Climate Dynamics (2002) 18: 545–561
DOI 10.1007/s00382-001-0196-6

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Reconstruction of sea level pressure fields over the Eastern North Atlantic and Europe back to 1500

Received: 30 April 2001 / Accepted: 17 August 2001 / Published online: 18 December 2001

Abstract Spatially and temporally high-resolution estimates of past natural climate variability are important to assess recent significant climate trends. The mid-latitude atmospheric circulation is the dominant factor for regional changes in temperature, rainfall, and other climatic variables. Here we present reconstructions of gridded monthly sea level pressure (SLP) fields back to 1659 and seasonal reconstructions from 1500–1658 for the eastern North Atlantic-European region (30°W to 40°E; 30°N to 70°N). These were developed using principal component regression analysis based on the combination of early instrumental station series (pressure, temperature and precipitation) and documentary proxy data from Eurasian sites. The relationships were derived over the 1901–1960 calibration period and verified over 1961–1990. Under the assumption of stationarity in the statistical relationships, a transfer function derived over the 1901–1990 period was used to reconstruct the 500-year largescale SLP fields. Systematic quality testing indicated reliable winter reconstructions throughout the entire period. Lower skill was obtained for the other seasons, although meaningful monthly reconstructions were available from around 1700 onwards, when station pressure series became available. The quality and the reconstructed SLP fields for two exceptionally cold years (1573, 1740) are discussed and climatologically interpreted. An EOF analysis of the 1500–1999 winter SLP revealed, firstly, a zonal flow pattern with pronounced decadal to centenial time scale variations, secondly, a monopole pattern over northwest Europe and thirdly, a pattern modulating the meridional flow component over Europe. These 500-year SLP reconstructions should be useful for modelling studies, particulary for analyses of low-frequency atmospheric variability and for circulation dynamics.

Electronic supplementary material for this paper can be obtained by accessing the Springer LINK Server at http://dx.doi.org/10.1007/s00382-001-0196-6

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1 Introduction

A better understanding of natural climate variability is an essential prerequisite to assist in the detection of any 'anthropogenic signal'. For this reason it is important to extend the record of climate variability as far back in time as possible (Jones et al. 2001). Therefore, reliable, spatially and temporally highly resolved estimates of past natural climate variability are necessary to assess recent significant climate trends.

Over the last 500 years, Europe and the whole Northern Hemisphere (NH) experienced complex climatic change, which is only partly understood. The overall NH temperature range over the last 500 years has been quite small, being of the order of around 0.5-1°C. Within this small variability all of the significant environmental changes often associated with the 'Little Ice Age' took place (Bradley 2000).

While the times of cooling and warming and the details of decadal variations vary with the region, records from Japan, China and Australia show overall temperature variations that are similar to those in the North Atlantic Area (Bradley and Jones 1993; Free and Robock 1999). Europe experienced several cold as well as warm intervals on a decadal time scale, on which shorter-period quasi-oscillatory behaviour was superimposed. Only a few extremely cold and warm decades appear to have been synchronous over the whole continent (Bradley and Jones 1993). There was one extended period of cool summers that lasted from about 1570 to 1720 (Bradley and Jones 1993; Wanner et al. 1995; Pfister 1999; Luterbacher et al. 2000, 2001a; Briffa et al. 2001) and another one in the early nineteenth century (~1800–1820). Warm summers were experienced in the first four decades of the sixteenth century (Bradley and Jones 1993; Glaser et al. 1999; Jacobeit et al. 1999), at the end of the eighteenth century (Beck 2000) and during the 1820s. Winters were extremely cold during the last third of the sixteenth century (Glaser et al. 1999; Jacobeit et al. 1999; Pfister 1999); these were the beginning of the second 'Little-Ice-Age-type event' (1600 to 1660) and characterized by remarkable glacier advances in the European Alps (Holzhauser and Zumbühl 1999; Wanner et al. 2000). Very cold winters in Europe were also experienced during the period 1675–1715 and in the last part of the nineteenth century. It is believed that all these changes between warm/cold and dry/wet periods were connected with a marked change of the atmospheric circulation.

European weather and climate develops downstream of the North Atlantic storm track and is therefore primarily steered by the Azores high and the Iceland low. In combination with the cold winter high over Scandinavia or western Russia, European climate patterns are particularly responsive to large-scale circulation variations.

The climatic changes and the circulation changes involved may have been caused by natural forcing (volcanic, solar), internal variability of the climate systems, anthropogenic changes in the atmosphere, and land surface changes (e.g. Lean et al. 1995; Overpeck et al. 1997; Mann et al. 1998; Briffa et al. 1998; Lean and Rind 1999; Bertrand et al. 1999; Crowley and Kim 1999; Rind et al. 1999; Free and Robock 1999; D'Arrigo et al. 1999; Hyde and Crowley 2000; Beer et al. 2000; Robock 2000; Zielinski 2000; Crowley 2000; Luterbacher et al. 2001a; IPCC 2001; Robertson et al. 2001).

Reconstructions of the atmospheric circulation over larger geographical areas provide more internally consistent and spatially coherent insight into climatic variability than (univariate) circulation indices (e.g. the North Atlantic Oscillation). These reconstructions can be compared with model-generated SLP reconstructions of forced (external and internal) and natural variability of the last centuries. Additionally, large-scale gridded (interpolation onto a regular grid) sea level pressure (SLP) fields are necessary to study both low and high frequency variability of the atmospheric circulation.

