851	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Neuchâtel	46.6	6.6	1864	2002	Auer et al. (2007)
PP-Nicosia*°	35.1	33.2	1866	2002	Allan and Ansell (2006)
PP-Nordby	55.52	8.57	1874	2002	Allan and Ansell (2006)
PP-Odessa	46.5	30.6	1842	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Oporto°	41.1	-8.6	1863	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Oslo	60	10.7	1816	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Padua	45.4	11.8	1750	2002	Maugeri et al. (2004)
PP-Palma	39.6	2.7	1850	2002	Allan and Ansell (2006)
PP-Paris	49	2.5	1764	2002	Jones et al. (1999); Slonosky et al. (1999), update from O. Mestre (Météo France, pers. comm.)
PP-Po Plain	45.12	9.66	1765	2002	Maugeri et al. (2004)
PP-Ponta Delgada	37.8	-25.7	1865	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Prag	50.1	14.3	1789	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Reykjavík	65.1	-22.8	1821	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Rome°	41.8	12.2	1851	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Säntis	47.2	9.2	1883	2002	Auer et al. (2007)

Table 3.2: *Table 3.1 continued*

PP-Salzburg	47.8	13.03	1842	2002	Auer et al. (2007)
PP-Sibiu°	45.8	24.2	1850	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Sonnblick	47.01	12.95	1887	2002	Auer et al. (2007)
PP-Split	43.3	16.26	1850	2002	Allan and Ansell (2006)
PP-Stockholm	59.4	18.1	1850	2002	Allan and Ansell (2006)
PP-St. Petersburg	60	30.3	1822	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Stykkishólmur	65.08	-22.73	1850	2002	Allan and Ansell (2006)
PP-Sulina°	45.15	29.67	1850	2002	Allan and Ansell (2006)
PP-Tashkent	41.2	69.18	1850	2002	Allan and Ansell (2006)
PP-Tbilisi	41.43	44.47	1844	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Tórshavn°	62.02	-6.77	1867	2002	Allan and Ansell (2006)
PP-Trieste	45.7	13.8	1841	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Tromsø	69.4	18.56	1874	2002	Allan and Ansell (2006)
PP-Trondheim	63.5	10.9	1768	2002	Jones et al. (1999); Slonosky et al. (1999), update from P.Ø. Nordli (Met. Inst. Norway, pers. comm.)
PP-Upernavik	72.47	-56.1	1874	2002	Allan and Ansell (2006)
PP-Uppsala	59.9	17.6	1750	2002	Bergström and Moberg (2002), updated
PP-Valentia (IRL)	51.93	-10.25	1866	2002	Vose et al. (1992)
PP-Vardø	70.4	31.1	1861	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Vienna°	48.3	16.4	1775	2002	Auer et al. (2007)
PP-Visby	57.38	18.17	1860	2002	Allan and Ansell (2006)
PP-Warsaw	52.2	21	1836	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Wrocław	51.1	16.88	1850	2002	Allan and Ansell (2006)
PP-Zagreb	45.8	16	1862	2002	Jones et al. (1999); Slonosky et al. (1999)
PP-Zurich	47.37	8.55	1864	2002	Auer et al. (2007)

* not continuous

° homogenized

[1] Boothville (USA) was extended with New Orleans (USA) 1981-2002

[2] Casa Blanca (Cuba) was extended with Miami (USA) 1955-2002

[3] Lockbourne (USA) was extended with Columbus Int. Airport (USA) 1981-2002

Table 3.3: *Table 3.1 continued*

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Chapter 4

Multidecadal changes in the circulation-climate relationship in Europe: frequency variations, within-type modifications and long-term trends

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Abstract

Advective processes exerted by the large-scale atmospheric circulation are known to strongly influence the spatial distribution and temporal variation of European winter climate. However, this connection is subject to important spatial and temporal variations. Applying a recently developed classification technique this study investigates in space as well as in time how the relationship between representative patterns of the European and North Atlantic atmospheric circulation and the European winter (DJF) temperature and precipitation fields has changed over the period 1750-2000. Although important changes in the frequency of the sea level pressure (SLP) clusters are found, none of them reveals any significant long-term trends. However, for most of the nine derived SLP clusters, a tendency towards overall warmer and partly also wetter conditions are found for the past 250 years, most pronounced over the last few decades. This points towards important within-type variations, i.e. the temperature and precipitation fields related to a particular SLP pattern change their characteristics over time. Using a decomposition scheme to distinguish between climate variations due to changed frequencies and due to within-type variations of the SLP clusters it is found for temperature as well as precipitation that the latter dominate over the former. Within-type variations appear to be the most important factor particularly for temperature and over Eastern Europe and Scandinavia, generally explaining more than 70% and up to 90% of the multidecadal temperature changes. This indicates that the recently observed warming over Europe cannot be explained by changed frequency of SLP patterns alone but to an important degree also to changed characteristics of the patterns themselves. So far, it can only be speculated about the specific origin of these within-type variations.

4.1 Introduction

European climate is known to be strongly related to the state of the atmospheric circulation (Walker and Bliss, 1932; Trenberth, 1995; Hurrell and Van Loon, 1997; Jacobeit et al., 2001; Slonosky et al., 2001; Xoplaki et al., 2004; Beck et al., 2007). Particularly during winter season advective processes exerted by the large-scale atmospheric circulation have a dominant influence on the spatial distribution and temporal variation of European climate. A better understanding of the relationship between the atmospheric circulation and European surface climate is therefore essential when assessing the driving mechanisms behind past and current climate variability. Europe with its wealth on long instrumental measurements as well as indirect information from proxy series offers a great potential to address these questions in detail over a timescale extending well beyond the 20th century.

Several studies have shown that the correlations between simple time series of atmospheric modes such as the North Atlantic Oscillation Index and European winter temperature and precipitation are subject to important decadal to multidecadal variations (Jacobeit et al., 2001; Pozo-Vázquez et al., 2001; Slonosky et al., 2001; Beranová and Huth, 2008; Vicente-Serrano and López-Moreno, 2008). However, these variations can partly be related to changes in the atmospheric dynamics including variations in location, strength and spatial extension of and interaction between the Azores High, the Icelandic Low and the cold Siberian High. Simple indices of the atmospheric circulation cannot account for such internal circulation dynamics, pointing towards the need to consider the full field information on the large-scale atmospheric circulation.

Studies relating changes in surface climate to the large-scale atmospheric circulation are mostly based on classified pressure fields, i.e. the pressure fields of the period of interest are grouped into a possibly small number of representative patterns. Using classified pressure fields several studies (e.g. Beck, 2000; Jacobeit et al., 2003, 2009; Beck et al., 2007; Philipp et al., 2007; Jones and Lister, 2009) have investigated whether the changes in past European climate are due to changed frequencies of particular circulation patterns or rather due to so-called within-type variations. The latter term comprises all changes in climate which cannot be related to changed frequencies of the circulation patterns but must rather be attributed to changed characteristics of the patterns themselves (e.g. Barry and Perry, 1973; Yarnal, 1993; Brinkmann, 1999). This means, that a particular pattern of the large-scale atmospheric circulation can be related to distinctively different responses of the temperature and precipitation field. As e.g. discussed in Beck et al. (2007), within-type variations might either be of dynamical or climatic origin. Examples of the former are processes working on smaller scale than resolved by the gridded pressure field, e.g. orographically induced precipitation. Changes in air mass characteristics due to changed climatic boundaries as e.g. increased North Atlantic sea surface temperatures (SST; Parker 2009) are an example of within-type variations of climatic origin. Working in this direction, Beck et al. (2007) found that roughly

53% (64%) of the changes in Central European mean January temperature (precipitation) over the period 1780-1995 can be related to within-type variations while the remaining percentages are due to changed frequencies of the circulation patterns. This was confirmed by other studies who also suggested that within-type variations dominate over frequency-related changes to explain variations of past European temperature and precipitation (e.g. Jacobeit et al., 2003, 2009; Philipp et al., 2007; Jones and Lister, 2009).

However, these studies either used spatial averages of temperature and precipitation or instrumental measurements from single stations to investigate the changes in the relationship between the large-scale atmospheric circulation and European climate. Therefore, spatial details were only marginally addressed, being however from a dynamical point of view of great importance. Furthermore, these studies were either limited to the post-1850 instrumental period (Philipp et al., 2007; Jacobeit et al., 2009; Jones and Lister, 2009) or were based on sea level pressure (SLP) reconstructions with reduced skill over the North Atlantic Ocean due to the absence of information from this region prior to the mid-19th century (Jacobeit et al., 2003; Beck et al., 2007). The latter is relevant since the position and strength of the Azores High and Icelandic Low driving weather and climate downstream are probably not accurately represented.

Here, a recently developed SLP reconstruction with particularly enhanced skill over the North Atlantic Ocean is used to spatially investigate how the relationship between representative patterns of the large-scale atmospheric circulation and gridded European winter temperature and precipitation fields has evolved over the past 250 years. The focus is thereby on assessing to what degree the spatial changes in European temperature and precipitation are due to within-type variations or due to changes in the frequency of SLP patterns.

This study is structured as follows: the gridded SLP, temperature and precipitation reconstructions covering the last 250 years are described in section 4.2. Section 4.3 introduces the methods applied to classify the SLP field into representative patterns and to spatially decompose variations in European temperature and precipitation into parts related to changed SLP pattern frequencies and parts due to within-type variations. The results are presented and discussed in section 4.4 with a particular focus on the dynamics behind multidecadal changes in European climate. Section 4.5 provides some final conclusions.

4.2 Data

Using terrestrial instrumental pressure series and marine wind information from ship logbooks, Küttel et al. (2009, chapter 3) reconstructed larger North Atlantic and European SLP fields on a 5° x 5° and seasonal resolution back to 1750. This reconstruction is based on multivariate principal component regression using the HadSLP2 dataset by Allan and Ansell (2006) as predictand. Regression models between the predictors and the predictand were developed during 1887-2000 and subsequently applied to the predictor data 1750-1886. Details on the reconstruction methodology are found in Küttel et al. (2009, chapter 3). For this study, the reconstruction was recalculated to cover 70°W-50°E and 20°N-70°N. Only winter (average of December, January and February) and 1750-2000 are considered here. Compared to earlier SLP reconstructions (e.g. Jones et al., 1999; Luterbacher et al., 2002) this new SLP reconstruction is more reliable during winter and for the region of the North Atlantic Ocean (Küttel et al., 2009, chapter 3). This allows a more realistic representation of the position and strength of the Azores High and Icelandic Low driving weather and climate downstream. For the sake of internal consistency, the reconstruction is used for the entire 250 years, i.e. it is not replaced by HadSLP2 during the calibration period 1887-2000. However, the reconstruction and HadSLP2 agree very well during the overlapping period with the subsequently presented results not being dependent on this step (not shown). In order to investigate how the relationship between the large-scale atmospheric circulation and the European climate fields has changed over the past 250 years, the winter temperature and precipitation reconstructions by Luterbacher et al. (2007) and Pauling et al. (2006) are used. These reconstructions are completely independent from Küttel et al. (2009, chapter 3), i.e. they share no common predictors. Both datasets have a spatial resolution of 0.5° x 0.5° with the temperature reconstruction by Luterbacher et al. (2007) covering 25°W-40°E and 35°N-70°N and the precipitation reconstruction by Pauling et al. (2006) covering 30°W-40°E and 30°N-71°N. 1750-1900 is in each

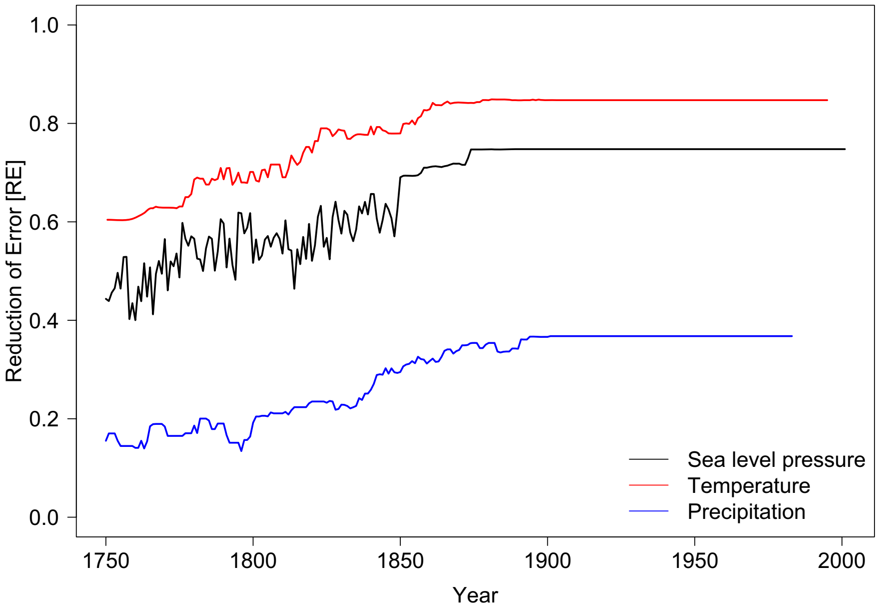

Figure 4.1: *Reduction of Error (RE; Cook et al. 1994) skill scores winters (DJF) 1750-2000 for the sea level pressure reconstruction by Küttel et al. (2009, chapter 3; black), 1750-1995 for the temperature reconstruction by Luterbacher et al. (2007, red) and 1750-1983 for the precipitation reconstruction by Pauling et al. (2006, blue). Values above zero indicate better performance than climatology, 1 indicates perfect skill.*

case the reconstruction while 1901-2000 is the reanalysis data by Mitchell and Jones (2005). This replacement is necessary since the temperature and precipitation reconstructions only cover 1500-1995 and 1500-1983, respectively. The results are, however, not significantly influenced by this step (not shown). For details on the reconstruction we refer to the original publications. The field averaged skill of the three reconstructions (expressed as the Reduction of Error score; Cook et al. 1994) is shown in Figure 4.1. The temperature (Figure 4.1; red line) and SLP reconstructions (black line) reveal very high skill over the entire 250 years. A lower reliability is found for precipitation (blue line) with, however, values still well above zero therefore indicating better performance than climatology.

4.3 Methods

In order to identify representative patterns of the large-scale atmospheric circulation, the winters of the SLP field reconstruction by Küttel et al. (2009, chapter 3) back to 1750 are grouped into classes of high within-class similarity and between classes dissimilarity. Classifying pressure fields has a long tradition and has over the last couple of decades yielded a large number of approaches and methodologies. A general distinction can be made between subjective (manual) classifications and objective (statistical/automated) classifications. Well known examples of the subjective classifications are the Lamb weather types (Lamb, 1972) or the Grosswetterlagen introduced by Hess and Brezowsky (1952). Objective classifications became more commonly used over the last few decades with the increase in computing power. They are based on statistical methods and include various techniques based on correlations (e.g. Lund, 1963; Schmutz and Wanner, 1998; Brinkmann, 1999) or on EOF and cluster analysis (e.g. Beck, 2000; Luterbacher et al., 2001; Jacobeit et al., 2003). Recently, Philipp et al. (2007) introduced a new classification algorithm based on simulated annealing and diversified randomization (SANDRA). This method uses the clustering technique of simulated annealing which allows each member of a cluster to change to another cluster at any time, even if the within-cluster similarity might decreases at first (Philipp et al., 2007). In SANDRA, this technique is combined with the concept of diversified randomization, i.e. the simulated annealing is repeated for 1000 times with the starting clusters being randomized at each iteration and the ordering of the clusters also being randomized throughout the process of checking and reassigning. For more details on the methodology we refer to Philipp et al. (2007) and references therein. In their application on daily resolved North Atlantic and European SLP fields back to 1850, Philipp et al. (2007) showed that SANDRA yields better results in terms of within-class stability and between-class separation than other commonly used clustering techniques such as k-means. This method was also recently used by Jacobeit et al. (2009) and Jones and Lister (2009) to investigate on a daily basis the changes in the relationship between the larger North Atlantic/European pressure field and European temperature and precipitation during the periods 1850-2003 and 1901-2000, respectively.

In order to determine the most appropriate technique to classify the SLP reconstruction by Küttel et al. (2009, chapter 3), SANDRA as well as other commonly used methods such as k-means (e.g. Brönnimann et al., 2007), PAM (e.g. Beranová and Huth, 2008) and t-mode principal component analysis (e.g. Luterbacher et al., 2001; Jacobeit et al., 2003) were applied to the dataset. The SLP field was thereby weighted by the square root of the cosine of latitude to account for the artificial increase in variability per grid box with increasing latitude. The different techniques resulted in very similar clusters with, however, the highest within-class similarity and between-class dissimilarity found for SANDRA (not shown). This method was therefore chosen here.

Determining the optimal number of clusters is one of the most challenging part in every clustering technique. Various authors (see Philipp et al. 2007 for a recent overview) suggested methods with, however, none of them having shown to be the most appropriate for all applications. We therefore here apply a straightforward approach by calculating SANDRA for different numbers of clusters and selecting the one yielding the highest within-class correlations, being in our case nine clusters. The same number of clusters has been reported for winter season by Philipp et al. (2007) though using daily SLP fields and the years 1850-2003. In order to check for years which can barely be assigned to a particular cluster, the silhouette index by Kaufman and Rousseeuw (1990) was used. Based on the dissimilarity matrix, negative silhouette widths indicate members who lie rather in-between clusters than can be clearly assigned to a cluster (Kaufman and Rousseeuw, 1990). Applying this technique to the nine SLP clusters derived from SANDRA, 30 years were found to have negative silhouette widths. These years were therefore eliminated prior to analysis. In all of the nine clusters members were removed with, however, almost one third of all located in cluster 1 (see Table 4.1). An overview of the final clusters is given in Table 4.1, demonstrating that the within-cluster correlations are generally well above 0.9 and therefore statistically highly significant ($p < 0.001$).

The temperature (Luterbacher et al., 2007) and precipitation (Pauling et al., 2006) fields 1750-2000 were also correspondingly split into the nine SLP clusters. The within-cluster stability of the so-derived SLP, temperature and precipitation clusters is determined by calculating scaled mean anomaly composites with the significance of the composites being assessed by a modified t-test (Brown and Hall, 1999). Scaled mean anomaly composites are more robust to outliers than simple mean composites since the associated variance of the members is also included. Furthermore, this method can also be applied to non-gaussian distributed data (Brown and Hall, 1999). Scaled mean anomaly composites in paleoclimatic applications have recently been presented by Touchan et al. (2005), Brönnimann et al. (2007) and Esper et al. (2007).

Finally, in order to quantitatively assign multidecadal changes in temperature and precipitation to frequency and within-type variations of the SLP clusters, the decomposition method-

Cluster	Members		Within-cluster correlation		
	Original	Final	Minimum	Maximum	Median
1	34	25	0.91	1.00	0.97
2	33	29	0.81	1.00	0.96
3	32	28	0.91	1.00	0.98
4	31	28	0.82	1.00	0.97
5	30	26	0.87	1.00	0.97
6	28	25	0.70	0.99	0.90
7	25	24	0.88	1.00	0.98
8	20	19	0.75	1.00	0.93
9	18	17	0.65	0.99	0.94

Table 4.1: *Overview of the nine SLP clusters obtained using the SANDRA classification algorithm by Philipp et al. (2007). The second column indicates the original number of members in the clusters, while the third column shows the final number after eliminating those with a negative silhouette width (Kaufman and Rousseeuw, 1990, see text for details). The fourth, fifth and sixth columns show the minimum, maximum and median of the within-cluster correlations of the final sets, all significant at* $p < 0.001$.

ology by Barry and Perry (1973) is used. Therein, the climate difference $\Delta\bar{C}$ between two periods is defined as

$$\Delta\bar{C} = \sum_{i=1}^{G} [\Delta F_i (C_i + \Delta C_i)/n] + [F_i \cdot \Delta C_i/n] \tag{4.1}$$

where

G = number of clusters
F_i = absolute frequency of cluster i during the first period
C_i = climatic mean of cluster i during the first period
ΔF_i = difference in the absolute frequency of cluster i between the second and the first period
ΔC_i = difference in the climatic mean of cluster i between the second and the first period
n = number of time units during the first period

The expression $\Delta F_i (C_i + \Delta C_i)/n]$ describes the change in climate between two periods which is related to variations in the frequency of the SLP clusters, i.e. an observed warming might be due to the more frequent appearance of warm clusters. Accordingly, the expression $[F_i \cdot \Delta C_i/n]$ describes differences in the climate of two periods related to a changed relationship between an SLP cluster and climate, i.e. changes due to within-type variations (see section 4.1). This method was recently used by Beck (2000) and Beck et al. (2007) to decompose the monthly changes in Central European mean temperature and precipitation 1780-1995. Here, we focus only on multidecadal changes, i.e. European temperature and precipitation averaged over 50-year periods are compared and decomposed. The length of fifty years is chosen in order to have for each cluster a sufficient number of cases. Results will only be presented for the difference in temperature and precipitation between the most recent 50-year period (1950-1999) and the preceding 50-year periods 1750-1799, 1800-1849, 1850-1899 and 1900-1949. Therefore, the second period in equation 4.1 is always 1950-1999. n is the number of winters per cluster in each 50-year period. Since some of the winters were removed due to negative silhouette widths, this number changes for each 50-year period. Equation 4.1 is applied to all grid boxes of the temperature reconstruction by Luterbacher et al. (2007) and the precipitation reconstruction by Pauling et al. (2006). This allows quantifying spatially to what degree changes in temperature and precipitation over Europe are due to variations in the frequency of the SLP clusters or due to within-type modulations. Therefore, this study might be considered an extension of the works by Beck (2000) and Beck et al. (2007) who focused on spatial averages.

4.4 Results and discussion

Figure 4.2 shows simple composites of the nine SLP (Küttel et al., 2009, chapter 3) clusters based on the absolute values (left) as well as the scaled mean SLP, temperature (Luterbacher et al., 2007) and precipitation (Pauling et al., 2006) anomaly composites for the winters 1750-2000. The anomalies are shown with respect to the 1750-2000 reference period. The 95% significance level (as determined from the modified t-test, see Brown and Hall 1999) is indicated by the grey shaded areas (SLP) and the green contour lines (temperature and precipitation). The nine SLP clusters presented in Figure 4.2 might be characterized as zonal (clusters 3, 6, 7, 8), half-meridional (1, 9) and meridonal (2, 4, 5) patterns. Of the zonal patterns, clusters 3 and 7 are dominated by enhanced westerly winds while easterly advection prevails in clusters 6 and 8. Cluster 1 is connected with anomalously northwesterly winds directed towards Europe while southeasterly flow dominates in cluster 9. In a very simplified manner, the westerly and northwesterly patterns might be referred to as positive modes of the North Atlantic Oscillation (NAO), while the easterly and southeasterly patterns represent variations of the negative mode. The meridional clusters 2, 4 and 5 are more complex patterns with anomalously low (high) pressure over the southern North Atlantic and western Russia / Scandinavia (Greenland and Northern Africa) in cluster 2 and opposite conditions in cluster 5, while anomalously low pressure is found over the Bay of Biscay in cluster 4. As indicated by the grey shaded areas in Figure 4.2 (second column), all of the nine SLP clusters are very robust patterns. This is of importance, since it allows dynamic interpretations henceforth, which do not suffer significantly from high within-cluster SLP variations.

As a result of the predominant circulation described above, warm/cold and humid/dry air masses are advected towards Europe. This is well reflected in the corresponding temperature (Figure 4.2, third column) and precipitation (fourth column) fields: The westerly (clusters

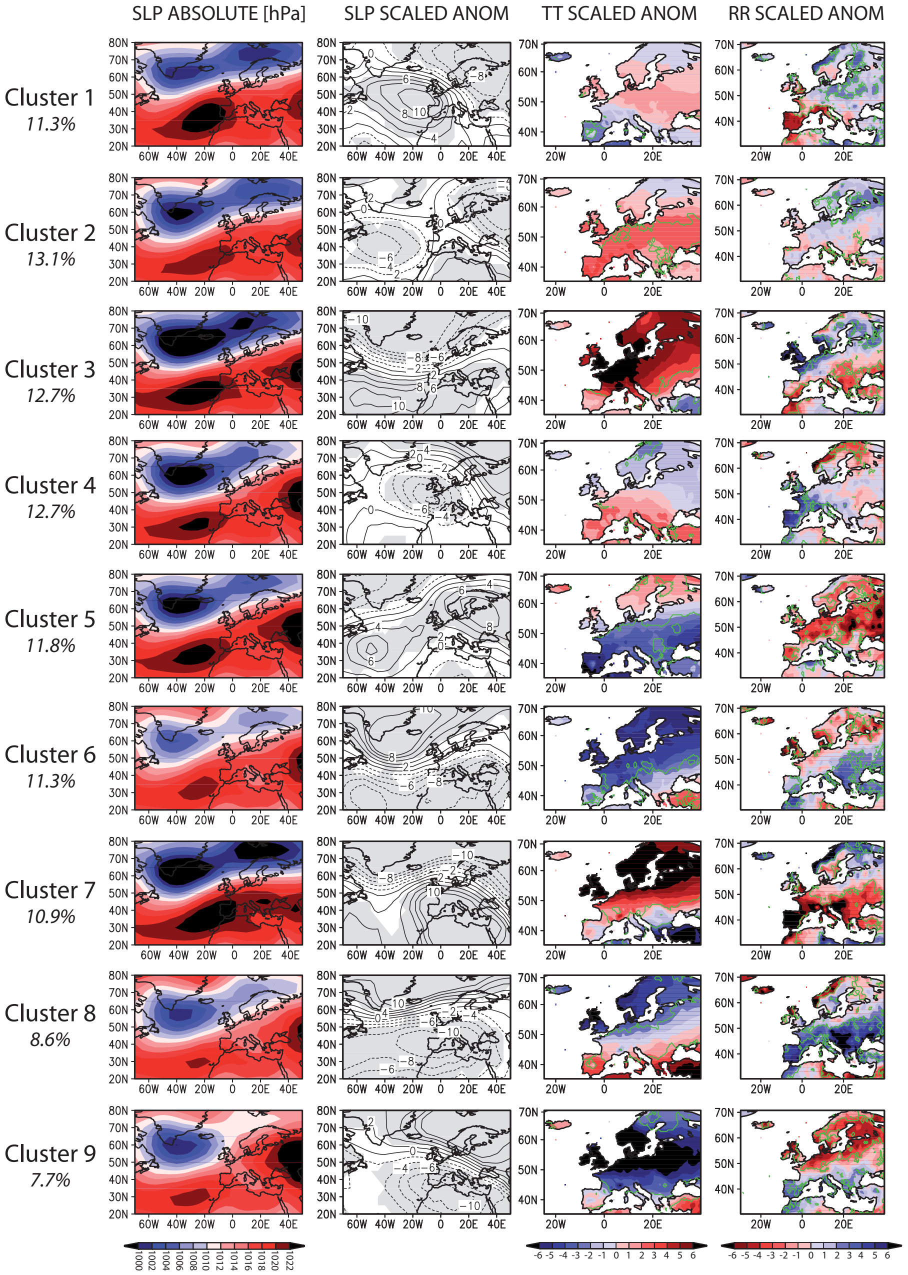

Figure 4.2: *SLP clusters derived using the SANDRA clustering technique (Philipp et al., 2007) and corresponding temperature (Luterbacher et al., 2007) and precipitation (Pauling et al., 2006) fields. The frequency of each cluster over the period 1750-2000 is indicated to the left. Columns 2-4 are scaled mean composites of the anomalies (Brown and Hall, 1999) with regard to 1750-2000. The grey shaded areas (SLP) and the green contour lines (temperature and precipitation) indicate significance at the 95% level using the modified t-test by (Brown and Hall, 1999). The units of columns 2-4 are arbitrary.*