Numerous reconstructions of the atmospheric circulation have been developed for specific North Atlantic-European regions or geographical locations in space. They can be divided into two groups: the subjective, hand-drawn reconstructions and those based on objective multivariate statistical methods. Using the former method, Jacobeit et al. (1999) reconstructed monthly surface pressure patterns over the European area for winters and summers during the sixteenth century with remarkable climatic anomalies. Wanner et al. (1995) presented, in a qualitative study, the position and extension of surface pressure centres over Europe for the winters and springs of 1675–1704. In both of these studies the main air pressure centres over Europe together with the advection of the main air masses were reconstructed rather than numerical air pressure values. These subjective SLP reconstructions mainly relied on a few early instrumental records and high-resolution documentary proxy data including specific information on weather elements (e.g. number of rainy days, direction of cloud movement, wind direction, warm and cold spells, freezing of water bodies, droughts, floods, information on vegetation). Lamb (1977, 1982) constructed monthly and seasonal mean sea level pressure (SLP) maps for specific severe winters within the period 1675–1715. Lamb and Johnson (1966) subjectively reconstructed monthly maps for January and July since 1750. These subjective reconstructions are constrained to represent the prevalent conditions rather than the real monthly or seasonal means thereby they tend to overestimate reconstructed patterns, which, in fact, do not occur when objective reconstruction techniques are applied.

In contrast to these subjective pressure reconstructions, several attempts have been made to reconstruct monthly and seasonal air pressure fields over the North Atlantic/European area, which are based on the objective multivariate statistical techniques. Briffa et al. (1986, 1987) used spatial regression techniques to reconstruct SLP anomaly patterns for the British Isles and the whole of Europe prior to 1873, based on ring-width chronologies and a small number of maximum latewood density chronologies. Cook et al. (1994) reviewed and compared two alternative spatial regression methods; they also used canonical regression with dendroclimatological data to reconstruct monthly mean European summer SLP dating back to 1750. Based on canonical correlation analysis (CCA), Luterbacher et al. (2000) reconstructed gridded monthly mean SLP fields for the 1675–1715 period for the eastern North Atlantic-European region. They showed the potential of reconstructing atmospheric pressure fields through the combination of both early instrumental data and continuous proxy and documentary information; the latter is derived from proxy data from several European data sites. Jones et al. (1987) used PCA regression technique to produce monthly gridded SLP fields (5°×10°latitude by longitude grid containing 60 grid points extending from 30°W to 40°E and 35°N to 70°N; Jones et al. 1987) back to 1780 for Europe by relating the principal component patterns of gridded pressure data to station pressure data. Jones et al. (1999) improved their earlier work (Jones et al. 1987) by using considerably more European station pressure series (51 homogenized series, Slonosky et al. 1999, versus 32 in Jones et al. 1987). The additional data in the new Jones et al. (1999) improved the reconstructed maps during much of the 1780–1880 period.

These reconstructions were decomposed into basic circulation patterns showing the temporal variability in terms of frequency and internal changes since 1780 (Jacobeit et al. 2001b). Furthermore, they were partly synoptically analyzed, interpreted and compared with the atmospheric circulation during the twentieth century (Beck 2000; Slonosky et al. 2000, 2001a; Jacobeit et al. 2001a; Luterbacher et al. 2001a; Xoplaki et al. 2001).

In this study, we do not intend to compare and discuss the advantages and drawbacks of the subjective and objective methods in reconstructing the atmospheric circulation. Instead we have developed a data set with temporally highly resolved (monthly, seasonal) continuous gridded SLP reconstructions for the eastern North Atlantic European area for the last 500 years based on objective methods, pushing back the gridded monthly SLP reconstructions from Jones et al. (1999) back to 1659. This, we achieve by using early instrumental station series (pressure, temperature and precipiation) in combination with documentary proxy data on a denser grid. Seasonal SLP fields, back further to 1500, are mostly estimated from thermal and precipitation index series, which are mainly reconstructed from documentary proxy data from various European areas. [This study mainly deals with the potential and the limitations of the monthly and seasonal large-scale SLP reconstructions over the eastern North Atlantic-European area for the last 500 years. In an additional paper these reconstructions will be used to study the low-frequency atmospheric variability and the circulation dynamics over the last 500 years in the area of the eastern North Atlantic European area; the study will include temperature and precipitation characteristics (Jacobeit et al. 2001c)].

Reconstructions involving early temperature and precipitation series as well as documentary data without pressure series, include the aspects of the changing influence which is exerted by the circulation on surface climate. It assumes that relationships have been stationary, and it ignores longer time scale changes related, for example, to variations in sea surface temperatures in the North Atlantic Ocean (Jones et al. 2001).

This work is structured as follows: Section 2 gives a description of the available instrumental and proxy data back to 1500, and presents the statistical model to reconstruct gridded monthly (seasonal) SLP fields back to 1659 (1500–1658). Section 3 provides objective quantitative measures to assess the reliability of the monthly and seasonal 500-year SLP reconstructions for five geographical areas. The model performance and the SLP distribution are presented for two selected years (1573 and 1740), which were among the coldest years over much of Europe. The 500-year winter SLP fields from 1500 to 1999 are projected onto their first few EOFs in order to derive the dominant spatial patterns and their temporal coefficients. These account for a substantial fraction of the SLP variances and describe the SLP variation over the last 500 years. Discussion and conclusions are presented in Sects. 4 and 5.

2 Data and methods

2.1 Predictor data including instrumental and documentary proxy data for the last 500 years

Figure 1a presents the locations of the predictors and the area of the reconstructed grid. Circles mark time-varying instrumental data series (pressure, temperature and precipitation), which were provided by different sources (see electronic supplementary material at http://dx.doi.org/10.1007/s00382-001-0196-6for a full description of the predictor data including sources), and triangles mark data series, which were estimated from high-resolution documentary evidence, and are not directly measured values. These ordinally scaled temperature, precipitation and other paleoenvironmental indices are estimations from very high-resolution documentary proxy data, such as observations of ice and snow features, and phenological and biological observations (see electronic supplementary material for corresponding references). The reliability of the documentary proxy based data, the reconstruction technique and the quality control procedures for these data are described in the publications (see electronic supplementary material). Prior to 1659 only reconstructed climatic indices, mostly on a seasonal resolution, are available. These reconstructed climate indices and the instrumental data stem from various sources (see electronic supplementary material for details). Instrumental data from the twentieth century were reduced to a corresponding integer value (ranging from +3 to −3) in order to place them at an equivalent level to the reconstructed temperature and precipitation indexed values at various European sites (Luterbacher et al. 1999, 2000, submitted 2001b). The accessability and the successful application of modern instrumental data, allowing use of earlier documentary data, has recently been shown for the sixteenth century for European sites (Glaser et al. 1999) and by Luterbacher et al. (2000) for the period of 1675–1715. More discussions on the validity of the non-instrumental predictors along with an acknowledgement of their inflated skill scores for NAO reconstructions can be found in Luterbacher et al. 2001b.