3, 7) and northwesterly (1) patterns lead to generally above (below) normal temperatures across Northern Europe (the Mediteranean) and above (below) normal precipitation amounts over Northern Europe (the Mediterranean) with, however, important spatial differences due to the latitudinal position, strength and direction of the winds. The easterly (6, 8) and southeasterly (9) patterns are generally connected with the advection of cold and dry air masses towards Northern Europe while the (western) Mediterranean region experiences anomalously mild and wet winters. The meridional patterns 2 (5) are related with above (below) normal temperatures and precipitation amounts across Europe, while cluster 4 reveals above (below) normal temperatures and precipitation amounts over southwestern Europe (Scandinavia).

4.4.1 Frequency changes

Figure 4.3 shows the decadal changes in the frequency of the nine SLP clusters over the period 1750-2000. To facilitate the interpretation, *C* and *W* in Figure 4.3 indicate whether a particular SLP cluster is mainly related to anomalously cold (clusters 5, 6 and 9) or warm (clusters 2, 3 and 7) conditions in Europe (see Figure 4.2). The European temperature field is more heterogeneous during clusters 1, 4 and 8 (Figure 4.2), not revealing overall cooler or warmer conditions. In order to characterize the precipitation field, the plus (minus) signs in Figure 4.3 indicate that a particular SLP cluster shows enhanced westerly (easterly) flow connected with generally above (below) normal precipitation amounts over Northern Europe and anomalously dry (wet) conditions over Southern Europe (Figure 4.2).

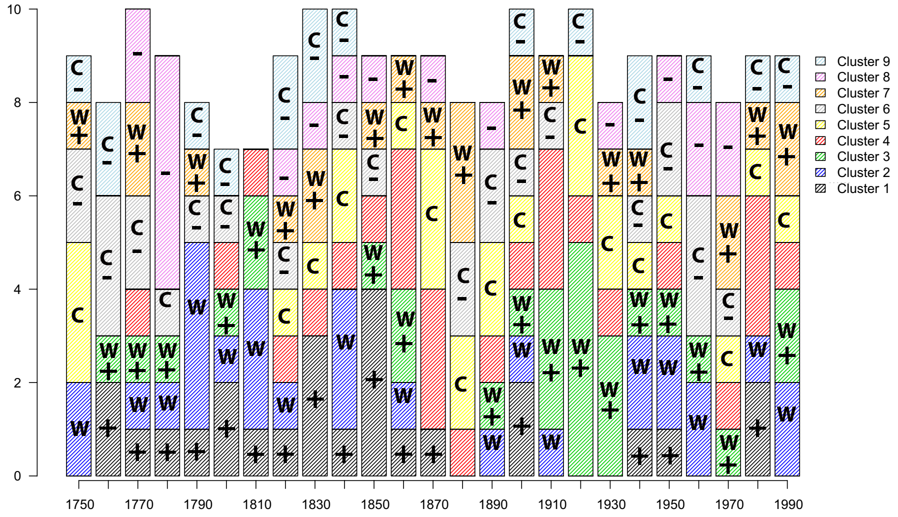

Figure 4.3: *Decadal frequency of the SLP clusters for the winters 1750-2000. W (C) indicates that the cluster is related to generally warmer (colder) than normal conditions in Europe, while + (-) denote anomalously westerly (easterly) advection. See text for details. The missing years (i.e. the bars are smaller than ten) represent the years where the SLP field could not be assigned to a particular cluster (see section 4.3).*

Although all clusters show decadal changes in their frequency (Figure 4.3), no significant (p <0.05) trends could be detected (not shown). However, there are some interesting features, e.g. the complete absence of the cold and dry cluster 5 from the 1760s to the 1810s or of the very cold cluster 9 from the 1850s to the 1890s. However, these decades are not found to be anomalously warm in the temperature reconstruction by Luterbacher et al. (2007). As can be depicted from Figure 4.3 this is partly due to the fact that their absence is compensated by the more frequent appearance of other SLP cluster connected with cooler temperatures across Europe. However, even the decades with 50% or more of all years belonging to a cold cluster (1750s, 1760s) were not found to be significantly colder than normal in Luterbacher et al. (2007). Similarly, the decades with a predominance of warm clusters (1790s, 1810s, 1910s, 1920s and the 1990s) were - with the exception of the 1990s -not anomalously warm. This disagreement might be surprising at first but, as will be shown next, can be explained by within-type variations, i.e. a particular SLP pattern can be connected with distinctly different temperature and precipitation fields. The decadal changes in the frequency of SLP patterns related with anomalously westerly (plus signs) or easterly (minus signs) flow reveals a better consistency with the precipitation field reconstructed by Pauling et al. (2006). For example, the period 1940-1970 (1990-2000) where a predominance of SLP patterns related with anomalously easterly (westerly) flow can be depicted in Figure 4.3 was indeed wetter (drier) than normal over the Mediterranean. The conditions over Northern Europe were accordingly of opposite sign (Pauling et al., 2006).

4.4.2 Within-type variations

As stated above, the European temperature and precipitation fields occurring during a particular SLP pattern might have changed their characteristics over time. The validity of this assumption is first assessed by calculating for each cluster and case the spatial average of the corresponding European temperature and precipitation fields 1750-2000 (Figure 4.4).

As was assumed, a particular SLP pattern can be related with considerably different European mean temperatures (Figure 4.4; left panels) as well as precipitation amounts (Figure 4.4; right panels). Interestingly, the European mean temperature and precipitation of some SLP clusters appear to have moved towards generally warmer and wetter conditions over the past 250 years. Using the Mann-Kendall trend test, the positive trends of the 1750-2000 period were found to be statistically significant at p <0.05 (0.01) for clusters 3, 5 and 7 (4) for temperature and at p <0.05 for clusters 3, 4 and 6 for precipitation, respectively. However, when only considering the period 1900-2000 where the most pronounced changes are found (Figure 4.4), none of the clusters shows a significant (p <0.05) trend. This highlights the strong dependence of trends on the length of the considered period as well as on the starting point of the presumed trend (e.g. Percival and Rothrock, 2005; Matti et al., 2009). Nevertheless, these findings demonstrate that the temperature and precipitation fields corresponding

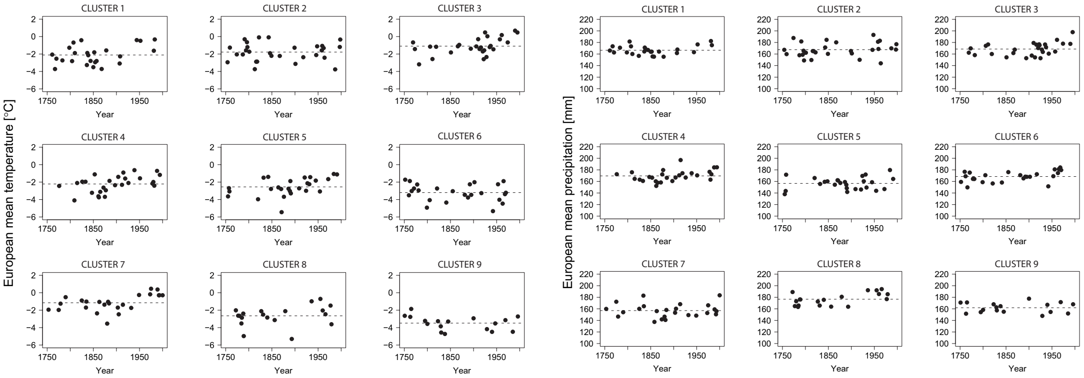

Figure 4.4: *Field averaged European winter mean temperature (Luterbacher et al., 2007, left) and precipitation (Pauling et al., 2006, right) for each SLP cluster and member. The dashed horizontal lines indicate the mean temperature and precipitation for each cluster, respectively.*

to a particular SLP pattern change their characteristics over time, i.e. they show important within-type variations. The deviations in temperature and precipitation from their respective long-term mean (Figure 4.4) appear to be largest during the last few decades. This agrees well with the study by Beck et al. (2007) who found for January and Central Europe that changes related to within-type variations became predominant over frequency related changes around 1860 for temperature and around 1900 for precipitation.

However, bearing the high spatial variability of particularly precipitation in mind (see Figure 4.2), it is problematic to only consider spatial means. We therefore focus next on the spatial changes in circulation-climate relationship over Europe by calculating for fifty-year periods and each of the nine clusters scaled mean anomaly composites of the European temperature (Figure 4.5) and precipitation (Figure 4.6) fields. Due to the length of fifty years, interannual or interdecadal variations as shown in Figure 4.4 cannot be detected. However, this length allows having for most clusters a large enough sample to make quantitative statements.

Figure 4.5 shows the scaled mean anomaly composites of the European temperature field over 50-year periods, with the green contour lines indicating significance at the 95% level. Important spatio-temporal temperature variations are found for all nine clusters, demonstrating that all clusters are subject to considerable within-type variations. Furthermore, the derived 50-year composites are only statistically significant for some regions and clusters (green contour lines in Figure 4.5), indicating that even within the fifty-year periods important changes in the characteristics of the temperature field corresponding to a particular SLP pattern take place. Nevertheless, the general tendency towards warmer conditions already found for the European mean temperature (Figure 4.4; left panels) can also be detected in Figure 4.5. Furthermore, the most recent fifty years (Figure 4.5; right column) appear to be the overall warmest for most clusters. The degree of warming is however spatially very diverse: while clusters 1, 5 and 7 appear to have become warmer mostly over Scandinavia and

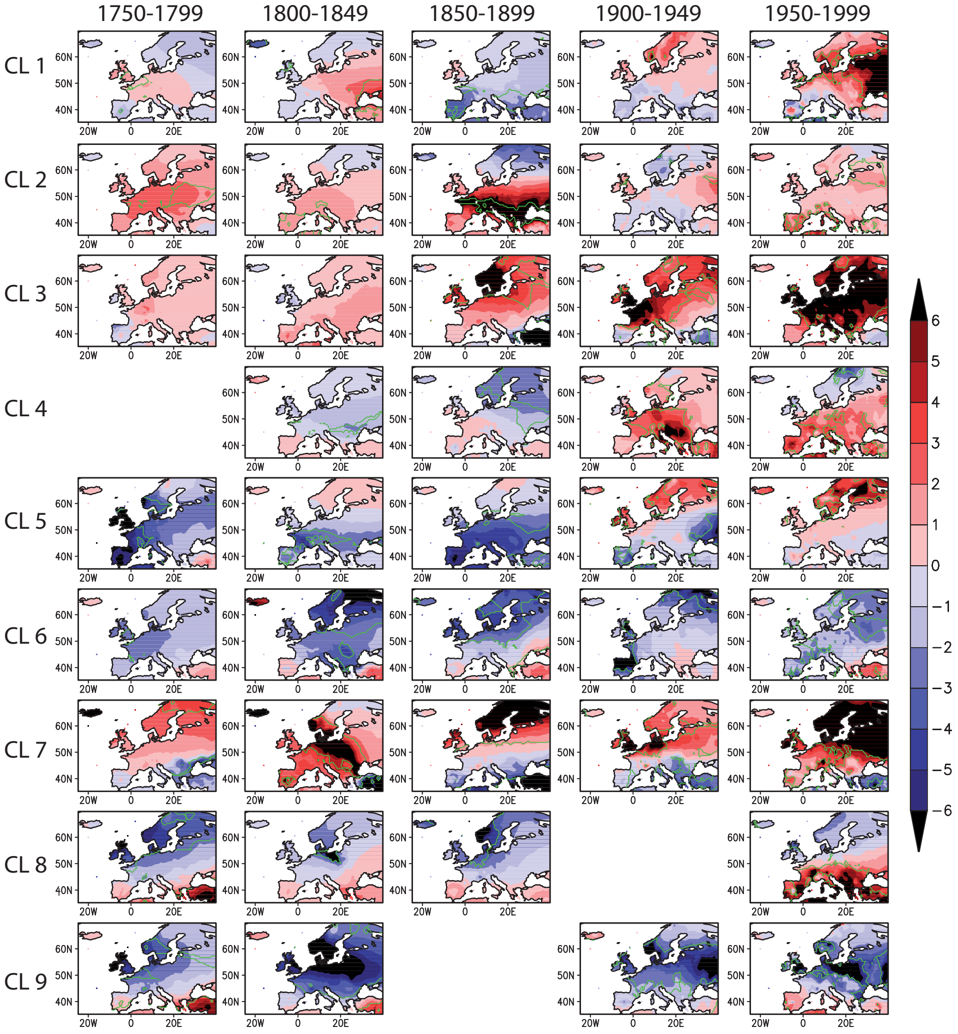

Figure 4.5: *50-year scaled mean anomaly composites (wrt 1750-2000; Brown and Hall 1999) of the temperature reconstruction by Luterbacher et al. (2007) split according to the nine winter SLP clusters derived from Küttel et al. (2009, chapter 3). The green lines indicate significance at the 95% level using the modified t-test by Brown and Hall (1999). Blank fields represent periods where a particular SLP cluster is only once or never found, not allowing the calculation of scaled mean anomaly composites. The units are arbitrary.*

Eastern Europe / Western Russia, clusters 4 and 8 warmed most over Central Europe and the Mediterranean (Figure 4.5). Since a warming is found for zonal, half-meridional as well as meridional patterns, it cannot be concluded that the warming is restricted to a particular circulation type.

The multidecadal changes in the SLP-precipitation relationship are shown in Figure 4.6. As for temperature, considerable temporal and spatial changes in the precipitation fields related to a particular SLP pattern are found. Due to the heterogeneity of the European precipitation field, the tendency towards overall wetter conditions found in Figure 4.4 (right panels) for the European mean can hardly be detected in Figure 4.6. At most, it might be speculated that some parts of Europe have become wetter in 1950-1999, as e.g. Scandinavia in cluster 3 or Central and Western Europe in cluster 8. Therefore, it can only be stated that the general precipitation pattern found over 1750-2000 (Figure 4.2) is maintained in most clusters with, however, considerable changes in the precipitation amounts (e.g. clusters 3, 5 and 7 during 1850-1899). Within-type variations are therefore also clearly detected for precipitation.

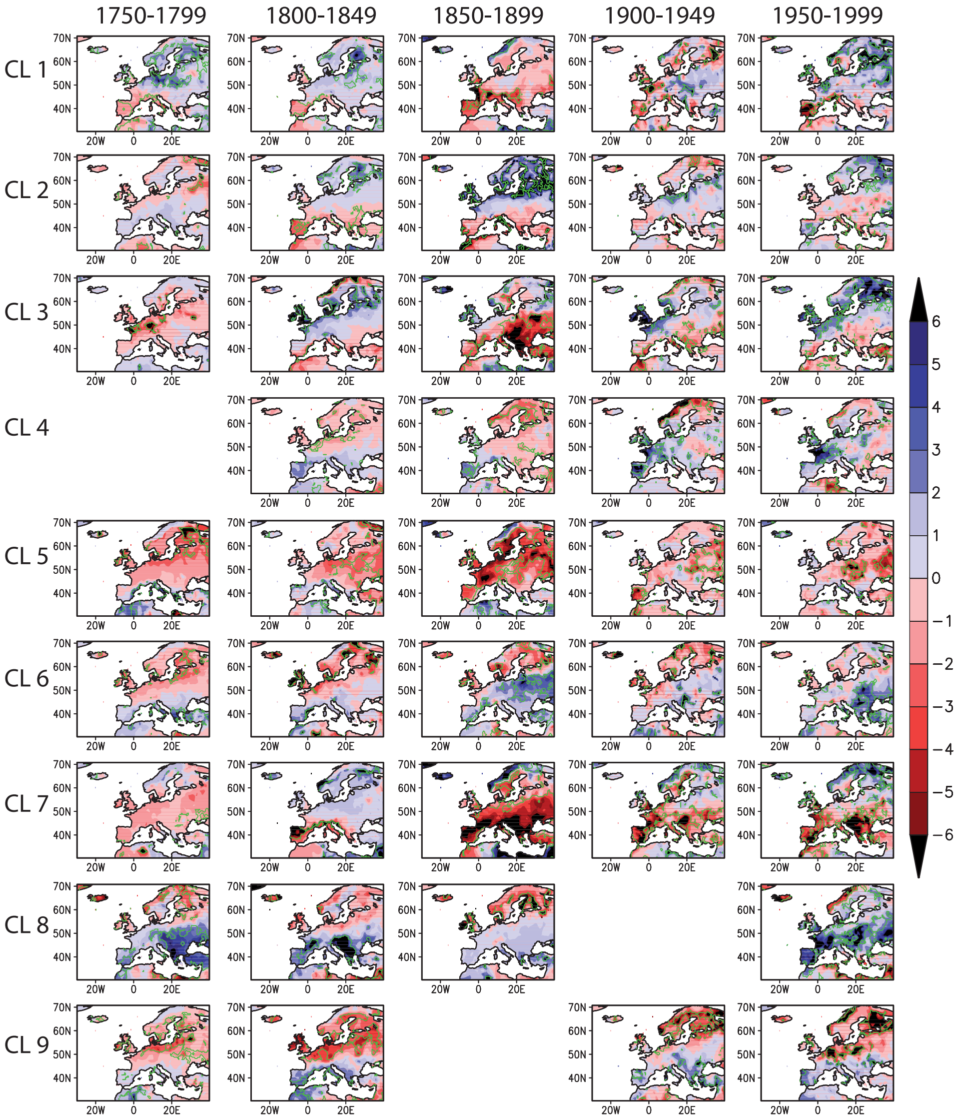

Figure 4.6: *As Figure 4.5 but for the precipitation reconstruction by Pauling et al. (2006).*

4.4.3 Decomposing multidecadal temperature and precipitation variations

The above presented results have indicated that large parts of the changes in the relationship between the SLP clusters and the European temperature and precipitation fields might be due to within-type variations. In order to make quantitative statements the decomposition method by Barry and Perry (1973) is applied to the 50-year averaged temperature (Figure 4.5) and precipitation (Figure 4.6) fields (see section 4.3 for details). Here, only the temperature and precipitation differences between the 1950-1999 average and the averages of all preceding 50-year periods are investigated. The results obtained for temperature are shown in Figure 4.7, those for precipitation in Figure 4.8. The estimations of the percentage of temperature and precipitation changes due to frequency and due to within-type related variations (greyish contour lines in Figures 4.7 and 4.8) are based on the corresponding absolute values.

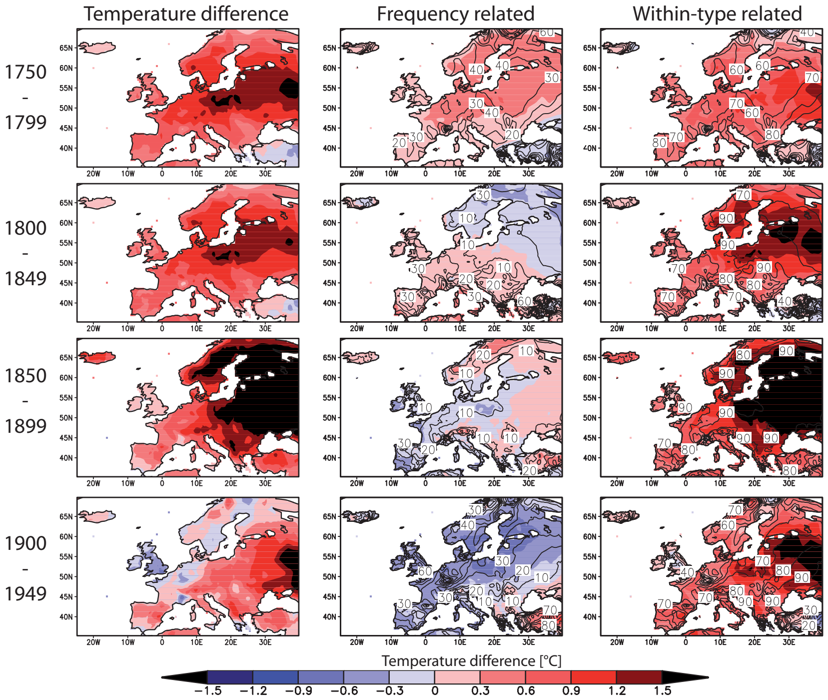

Figure 4.7: *Absolute temperature difference (first column), temperature difference due to variations in SLP cluster frequency (second column) and due to within-type variations of the SLP clusters (third column) between the 1950-1999 average and preceding 50-year periods (rows). Reddish (bluish) colours indicate that the winters 1950-1999 were on average warmer (colder) than the preceding 50-year period. The greyish contours and labels indicate the percentage of the absolute temperature change which can be attributed to the cluster frequency and within-type variations, respectively. The darker the contour lines, the higher the percentage.*

The 1950-1999 average was in almost all parts of Europe warmer than in the preceding 50-year periods, particularly when compared with 1850-1899 (Figure 4.7; left column, see also Luterbacher et al. 2007). The multidecadal temperature changes due to variations in the frequency of SLP patterns (Figure 4.7; centre column) are generally small and even led to overall cooler conditions during 1950-1999 compared with 1900-1949 (Figure 4.7; center column, bottom row). Frequency-related changes are only found dominant over some restricted regions of Europe, e.g. over the UK relative to 1900-1949 or over Turkey compared with 1800-1849. Accordingly, most of the multidecadal temperature changes are related with within-type variations with their contribution generally being well beyond 70% (Figure 4.7; right column). Within-type variations are particularly of importance over Eastern Europe and Scandinavia with percentages of up to 90%. However, important spatial and temporal changes are found for both sources of variations with the predominance of within-type variations generally being strongest comparing 1950-1999 with 1850-1899 and weakest compared with 1750-1799.

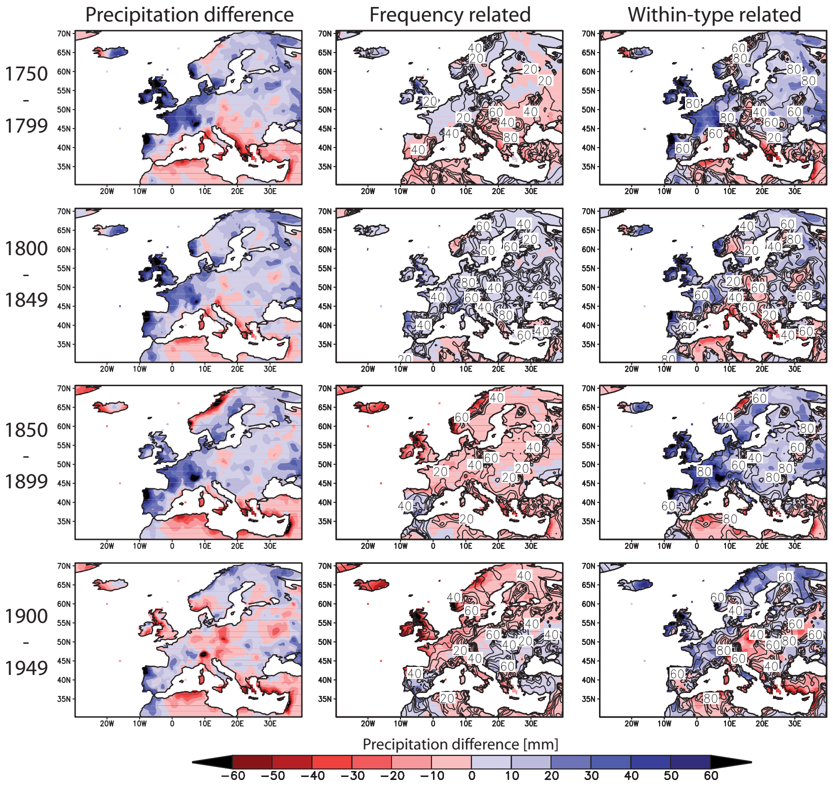

Figure 4.8: *As Figure 4.7 but for precipitation. Reddish (bluish) values indicate that the 1950-1999 average was drier (wetter) than the preceding 50-year period.*

The decomposition results for precipitation are shown in Figure 4.8. As found earlier (Figure 4.4, right panel), the 1950-1999 period appears to be overall wetter than the preceding 50-year periods (Figure 4.8, left column), however with important spatial and temporal differences. For example, the Scandinavian west coast was remarkably drier during 1950-1999 than during 1850-1899 (Figure 4.8, left column, third row). This might be related to a more frequent appearance of clusters 1 and 7 during 1850-1899 which are patterns related with anomalously westerly and northwesterly flow towards Europe (Figure 4.2) bringing humid air masses to western Scandinavia. Indeed, the center column of Figure 4.8 reveals that frequency-related variations in precipitation over western Scandinavia between 1850-1899 and 1950-1999 are dominating over within-type variations. Overall, the parts of European precipitation change due to frequency and due to within-type variations are more balanced than for temperature (Figure 4.7), with a slight dominance of within-type variations particularly over Eastern Europe / Western Russia.