These reconstructions provide seasonal fields from 1500 to 1658 and monthly estimates since 1659, exactly the time when the Central England Temperature (CET) series starts (Manley 1974).

The dependent variable is the mean sea-level pressure (SLP) given on a 5°×5°latitude by longitude grid containing 135 grid points and extending from 30°W to 40°E and 30°N to 70°N (see Fig. 1a). In this study, we have chosen nearly the same geographical area as Jones et al. (1999) though on a denser spatial resolution. The monthly SLP data for the period 1901-1990 were prepared by NCEP (National Centres for Environmental Prediction) (see Trenberth and Paolino 1980, for source details). Missing pressure values for some months prior to 1940 were replaced by linear interpolation between adjacent grid points. Trenberth and Paolino (1980) found no substantial homogeneity problems for the area of the North Atlantic and Europe.

Figure 1b presents the temporal development of the number of predictors. It shows a large time-varying data base over the last 500 years with only a few seasonal predictors for the pre-1659 period and a steady increase of monthly predictors after the beginning of the eighteenth century.

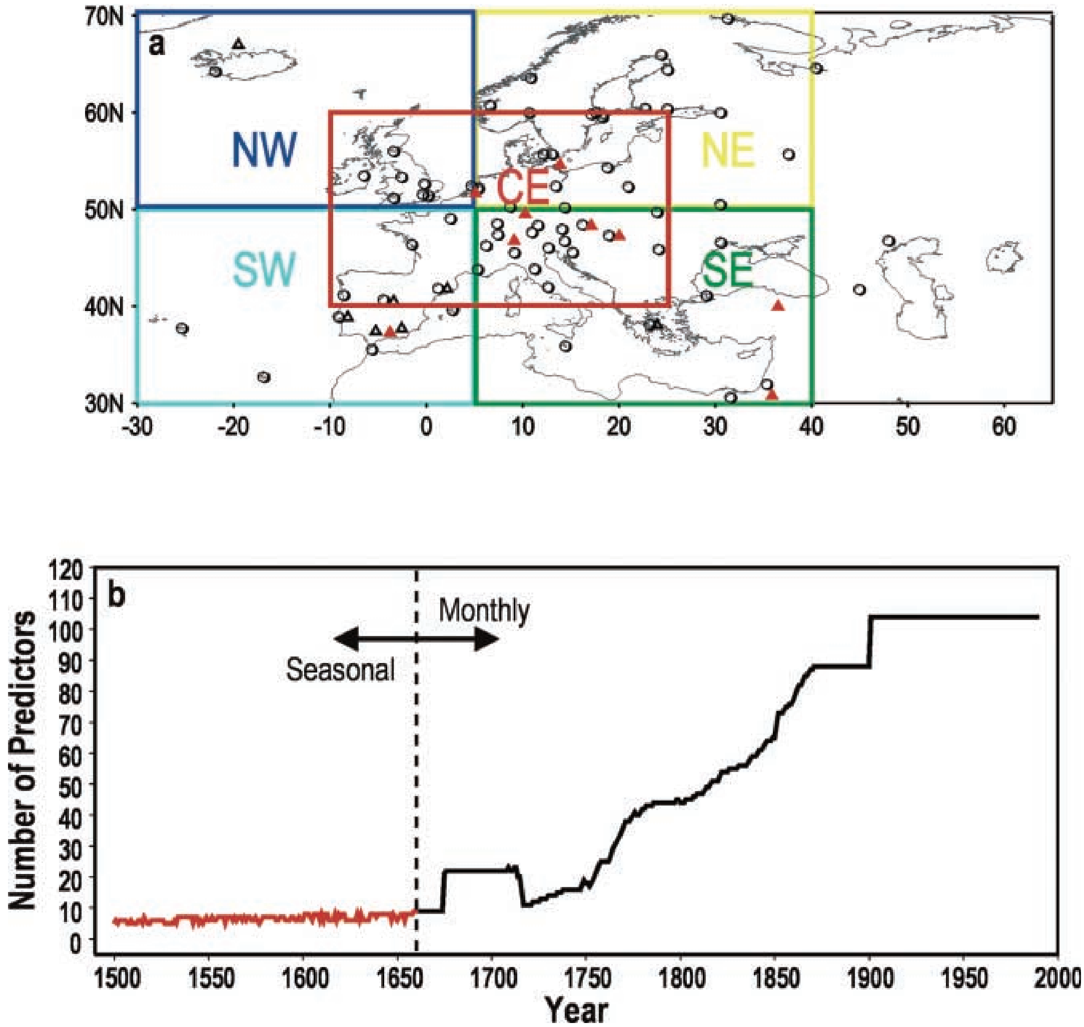

Fig. 1. **a** Geographical distribution of the locations (predictors) and domain of the area to be reconstructed (30°N-70°N; 30°W-40°E). Here 135 grid points (predictands; rectangular 5°×5°grid) are used to represent the SLP field. Five different sectors enclosed by the *coloured boxes* have been selected for the model performance (see text for details). *Circles* mark instrumental data series (pressure, temperature and precipitation), *triangles* mark data series estimated from documentary evidence (see text for details). *Red triangles* indicate available predictors for the whole or parts of the pre-1659 period (see electronic supplementary material at http://dx.doi.org/10.1007/s00382-001-0196-6 for details). **b** Temporal development of the number of predictors used for the SLP reconstructions

2.2 Reconstruction method for 500 years large-scale SLP fields

Principal component regression analysis was used to develop monthly SLP reconstructions back to 1659 and seasonal SLP reconstructions from 1500–1658. In order to reconstruct the gridded SLP for a given month, we first identified all available predictors and the other months from the same climatological season (i.e. winter is December, January and February).