4.5 Conclusions

We have used a recently developed clustering technique (Philipp et al., 2007) to classify the larger European/North Atlantic winter SLP fields 1750-2000 by Küttel et al. (2009, chapter 3) into nine representative patterns. Since this SLP reconstruction is fully independent from the European temperature and precipitation reconstructions by Luterbacher et al. (2007) and Pauling et al. (2006) it was dynamically investigated whether changes in European temperature and precipitation over the 1750-2000 period are due to variations in the frequencies or due to within-type modifications of the SLP clusters. This study builds on earlier works by e.g. Beck (2000), Jacobeit et al. (2003, 2009), Beck et al. (2007) or Jones and Lister (2009), however focusing on spatial differences and over a longer time period.

For most of the nine derived SLP clusters a tendency towards warmer and wetter conditions over Europe is detected, strongest over the most recent decades. This agrees well with studies who found that European winters became warmer and generally wetter during the last couple of decades (e.g. Klein Tank et al., 2002; Jones and Moberg, 2003; Luterbacher et al., 2004, 2007; Casty et al., 2005; Pauling et al., 2006). Using a decomposing scheme it could be shown that large parts of these changes cannot be related to variations in the frequency of the SLP patterns but must rather be attributed to within-type variations. This is particularly true for temperature where within-type variations generally explain 70% or more of the changes. Their contribution is particularly high over Eastern Europe and Scandinavia with percentages of up to 90%. The results are more balanced for precipitation with, however, within-type variations being the dominant factor over Eastern Europe and Western Russia. These findings agree well with earlier studies, all pointing towards a predominance of within-type related variations over those due to frequency changes (e.g. Brinkmann, 1999; Beck, 2000; Yarnal et al., 2001; Jacobeit et al., 2003, 2009; Beck et al., 2007; Jones and Lister, 2009). However, it was shown that it is of importance to consider climate fields and not only spatial averages which tend to cancel the spatial variability. This is of particular importance for precipitation, which shows very distinct spatial differences.

The source of these within-type variations can be manifold. As shown in section 4.1, it may be distinguished between sources of dynamical and sources of climatic origin. As considers the former, the rather coarse 5° x 5° resolution of the SLP reconstruction by Küttel et al. (2009, chapter 3) might limits the proper representation of small-scale features of the atmospheric circulation. Indeed, Jones and Lister (2009) found that subgrid-scale effects originating from orography or land-sea contrast can strongly contribute to within-type variations. As a further source of dynamical within-type variations, it was found in this study that the pressure gradient between the Azores High and the Icelandic Low has slightly increased during the last few decades (not shown), leading to stronger westerlies over Europe which might be related to the found overall warming and wetting of Europe during winter. However, this increase is small and not found for all SLP clusters (not shown), agreeing with the study by Beck et al. (2007) who found an increase in the intensity of some Grosswetterlagen over the last few decades, which however cannot fully explain the changes in Central European temperature and precipitation. Another source of (dynamical and climatic) within-type variations in this study might be considered artificial, originating from the uncertainties of the SLP, temperature and precipitation reconstructions. However, within-type variations were found to be of equal or even higher importance during the latest decades where the reconstructions might be considered to be very reliable. Besides these dynamical and 'artificial' within-type variations, it must be assumed that significant parts of the found within-type variations also originate from changed climatic boundaries. As was suggested by Stahl et al. (2006), these climatic changes might stem from internal oscillations such as the El Niño Southern Oscillation (ENSO) which, through teleconnections, might change the climatic boundary conditions over Europe (e.g. Brönnimann et al., 2007). Parker (2009) recently demonstrated for central England temperatures that increased SSTs can also significantly contribute to within-type variations. However, results showed that within-type variations are important in all SLP patterns, i.e. also those related with advection from predominantly continental areas. Finally, these climatic within-type variations might also be related with an increased forcing due to anthropogenic emissions (e.g. IPCC, 2007). This important issue was however not investigated here, should however be addressed in future studies.

Acknowledgments

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Chapter 5

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 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.

5.1 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 and Moberg, 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, Padua 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 back 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., 2009) and one for Stockholm (Leijonhufvud et al., 2009) 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. Trenberth, 1990, 1995; Hurrell, 1995; Hurrell and Van Loon, 1997; Jacobeit et al., 2001; Slonosky et al., 2001; Luterbacher et al., 2002; 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 at 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).

5.2 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 Dobrovolný et al. (2009) 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 January-April (JFMA) season.

5.2.1 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 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 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. 2009) and the growth of urban heat islands (Dobrovolný et al. 2009).
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 it with contemporary series at 15 locations in the Netherlands (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 (Camuffo, 1984, 2002a,b,c; Brunetti et al., 2001; Cocheo and Camuffo, 2002; Maugeri et al., 2002a,b, 2004), Florence and Vallombrosa (Camuffo et al. 2009). The original data have been corrected for instrumental errors, observation 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 from Stockholm and St. Petersburg and the shorter series from 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. The years 1790-1799, 1808-1828 and 1886-1914 have been established as being non-homogeneous. 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.

5.2.2 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.

i) **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 to 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 the use of linear regression for the quantification of 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. 2009).

iii) **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. Comparison of 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).

iv) **Northern Italy** (1500-1759): Indices are derived from the analysis of 70 contemporary documentary sources. The considered 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. (2009).

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. 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 statistical regression model has been calculated fitting the proxy information 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).

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.

5.2.3 Gridded SLP

We used the new 5° x 5° gridded seasonally resolved SLP dataset produced by Küttel et al. (2009, chapter 3). 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 HadSLP2 data (Allan and Ansell, 2006) over the period 1887-2001, with these models then applied to the available data during the 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, chapter 3 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.

5.2.4 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.

ECBilt-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) 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 3° x 3° and it has 20 unevenly spaced layers in the vertical.

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° x 2.8° 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 (González-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.

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.

5.3 Methods

5.3.1 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 CEu), Northern Europe (Stockholm and Tallinn) and Southern Europe (Padua). 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.

5.3.2 Canonical correlation analysis

To assess the connection between the gridded large-scale SLP data of Küttel et al. (2009, chapter 3) 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 et al., 1999; Wilks, 2005). It has been used extensively throughout the meteorological and climatological literature (e.g. Graham et al., 1987; Nicholls, 1987; Zorita et al., 1992; González-Rouco et al., 2000; Dünkeloh and Jacobeit, 2003; Xoplaki et al., 2003). 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, chapter 3) 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 determines how many PCs are 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 as 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 randomized 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 the long-term trends in the temperature and MSLP series.

5.3.3 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 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). 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, chapter 3) is used as input to ECBilt-Clio. We use the technique to illustrate, for two selected years (1817 and 1829) anomalous patterns of simulated temperature, snow depth, albedo and precipitation.

5.3.4 Analog case search for large-scale SLP fields based on anomalous European temperatures

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) are 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; Luterbacher et al. 2002; Küttel et al. 2009, chapter 3). 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. Glaser et al., 1999; Brázdil et al., 2005; Dobrovolný et al., 2008, 2009). 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.

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, chapter 3), 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. 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 the 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 (González-Rouco et al., 2006, 2009) 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.

5.4 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 the 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.

5.4.1 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 Figures 5.1 and 5.2). Further, the major circulation patterns and variances explained are similar for Padua and Central Europe, therefore we only present the maps for Central Europe. Warm anomalies in Central Europe (Figure 5.1; left) are connected with a northeastward extension of the Azores High. In the case of Northern Europe (Figure 5.1; right) the anticyclonic centre is shifted up to southwest England thus inducing a mixed circulation pattern (between zonal and meridional configurations).

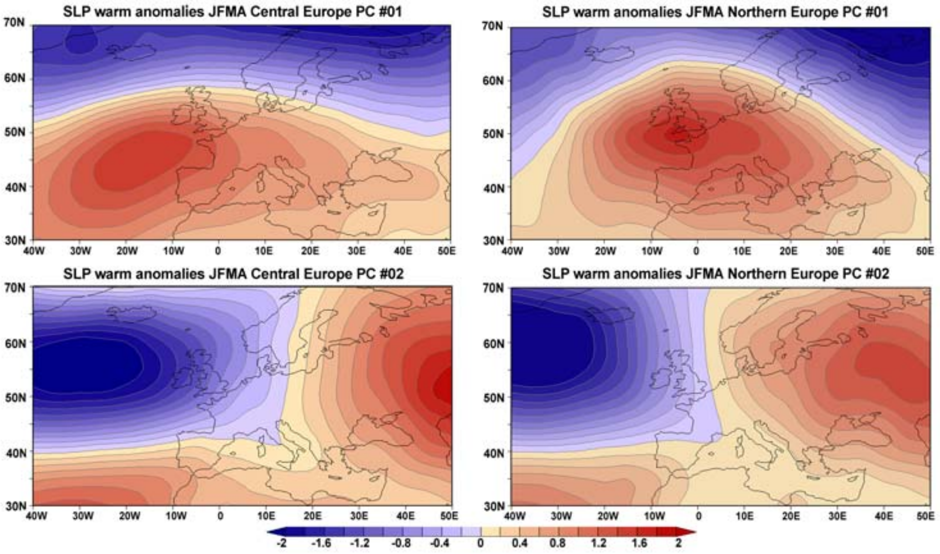


Figure 5.1: *Major circulation patterns associated with warm JFMA seasons in Central Europe (left) and Northern Europe (right) over the 1760-2007 period, derived from objectively reconstructed SLP fields according to the procedure developed in Jacobeit et al. 1998 (normalized T-mode PCA scores). Explained variance for the two PCs (Central Europe) is 61.3% and 34.1%, for Northern Europe it is 39.2% and 35.6%.*

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 Padua (not shown) and distinctly shifted westward for Northern Europe (Figure 5.1). 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 (Figure 5.2) 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., 2001, 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

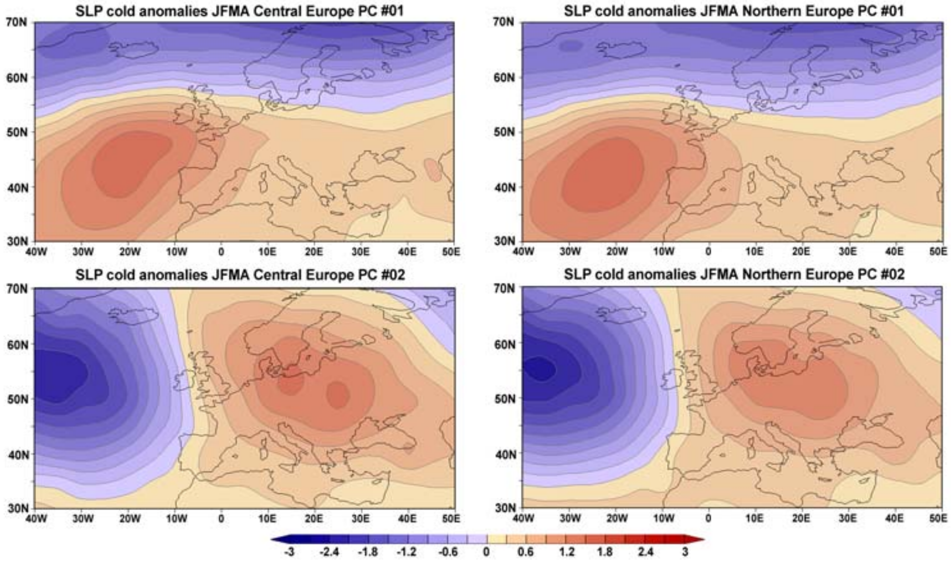


Figure 5.2: *as Figure 5.1, but for cold JFMA seasons in Central Europe (left) and Northern Europe (right). Explained variance for the two PCs (Central Europe) is 32.9% and 32.1%, in the case of Northern Europe it is 41.0% and 33.2%.*

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 (Philipp et al., 2007; Jacobeit et al., 2009) 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.

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

We extend the analysis of results from the previous section 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 Figure 5.3.

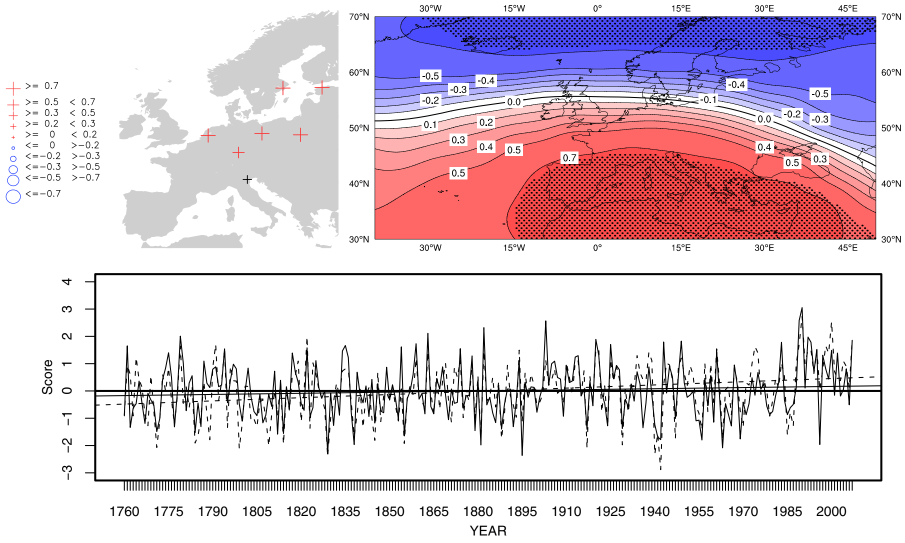


Figure 5.3: *The first CCA between JFMA mean SLP and the seven temperature stations over the period 1760-2007. Top left: the JFMA temperature canonical pattern for the seven stations. Top right: the SLP canonical pattern, bottom: the canonical score series from 1760-2007. Red (blue) areas indicate positive (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 detrended according to the 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).*

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 strong westerly flow is responsible for the significant positive temperature anomalies at six of seven stations. The scores in Figure 5.3 (bottom, dashed straight line) indicate a 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 and Wang (2005). The variance that is explained by the second CCA pattern (not shown) is 4% for SLP and 5% for temperature. The second canonical map of SLP shows 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 Padua (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 Figures 5.1 and 5.2 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).

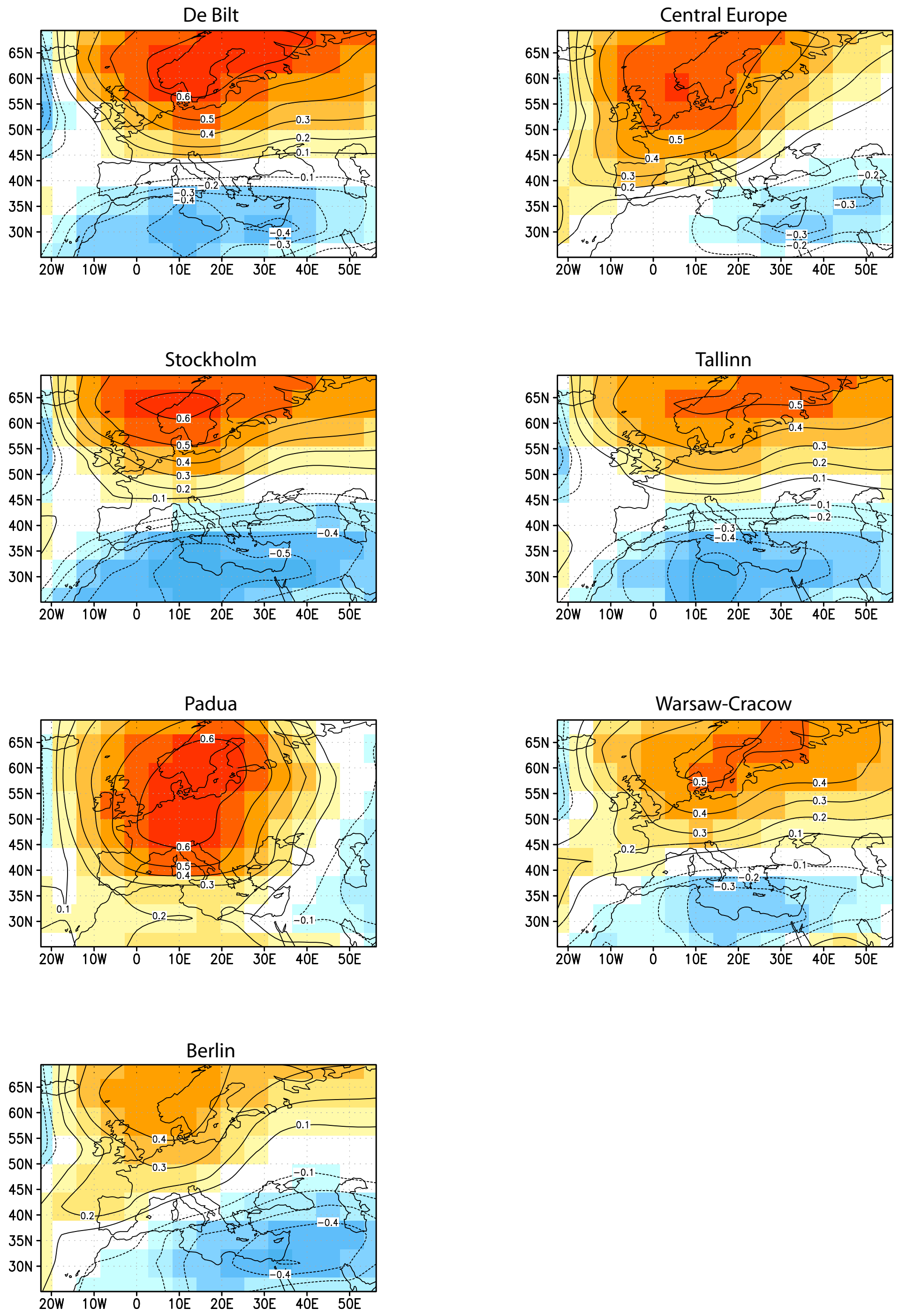
5.4.3 Assimilation of the SLP reconstruction in a simplified GCM

The assimilation method described above is used here to simulate a climatic trajectory for which the atmospheric circulation, averaged over JFMA is close to the present SLP reconstruction (Küttel et al., 2009, chapter 3). 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 5.4 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 (Figure 5.4), 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 variations 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 Figure 5.5.

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, Figure 5.6) is the warm winter after the Tambora eruption in April 1815. The second winter (1829, Figure 5.7) 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 determining 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.



De Bilt

Central Europe

Stockholm

Tallinn

Padua

Warsaw-Cracow

Berlin

Figure 5.4: *Temporal correlations between the simulated 2m temperature, averaged over JFMA, and the instrumental records from De Bilt, Central Europe, Stockholm, Tallinn, Padua, 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.*

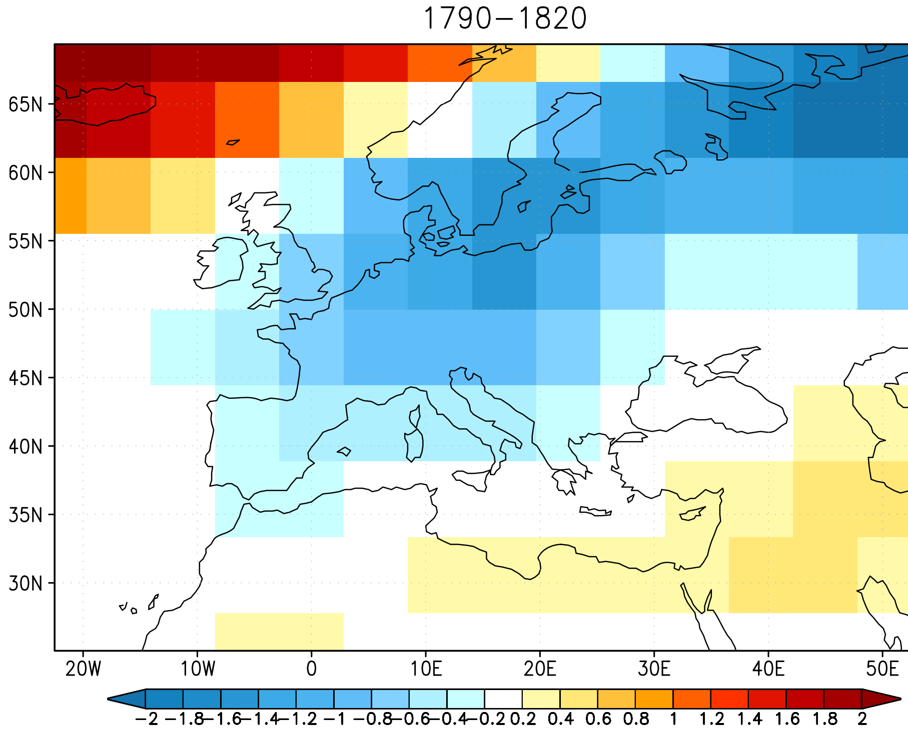


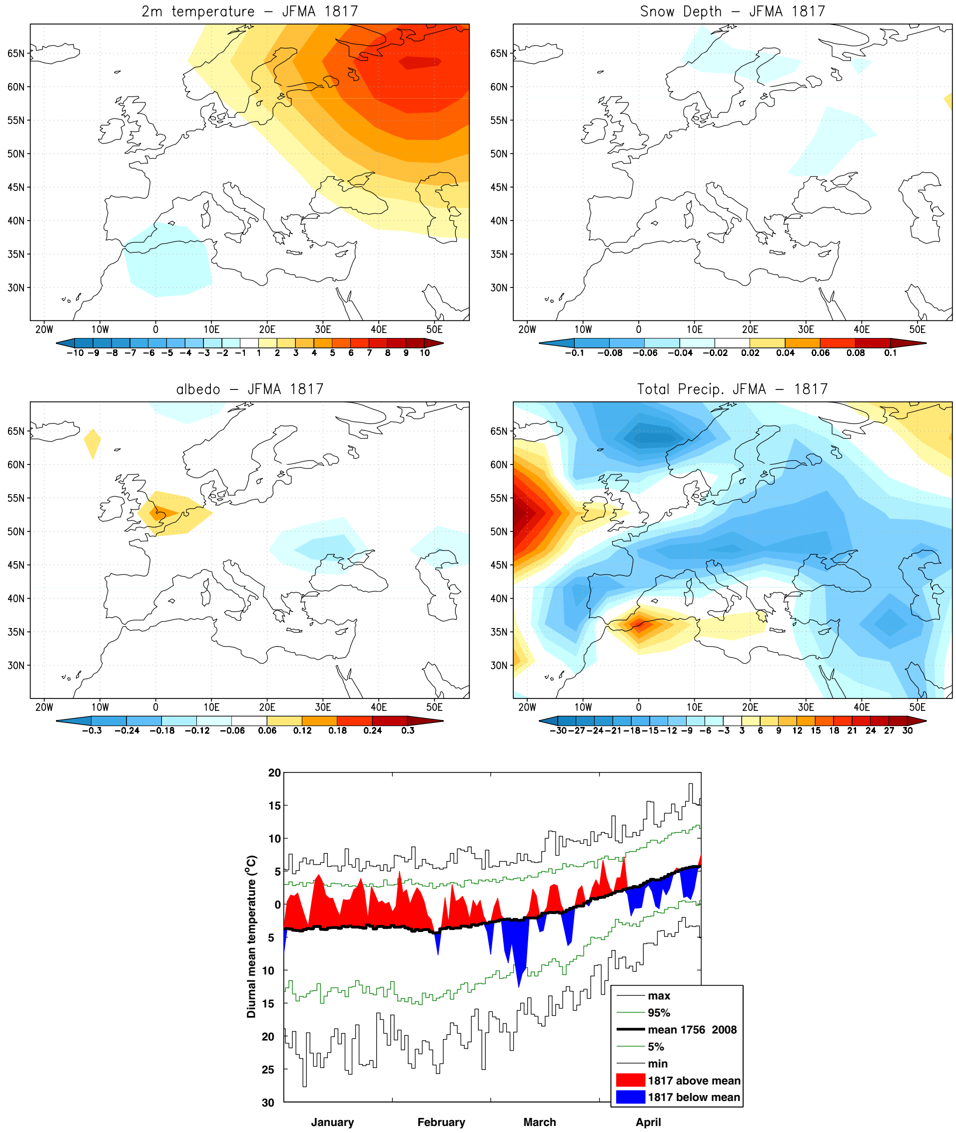
Figure 5.5: *Assimilated anomalous 2m temperature for the JFMA season in degrees Celsius according to the data assimilation experiment, averaged over the years 1790-1820, as a deviation from the reference period 1961-1990.*

A consistent result between observed and simulated 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 5.6 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 (Luterbacher et al., 2004; Xoplaki et al., 2005; Fischer et al., 2007; Zerefos et al., 2007; Trigo et al., 2009). The simulated 2m temperature (Figure 5.6) over the area 40°N-67.5°N and 0°-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).



2m temperature − JFMA 1817

Snow Depth − JFMA 1817

albedo − JFMA 1817

Total Precip. JFMA − 1817

Figure 5.6: *Top panels: 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. Bottom panel: instrumental temperature series from Stockholm for January-April 1817.*

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 phenology 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 (Figure 5.6; 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 5.7 shows the anomalous fields of 2m temperature, albedo, snow depth and precipitation as simulated for the anomalously cold JFMA season of the year 1829.