Due to the large time-varying data base over the last centuries (Fig. 1b), 297 different models for the monthly reconstructions back to 1659 had to be developed. Statistical models of the relationship between pressure, temperature, precipitation and other proxy based data (predictors), and gridded SLP (predictands) were developed and applied to data over a calibration period (1901–1960). These transfer functions were then applied to the corresponding predictor variables for the independent period (verification period; 1961–1990).

Let $P_{\text{calib}}(t, x)$ denote the mean monthly standardized SLP at the q grid points $x=1, \ldots, q$ for observation time $t=1, \ldots, n$ (predictands) for the calibration period 1901–1960. The $S_{\text{calib}}(t, y)$ data field consists of standardized observations (predictors are instrumental pressure, temperature and precipitation series and/or documentary proxy based reconstructions) at p stations $y=1, \ldots, p$ at the same observation time $t=1, \ldots, n$ for the calibration period 1901-1960. The data time series $P_{\text{calib}}(t, x)$ and $S_{\text{calib}}(t, y)$ are decomposed for each climatological season, including three months in series of patterns (i.e. $n=60*3$ months = 180 months for each climatological season). Both, the predictands and the predictors were first truncated by retaining only the first few EOFs (empirical orthogonal functions, Preisendorfer 1988; von Storch and Zwiers 1999). This was done to separate the dominant spatial patterns of variability, accounting for a substantial fraction of the predictors and predictands variances, from noise and irrelevant details.

$$M_{\text{calib}}(t, i) = \sum_{y=1}^{p} S_{\text{calib}}(t, y) \cdot \alpha_{yj} \qquad (1)$$

$$N_{\mathrm{calib}}(t,j) = \sum_{x=1}^{q} P_{\mathrm{calib}}(t,x) \cdot \beta_{xj} \tag{2}$$

where $M_{\mathrm{calib}}(t, i)$ and $N_{\mathrm{calib}}(t, j)$ are the i-th and j-th 'EOF-time series', respectively, and α_{yi} and β_{xj} the i-th and j-th 'EOF-patterns', respectively; $i = 1,\ldots, p^* < p$ and $j = 1,\ldots, q^* < q$. The EOFs are orthonormal linear combinations of the original data for the calibration period (1901-1960), each representing decreasing amounts of the original total variances. There are no definitive rules to decide how many (p^* and q^*) EOFs should be retained. Because the model performance largely depends on the input variables, the selection procedure of the number of EOFs from the predictand and the predictor fields is of great importance (von Storch and Zwiers 1999; Livezey and Smith 1999a, b; Smith and Livezey 1999). Using too many EOFs will fit the statistical models too strongly to particular data sets considered, most likely missing an adequate description of the underlying process. Too few EOFs will omit part of the significant signal, thus resulting in a poorer prediction of the overall model.

In our study, the leading predictor data EOFs, accounting for 95% of total variance and the leading SLP EOFs, explaining 90% of the SLP variability, are selected to represent the subspaces of the parameters.

A multivariate regression was then performed regressing each of the grid-point EOFs of the calibration period in turn against all the retained EOFs of the predictor data for the same period. The multivariate regression yielded an expansion of the EOF subspaces of the predictors and predictands

$$N_{\mathrm{calib}}(t,j) = \sum_{i=1}^{p*} M_{\mathrm{calib}}(t,i) \cdot \gamma_{ij} + Error(t,j) \tag{3}$$

where $j = 1,\ldots, q^*$, where γ are the unknown regression coefficients and *Error* is the residuum. We estimated the regression coefficients $\hat{\gamma}_{ij}$ by the usual least squares method. Since the EOFs are assumed to be standardized in columns, no intercepts need to be estimated.

As we then wished to have a prediction $P_{\mathrm{verif}}(t, x)$ and a predictor data set $S_{\mathrm{verif}}(t, y)$ (the number of colums of $S_{\mathrm{verif}}(t, y)$ must be equal to p) for the verification period (1961–1990). We assumed that $S_{\mathrm{verif}}(t, y)$ is standardized by the same values as $S_{\mathrm{calib}}(t, y)$ and calculated

$$M_{\mathrm{verif}}(t,i) = \sum_{y=1}^{p} S_{\mathrm{verif}}(t,y) \cdot \alpha_{yi} \tag{4}$$

where $i = 1,\ldots, p^*$

$$\hat{N}_{\mathrm{verif}}(t,j) = \sum_{i=1}^{p*} M_{\mathrm{verif}}(t,i) \cdot \hat{\gamma}_{ij} \tag{5}$$

and transform the q^*-components of the EOFs back to

$$\hat{P}_{\mathrm{verif}}(t,x) = \sum_{j=1}^{q*} \hat{N}_{\mathrm{verif}}(t,j) \cdot \beta_{xj.} \tag{6}$$

Finally, we had to reverse the standardization we made on the gridded SLP fields in order to obtain the SLP reconstructions for the verification period 1961–1990.

For the seasonal reconstructions from 1500 to 1658, the same method was applied but regressing the seasonal means of the grid-point EOFs in turn against all the retained seasonal predictors EOFs. In this case 36 series of equations for the different networks were developed.

To guarantee as much as possible recent variability within the reconstruction models, it is more appropriate to include the whole period 1901–1990 for establishing transfer functions to derive the final reconstructions back to 1500 instead of the shorter calibration period used above. Thus, Eqs. 1 to 6 were applied, being 1901–1990 the calibration period. The verification time 1961–1990 (Eq. 6) was replaced by the period to be reconstructed (1500–1990).

2.3 Model verification

The reconstructions are compared with the observed time series over the verification period, grid point by grid point, for the whole defined region. The strength of the linear statistical relationship between reconstruction and observation is measured by the reduction of error (RE) discussed in Cook et al. (1994). RE ranges from +1 (perfect agreement between reconstructions and analysed fields) to $-\infty$ with RE = 0 no better than climatology (i.e. the mean of the climatological data in the calibration period), RE > 0 better than the calibration mean and RE < 0 no useful information in the reconstructions.

The quality of our SLP reconstructions was tested by applying each of the 297 monthly (back to 1659) and 36 seasonal (1500–1658) models fitted during the period 1901–1960 and verified over the verification period 1961–1990. For each of the 135 grid points a RE for every model was calculated. Instead of giving one overall mean value over the whole grid, we divided the whole reconstructed area into five subregions of similar size and calculated a sectoral mean RE including 40 grid points. This allows for regional considerations about the model quality back to 1500. In Fig. 1a the five sectors (NW, NE, SW, SE and CE) are enclosed by rectangular boxes. The CE (Central Europe) sector has been defined since a lot of predictors lie within this area and it is therefore expected to provide the most reliable results in the reconstruction procedure. However, CE is not independent since it includes information from the other four sectors. In addition, the model performance in this area is of great importance for the analysis, namely in terms of circulation dynamics, and of extended periods with enhanced and reduced flood frequency from the northern Alps to the North Sea which is under investigation. The averaged RE values for each sector (Fig. 1a) and season were plotted against the time period for which a given model was used, yielding a time series for every sector on the quality of our SLP reconstructions from 1500 onwards (Fig. 2).

3 Results

3.1 Model performance of the SLP reconstructions

Figure 2 presents the seasonal sectoral model performance (RE) for the reconstructed SLP plotted against the time period for which a given multivariate model (for the verification period 1961–1990) was used. For all sectors, the best model performance with RE > 0 over the whole period, was obtained for winter, thus indicating greater spatial coherence of the atmospheric circulation and of climate variables during the cold season. Therefore, we can expect meaningful reconstructions for all the 500 years and for the whole Eastern North Atlantic European area. The lowest RE values are found in the sixteenth and seventeenth century (where only a few and mostly non-instrumental data are available), whereas increasing skill is prevalent for the subsequent centuries. For the pre-1659 period, the model performance for most of the sectors shows rather small predictive skill except for winter, thus it has less potential to reconstruct SLP from a few non-instrumental predictors. For spring and summer, the CE sector shows the best model performance for the whole 500 years. However, this is not the case for winter and autumn where the highest RE values are obtained for the SW sector, this is an indication for the importance of the reconstructed precipitation time series of Andalusia (Spain) by Rodrigo et al. (2001). For winter and spring, surprisingly, the NW sector shows best skill for the pre-1659 period although there is no predictor available.

3.2 Model performance and reconstructed SLP fields for the years 1573 and 1740

The SLP reconstructions for the two very cold years, 1573 and 1740, were chosen in order to illustrate the potential and limitations of reconstructing temporally highly resolved SLP fields which are based on a few early instrumental (for 1740) and proxy data predictors. These examples are also selected to demonstrate that different SLP fields might be related to similar severe climate conditions over Europe.

3.2.1 The year 1573

An extended overview of the specific climatic conditions, the interactions with other natural phenomena and the