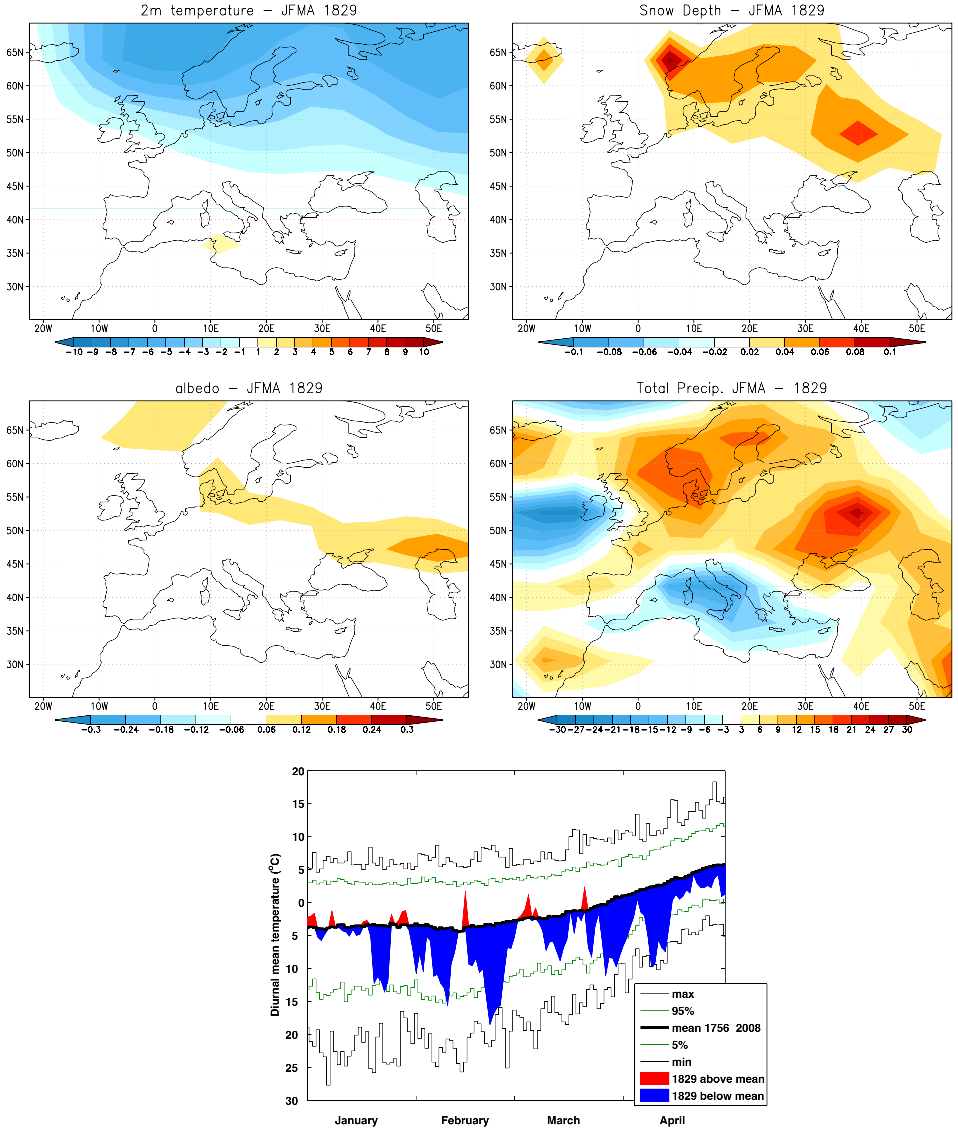


Figure 5.7: *As Figure 5.6 but for 1829.*

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 (Figure 5.7; 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 Alpine Switzerland (Holopainen et al., 2006; Rutishauser et al., 2009) an indication of distinctive lower temperature in wide spread Europe.

These examples (Figures 5.6 and 5.7) 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.

5.4.4 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 (Moberg et al., 2002; Leijonhufvud et al., 2008, 2009) and CEu temperature (Dobrovolný et al. 2009) can be considered as representative to cover broad regions of Europe (Figure 5.8; see also Zorita et al. 2009).

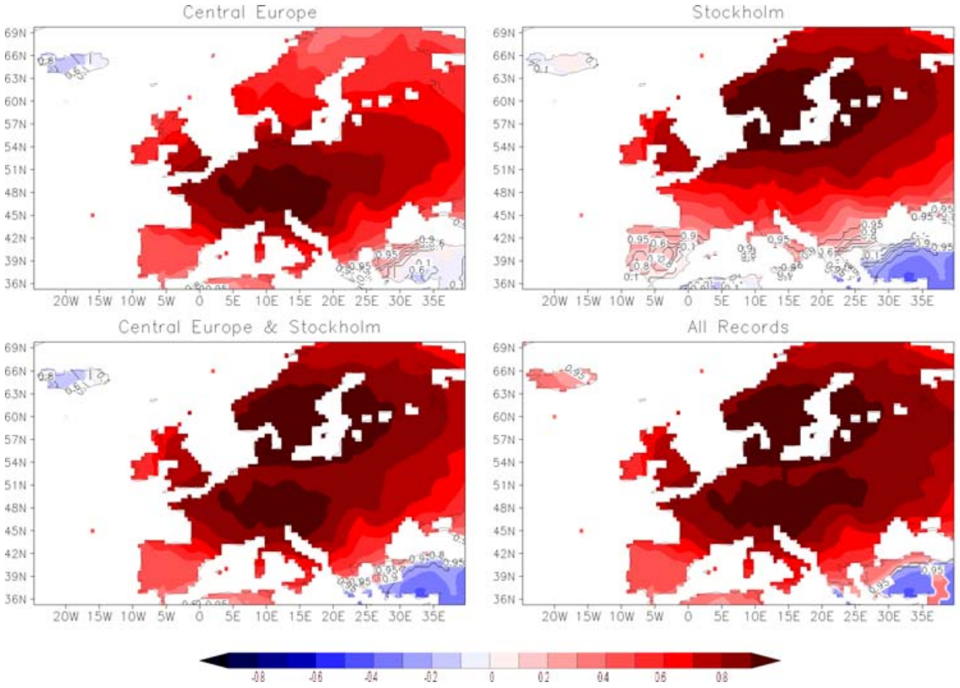


Figure 5.8: *Spatial representativity for selected documentary records for Central Europe (top left) and Stockholm (top right), their combination (lower left), and all seven documentary series for JFMA being considered (lower right). The values are expressed in grid point squared correlation coefficients 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.*

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 5.1 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.

Table 5.1: *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.*

Period	Year AD
pre-instrumental (1500-1759)	1569, 1573, 1586, 1595, 1600, 1601, 1614,1658, 1663, 1684, 1685, 1688, 1692
instrumental (1760-2006)	**1784, 1785, 1799, 1808, 1829, 1838, 1839, 1847, 1853, 1888, 1917, 1940, 1942, 1963**

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 Erik 2 simulation and 19 cold years for the 500-year long HadCM3 simulation.

Anomalous European cold composite analysis

Figure 5.9 presents anomaly (1961 to 1990 average subtracted) composites of SLP (Küttel et al., 2009, chapter 3), 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.

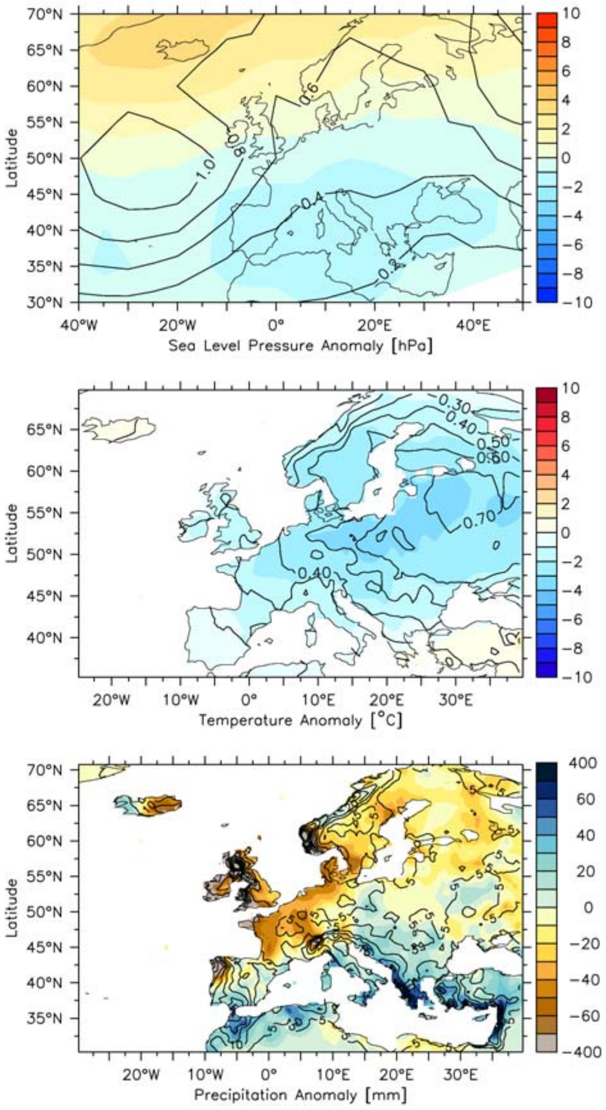


Figure 5.9: *Anomaly composites (with respect to the 1961-1990 reference period) of selected extreme cold winters with corresponding standard deviation for the post-1759 period. SLP (top), temperature (center), and precipitation (bottom). The contours represent the standard deviation divided by the square root of the number of extreme cases that are averaged in the composite.*

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, 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 over the Mediterranean. The results of the analog case search also show that certain assimilated anomalous winters mentioned previously (e.g. winter 1829, Figure 5.7) 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 (Figure 5.10) are in good agreement with the anomaly composite presented in Figure 5.9.

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

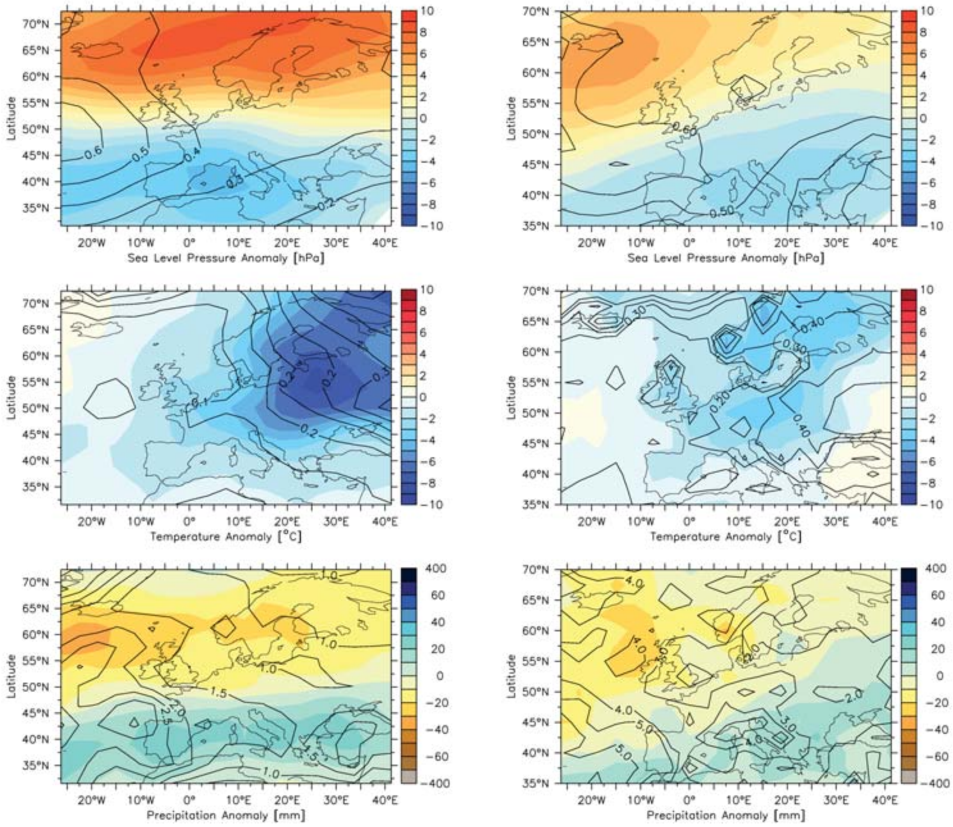


Figure 5.10: *As Figure 5.9, but for ECHO-G Erik 2 (left) and HadCM3 (right).*

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.

5.5 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, chapter 3). 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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Chapter 6

Concluding remarks

In order to put the recently observed warming at regional to global scale into a historical context, it is of great importance to extend our knowledge on past climate variability as far back in time as possible. This is particularly true for the local to regional scale where the socially, ecologically and economically relevant processes take place.

The wealth of long instrumental measurements as well as high-quality proxy series from various sources makes Europe a unique place to obtain temporally and spatially highly resolved reconstructions of past climate. Embedded in the NCCR Climate project PALVAREX 2, this thesis addresses various aspects of European climate dynamics over the past centuries. Firstly, the reliability of an existing, highly resolved gridded European winter temperature reconstruction back to 1500 is assessed in the surrogate climate of two AOGCMs. Secondly a new SLP field reconstruction based on instrumental pressure series and wind information from ship logbooks is presented. This marks the first attempt to combine these terrestrial and marine sources. Thirdly, since this SLP reconstruction is fully independent from existing temperature and precipitation reconstructions, dynamical studies relating climate variations during winter (DJF) to the state of the atmosphere can be performed back to 1750. Finally, the derived SLP reconstruction is recalculated to cover January-April (JFMA) and is used in various methodological approaches to relate changes in European JFMA climate to the large-scale atmospheric circulation. This should help to shed some light on the driving factors behind past and current changes in European climate.