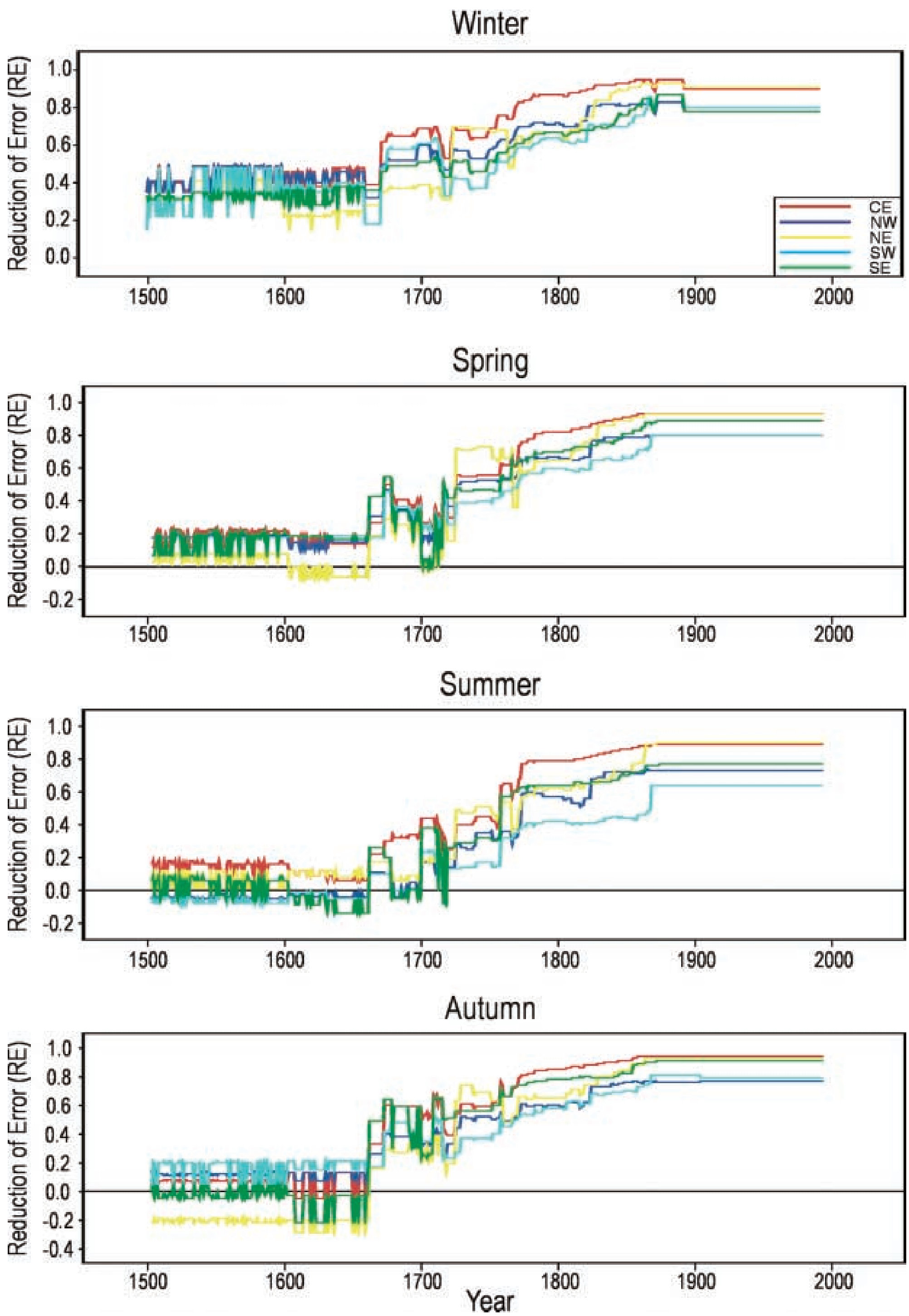

Fig. 2. Seasonal sectoral model performance (RE) for the reconstructed SLP plotted against the time period for which a given multivariate model (for the verification period 1961-1990) was used. The five sectors correspond to the defined regions in Fig. 1a. For each sector an areal RE mean over 40 grid points was calculated. Any RE > 0 is considered to represent significant regression skill

impact on human society for Central and Eastern Europe for the year 1573 is given in Glaser et al. (1999). From November 1572 to April 1573 large parts of Europe experienced severe cold (Glaser et al. 1999; Pfister 1999). Temperatures for these European regions were several degrees lower compared to the long-term twentieth century winter mean. In addition, severe sea ice conditions were prevalent in the western Baltic Sea (Koslowski and Glaser 1999). From May to August the deviation from the average weather patterns over great parts of Europe was rather small (Glaser et al. 1999). With the available predictors for 1573 (Table 1) a model for each season for the 1901–1960 period has been calculated and verified within 1961–1990. The calculated RE for each grid point and season are given at the top of Fig. 3. The model performance for winter shows mostly positive RE values over the whole grid, an indication of skill in the reconstructions. The highest values are within a belt from Iceland over the North Sea and Central and Eastern Europe to the Black Sea area. The transition seasons show a similar pattern with some skill from Iceland over the British Isles and Central Europe towards the central and western Mediterranean. No meaningful SLP estimations are possible east of approximately 20°E and west of 20°W over the Atlantic area. For summer, meaningful reconstructions can be expected over continental Europe whereas unreliable SLP reconstructions can be found over western Russia, the Atlantic Ocean and the southern Mediterranean area. The reconstructed SLP field for winter 1573 (Fig. 3 middle) shows extended low pressure from the North Atlantic to the eastern Mediterranean area. High pressure was reconstructed over Scandinavia and Eastern Europe. The SLP anomaly field (Fig. 3 bottom) shows a strong positive SLP anomaly north of around 53°N and below normal SLP over Central and Southern Europe. The other seasons show generally positive SLP anomalies over the northwest part of the grid and below normal SLP over the continent, an indication of enhanced blocking over the Atlantic.

3.2.2 The year 1740

The year 1740 was the coldest in the Central England Temperature series (CET, Manley 1974) since 1659 with an average temperature decrease of 2.7 °C below the 1961–1990 mean. In other European regions (Scandinavia, northern Germany, Western, Central and Eastern Europe) this year was also among the coldest over the last few centuries. In Ireland, as many people died of famine in this year as in the well-known 'potato' famine of 1845-7, and it is known as the forgotten famine (Dickson 1997). The western Baltic area was completely covered with ice (Koslowski and Glaser 1995, 1999).

The available predictors for the monthly reconstructions are given in Table 2 (see also electronic supplementary material at http://dx.doi.org/10.1007/s00382-001-0196-6). Figure 4 presents the reconstructed monthly SLP fields for the year 1740 and the model performance (RE values) for January, April, July and October. Winter and autumn show the best model performance. The highest RE values can be found over Central and Eastern Europe and especially over Scandinavia. This can be attributed to the Uppsala (southern Sweden) pressure series (Bergström and Moberg 2001), which is the most important predictor.

The reconstructed January and February SLP fields show a stationary anticyclone, centred over the British Isles. Easterly and northeasterly winds prevailed along the coast of the Netherlands, France, northern Spain and Portugal. A similar SLP pattern was also present during March and April. This means that the change from the winter to the spring circu-

Table 1. Climatological time series available for the seasonal sea-level pressure (SLP) reconstructions for the year 1573. TT denotes temperature, RR precipitation. Note that the indexed temperature and rainfall indices mostly represent the climatic conditions over a broader geographical area and do not refer to a single station. Thus, the latitude, longitude and elevation indications are discarded for these predictors and only the region or representative station is given

Station name	Latitude (N)	Longitude (E)	Elevation (m)	Sources
RR-Germany	Southern			Glaser (2001)
TT-Germany	Southern			Glaser (2001)
RR-Switzerland	Swiss Plateau			Pfister (1998,1999)
TT-Switzerland	Swiss Plateau			Pfister (1998, 1999)
Western Baltic-Sea-Ice-Index	German and Danish coasts			Koslowski and Glaser (1999)
RR-Czech Republic	Bohemia[a]		469	Brázdil (1992), Brázdil et al. (2001)
TT-Czech Republic[b]	50.05	14.42	191	Brázdil and Kotyza (2000)
RR-Southern Spain	Guadalquivir valley (Andalusia)[c]	~37	~Sea level	Rodrigo et al. (1999, 2001)

[a]Bohemia (mean of around 51 000 km^2); only available for spring and summer 1573
[b]According to R. Brázdil (Masaryk University, Brno, Czech Republic) Prague-Klementinum (50.05°N; 14.42°E; 191 m elevation) has been taken as a reference station for the model calibration in the twentieth century
[c]Gibraltar (UK), 36.2°N; 5.4°W; 5-ndash;m elevation) has been taken as a reference station for the model calibration in the twentieth century (Rodrigo et al. 1999, 2001)

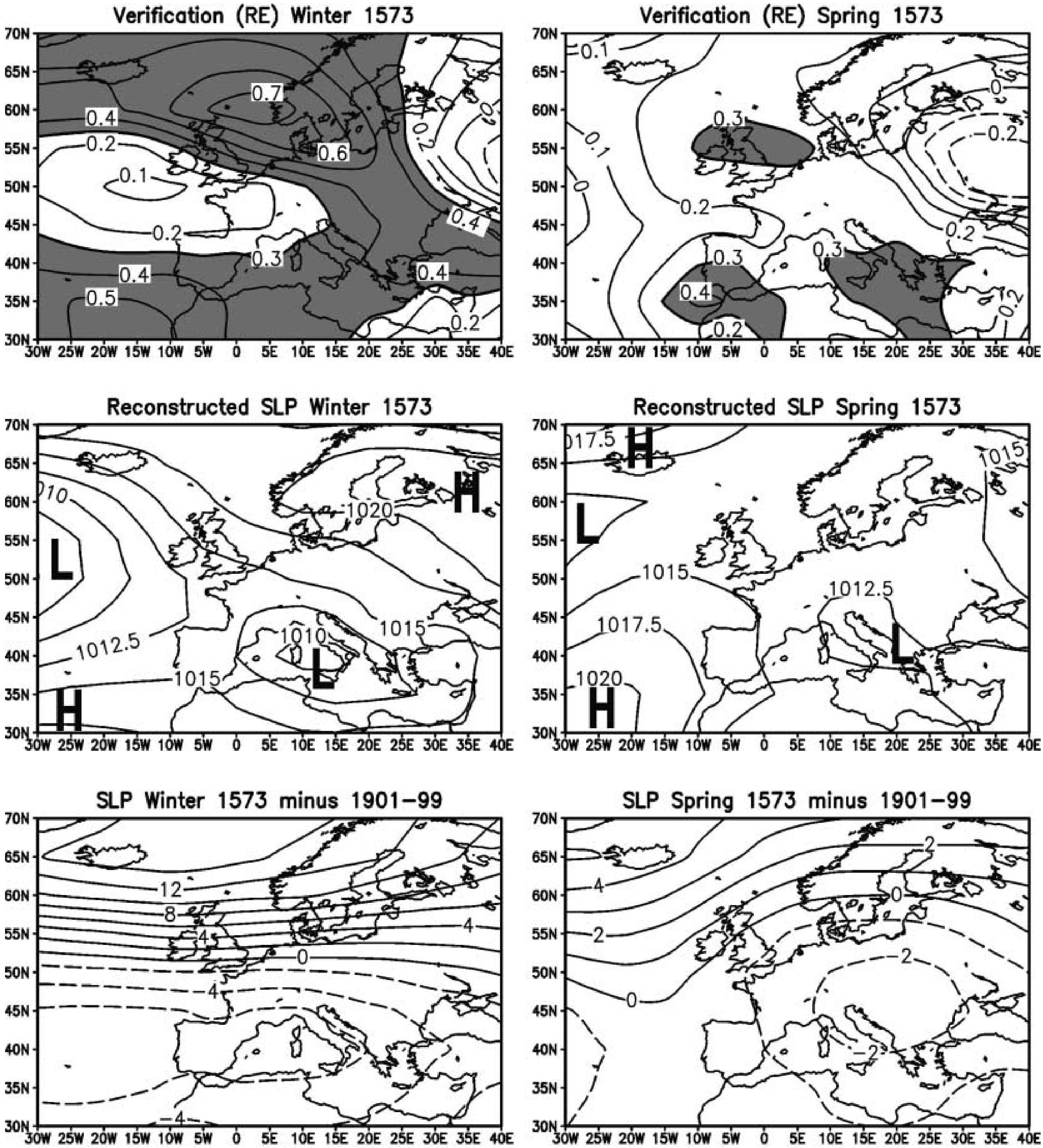

Fig. 3. Seasonal model performance (RE) for the SLP reconstructions for the year 1573 (*top*) (see text for details). Areas with values of RE ≥0.3 are *shaded*. Reconstructed seasonal SLP fields for 1573 (*middle*). The contours of the isobars are drawn at 2.5 hPa intervals. Seasonal SLP difference patterns (season 1573 minus long-term seasonal mean of 1901-1999). *Continuous lines* mark positive SLP deviations, and *dashed lines* negative SLP deviations (in hPa)

lation over Western Europe did not result in a significant warming, the reason being the advected air from the west, which remained colder than usual. Except for September, the remaining months of 1740 reveal anomalously high pressure over the Atlantic and Western Europe.