Robustness of a European winter temperature reconstruction

Over the last couple of years, climate simulations have become increasingly realistic allowing to use AOGCMs as a surrogate climate to test the reliability of existing real-world climate reconstructions. While this approach has been widely used to evaluate reconstructions of past hemispheric temperatures, we here present the first application on continental scale by testing a European winter temperature reconstruction covering 1500-2000. To reduce the dependence on the climate model considered, two AOGCMs are used as testing ground.

Results indicate that European winter temperatures can be reliably reconstructed back to the mid-18th century. With the number of available instrumental series rapidly diminishing further back in time, the skill of the reconstruction becomes strongly dependent on the quality and spatial availability of indirect information from documentary and natural proxies. Accordingly, the variability of the simulated European mean temperature is significantly underestimated by the reconstruction prior to ∼1750. Investigating the spatial origin of these uncertainties, it is found that they mainly stem from Scandinavia where no predictors are available prior to the mid-18th century. The addition of one artificial predictor in this region for the period 1500-1750 leads to a considerable increase in reconstruction skill over Scandinavia, thereby significantly reducing the underestimations of the European mean temperatures prior to 1750. This means, that the spatial distribution of the predictors is the key factor determining the reconstruction skill. The quality of the predictors is accordingly only of subordinate importance, however being of relevance in real world settings which usually suffer from spatially insuffіcent predictor networks. This example strongly supports the value of using AOGCMs as a surrogate climate to test various aspects of real world reconstructions. It is therefore recommended that such experiments should become part of every reconstruction.

Using ship logbooks to derive a fully independent SLP reconstruction

So far, reconstructions of the large-scale European and North Atlantic atmospheric circulation have mainly relied on instrumental and proxy information from terrestrial regions. Accordingly, these reconstructions show decreased skill over the marine North Atlantic and therefore represent Azores High and Icelandic Low only insufficiently. Furthermore, currently available reconstructions are mostly not independent from European temperature and precipitation reconstructions since they share common predictors, leading to circular reasoning in dynamical studies.

The CLIWOC project significantly improved the data availability over the world's oceans by exploring and digitizing numerous ship logbooks from the colonial powers of Europe. Here, a new, fully independent and seasonally resolved reconstruction of North Atlantic, European and Mediterranean SLP fields back to 1750 is presented by combining marine wind information from CLIWOC with terrestrial instrumental pressure series. Compared to existing reconstructions relying on terrestrial information only, enhanced skill is found over the marine North Atlantic and particularly during winter season. Therefore, the position and strength of the atmospheric centers of action driving weather and climate downstream can now be estimated more accurately. However, reduced skill is obtained for summer season which might be attributed to the smaller pressure gradients prevailing during this season. Nevertheless, it can be concluded that wind information derived from ship logbooks is a very reliable and valuable direct source on past atmospheric circulation. With the great number of yet to be explored and digitized logbooks located in European archives and elsewhere, this data source has an immense potential to increase our knowledge of the state of the large-scale atmospheric circulation over the past centuries. Furthermore, since wind information from ship logbooks have not been included in any European temperature or precipitation reconstructions, dynamical studies relating past and current changes to the state of the atmosphere can now be conducted back to 1750 without the issue of circular reasoning.

Relating European winter climate variability to the state of the atmosphere

Based on the knowledge that particularly European winter climate is strongly coupled to the state of the atmospheric circulation, it is investigated how this relationship has changed over the past 250 years. For this purpose, the larger North Atlantic and European SLP field reconstruction presented in this thesis is used, however only considering winter season where the highest skill is found. While earlier studies focused on the changes in the connection between the large-scale atmospheric circulation and climate averaged over a geographical region, this study investigates the spatial changes using highly resolved and independent reconstructions of the past European temperature and precipitation fields.

Applying a recently developed clustering technique, nine very robust SLP clusters are obtained for the winters 1750-2000. These patterns can be distinguished as either being more zonally, half-meridional or meridional oriented. Accordingly, the SLP clusters are related with specific European temperature and precipitation fields. Although there exist important changes in the frequency of the SLP clusters with some being found absent for up to sixty years, no significant long-term trends are found for any cluster. Furthermore, periods found to be anomalously warm/cold or wet/dry do not generally coincidence with the more frequent appearance of corresponding SLP clusters. Therefore, changes in European climate cannot only be related to changes in the *frequency* of the SLP patterns but also to so-called *within-type variations*. The latter means that a particular SLP field can be related to considerably different temperature and precipitation fields.

Investigating how the temperature and precipitation field during a particular SLP cluster has changed over time (i.e. within-type variations), it is found that winters in almost all SLP clusters have become warmer and generally wetter during the last 250 years. This tendency is strongest during the most recent decades. Using a decomposing technique to distinguish changes in European temperature and precipitation due to frequency and due to within-type variations of the SLP clusters it is revealed that roughly 70% (60%) of multidecadal changes in temperature (precipitation) can be attributed to within-type variations. Important spatial differences are however found with within-type variations explaining up to 90% of the long-term changes in climate over Eastern Europe and Scandinavia.

It can only be speculated about the the origin of these within-type variations. One reason could be that important small-scale features of the atmospheric circulation are not captured by the 5° x 5° resolution of the SLP reconstruction. Furthermore, it is found that the pressure gradient between the Azores High and the Icelandic Low has slightly increased over the last few decades in some of the SLP clusters. The resulting enhanced westerly flow might partly explains the found tendency towards warmer and more humid conditions over Europe. This very important issue should however be investigated in more detail in future studies.

Circulation dynamics and changes in European January-April climate

Using the SLP reconstruction developed in this thesis but extended to represent January-April (JFMA) season, different approaches are used to relate the changes in European JFMA climate to the state of the large-scale atmospheric circulation.

Results using T-mode principal component analysis (PCA) and canonical correlation analysis (CCA) indicate that extremely cold and warm JFMA seasons are related to particular SLP fields with, however, important within-type variations. For example, zonal circulation patterns can be connected with anomalously warm as well as cold conditions over Europe. It is suggested that radiative losses as well as small differences in the exact position and strength of the atmospheric centers of action contribute to these within-type variations. Furthermore, sub-types related with persistent cold or warm conditions might occur within a JFMA season but are too short-lived to be resolved in the seasonal mean SLP field.

The use of a data assimilation approach gave more insights into the dynamics of past extremely cold or warm years, also pointing towards the importance of snow cover as an altering effect possibly being an important source of within-type variations. Being confined by real world climatic boundaries from reanalyses or reconstructions, data assimilation techniques have proven to be of great use in gaining more insights into the dynamics and influences of various climatic variables not being resolved by real world data sets.

Finally, the analog case technique has been introduced and successfully applied in real world settings as well as within two AOGCMs. This method bears great potential to extend SLP reconstructions well beyond the period with widespread instrumental availability.

Concluding, it can be stated that the application of different techniques gives in a combined way more insights into the dynamics behind past European climate variability than would any of the approaches yield by itself.

Chapter 7

Outlook

This PhD thesis contributes to an enhanced understanding of European climate variability by addressing and reducing uncertainties in currently available climate reconstructions as well as by investigating the dynamical forcing behind European climate variations over the past centuries. As emphasized throughout this thesis there are many important aspects of past climate variability which need to be addressed in future research. In this chapter a few of them are listed and shortly discussed.

Rescue, digitize and homogenize more instrumental and semi-instrumental data

Instrumental data are the most precise and reliable information on past climate, being the only source which records variables like temperature, precipitation or sea level pressure directly. In archives spread across the entire globe there exist numerous yet to be explored and digitized instrumental series going as far back in time as the early 17th century. There are currently several ongoing international initiatives on this topic like the Atmospheric Circulation Reconstructions over the Earth (ACRE; *http://www.met-acre.org*) or the MEditerranean climate DAta REscue (MEDARE; *http://www.omm.urv.cat/MEDARE*) projects which should significantly improve the data availability within the next couple of years. Besides exploring and digitizing the data, these initiatives also focus on the essential part of homogenizing these series. A particular focus should thereby be to increase the data availability over currently underrepresented areas like Africa but also to rescue data from the vertical dimension (e.g. Brönnimann, 2003). As shown in this thesis, semi-instrumental information from ship logbooks are a very promising and valuable source on past climatic conditions in and above the world's oceans. However, the CLIWOC project only explored about 5% of logbooks in British Archives (García-Herrera et al., 2005). Recent efforts by Wheeler and Suarez-Dominguez (2006) as well as Wheeler et al. (2009) explored further semi-instrumental logbook data from the English Channel back to 1685. In a pilot study of the RECovery of Logbooks And International Marine data (RECLAIM; *http://icoads.noaa.gov/reclaim*) project, Brohan et al. (2009) made 1,500,000 instrumental measurements of SST, SLP and other variables from the period 1938-1947 available, significantly increasing the data availability during the poorly covered Second World War period. The RECLAIM project should also yield additional data in the near future. Nevertheless there remain many thousand logbooks untouched which would be of great use in paleoclimatic research (see e.g. Wheeler and García-Herrera 2008 for an overview). Danish logbooks or logbooks from whaling fleets would be of particular use since they have the potential to significantly increase the data availability over the Arctic sea.

Explore new proxy sources from documentary as well as natural archives

Even if the instrumental and semi-instrumental data availability will hopefully be significantly increased within the next years, climate prior to the mid-19th century will still primarily have to be reconstructed from indirect proxy sources. As is the case for the instrumental data, there currently exist international projects focusing on proxy data (e.g. the European MILLENNIUM project; *http://geography.swansea.ac.uk/millennium*). As shown in this thesis, not only should more proxy data be retrieved but particularly from regions which are not yet well covered and which were found to be optimally located for reconstructions of past European climate. Very recently, Luterbacher et al. (2009) showed that the winter temperature and to a lesser degree also precipitation variations of the past 500 years over Poland are highly correlated to the temperature and precipitation evolution of the European mean. This means that proxy information from this region are particularly useful for reconstructions of European climate. In his attempt to detect optimally located sites to reconstruct the European precipitation field, Stössel (2008) also showed that it is not necessary to include all available proxy data when they stem from the same region as e.g. Central Europe. He found that this redundant information can actually *decrease* the reconstruction skill since they can outweigh relevant information from other regions of Europe.

Methodological improvements of reconstruction techniques

Over the last few years, further research has been conducted on testing different reconstruction techniques within the surrogate climate of AOGCMs but also in real world settings (e.g. Lee et al., 2008; Riedwyl et al., 2008, 2009). As shown earlier, the best method for all aspects of paleoclimatic reconstructions has yet be found. Therefore, more research in this direction is needed. A major challenge in reconstructing past climate using proxy data is the lack of knowledge of the structure of error inherent to proxy data. Without this knowledge, a reconstruction technique cannot properly account for these errors, leading to additional uncertainties in paleoclimatic reconstructions. As shown in Jones et al. (2009) there are currently efforts to better understand these errors in the various proxy sources. One promising approach is proxy forward modeling which attempts to quantify the different influences on a proxy by modeling the growth of e.g. speleothems (Kaufmann and Dreybrodt, 2004) or trees (Evans et al., 2006). Furthermore, within almost all reconstruction techniques parameters have to be chosen, e.g. how many principal components should be included, over which period the calibration should be performed, or at which level the convergence criterion is assumed to be fulfilled (RegEM). Since reconstructions are quite sensitive to these parameters, they should be chosen very carefully, demanding extensive testing in modeling as we well as real world settings.

Determine sources of within-type variations in dynamical studies

As confirmed in this thesis, within-type variations are a major part explaining changes in the relationship between the large-scale atmospheric circulation and climate. However, it has mostly to be speculated about the specific origin of these variations. Future research should therefore try to distinguish the various sources, particularly to separate those of dynamic origin (e.g. increased pressure gradient) from those of climatic origin (e.g. changed climatic boundary). For example, it would be worthwhile to assess how the variations in the Atlantic Multidecadal Oscillation (AMO) contribute to these within-type variations. Modeling approaches including data assimilation (e.g. van der Schrier and Barkmeijer, 2005) as well as detection and attribution studies would also help to gain more insights into the origin of within-type variations, particularly as also considers the forcing due to greenhouse gas emissions (e.g. Hegerl et al., 2006).

This thesis has exclusively focused on past climate variability across the larger North Atlantic and European realm. However, such studies have been and should be performed in other parts of the world, particularly on the socially, ecologically and economically relevant local to regional scale. Within the PALVAREX 2 project, the LOTRED-South America initiative represents a first and important step to also perform such highly resolved reconstructions of temperature, precipitation and the large-scale atmospheric circulation on the southern hemisphere.

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Appendix A

Supervised Bachelor and Master theses

References

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Erklärung

gemäss Art. 28 Abs. 2 RSL 05

Name/Vorname: Küttel Marcel

Matrikelnummer: 01-115-021

Studiengang: Climate Sciences

Bachelor ☐ Master ☐ Dissertation ☒

Titel der Arbeit: European climate dynamics and long-term variations over the past centuries

LeiterIn der Arbeit: Prof. Dr. Heinz Wanner

Ich erkläre hiermit, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäss aus Quellen entnommen wurden, habe ich als solche gekennzeichnet. Mir ist bekannt, dass andernfalls der Senat gemäss Artikel 36 Absatz 1 Buchstabe o des Gesetztes vom 5. September 1996 über die Universität zum Entzug des auf Grund dieser Arbeit verliehenen Titels berechtigt ist.

Bern, 23. April 2009
Ort/Datum

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Unterschrift

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