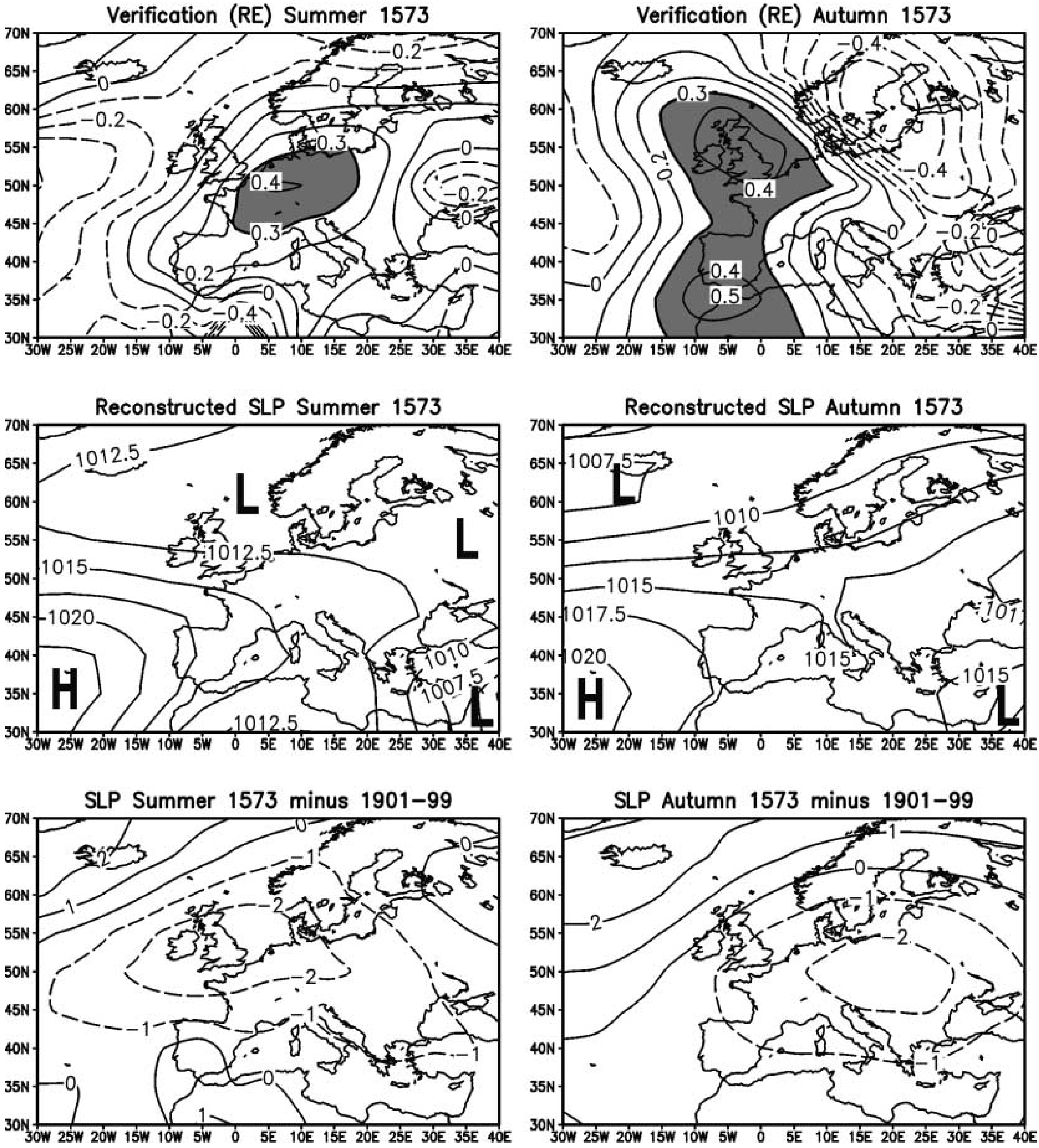

Fig. 3. (Contd.)

3.3 Seasonal winter EOF analysis of European SLP 1500–1999

Figure 5 presents the first three EOFs of winter (December to February) SLP for the period 1500–1999 together with the corresponding scores. The data from 1991 to 1999 are reanalysis winter data (Kistler et al. 2001).

Since SLP grids for the pre-1900 period have been reconstructed from regression models calibrated with EOFs of the 1901–1990 period, the EOFs of Fig. 5 for the whole period (1500–1999) are associated with the major SLP modes known from the twentieth century with explained variances of more than 90%. Differences between historical and recent atmospheric circulation, however, may be extracted from the corresponding time coefficients (see later).

The leading winter EOF pattern (Fig. 5) shows the well-known dipole structure with negative (positive) loadings north of about 50°N and maximum positive (negative) loadings over the Mediterranean area. This EOF represents a pattern of European zonal flow (Slonosky et al. 2000) and has similarities with the North Atlantic Oscillation (NAO), though the southern centre is displaced more to the east.

The associated scores describe its variation over the last 500 years, thereby revealing strong decadal to interdecadal variations. Sub-periods of enhanced and reduced variability can be discerned. In the middle of the sixteenth century, during the late seventeenth and early eighteenth century marked negative scores can be found. These periods are known for their low temperatures over wide parts of Eurasia, as also show data not used in this reconstruction procedure (Glaser et al. 1999; Jacobeit et al. 1999; Luterbacher et al. 2001b; Tarand and Nordli 2001). Prominent also is the unprecedent strong upward trend of the last decades of the twentieth century. Rather low, but significant correlations have been found between the time series of EOF 1 and recent published NAO reconstructions (Cook et al. 1998, 2001; Rodrigo et al. 2001).

The second winter SLP EOF is characterized by a monopole pattern, its centre being over the North Sea, and a simultaneous lower (higher) SLP showing over the whole area. It indicates resemblence to the east Atlantic Pattern of Barnston and Livezey (1987). The variability of the scores prior to 1659 can be discerned from Fig. 5.

The third EOF shows a contrast between Western and Eastern Europe, showing positive (negative) loadings west of around 5°E and negative (positive) loadings eastwards. This pattern is similar to EOF 3 from Slonosky et al. (2000), and linked to the EU (Eurasian) pattern, whose time coefficient describes variability in the meridional flow component over Europe (Barnston and Livezey, 1987). No trend is obvious in the scores, however, a striking feature is the reduced variability for the pre-1659 period, a point which is taken up again in the following sections.

4 Discussion

4.1 Reconstruction quality, assumption of the statistical approach and stability of the results

The quality of the 500 year SLP reconstructions strongly depends on the data availability, principally a function of the number of predictors. The seasonal sectoral model

Table 2. Climatological time series available for the monthly sea-level pressure (SLP) reconstructions. TT denotes station temperature, RR station precipitation, PP station pressure, (I) stands for indexed data (estimated from high resolution documentary evidence (see text for details): Note, the indexed temperature and rainfall indices mostly represent the climatic conditions over a broader geographical area and do not refer to a single station. Thus, the latitude, longitude and elevation indications are discarded for these predictors and only the region or representative station is given

Station name	Latitude (N)	Longitude (E)	Elevation (m)	Sources
RR-Germany (I)	Southern			Glaser (2001)
TT-Germany (I)	Southern			Glaser (2001)
RR-Switzerland (I)	Swiss Plateau			Pfister (1998, 1999)
TT-Switzerland (I)	Swiss Plateau			Pfister (1998, 1999)
Western Baltic-Sea-Ice (I)	German and Danish coasts			Koslowski and Glaser (1995, 1999)
TT-Central England	51.47	−0.32	5	Manley (1974)
RR-Southern Jordan[a]	30.47−30.63	35.5−35.72	1100−1400	Touchan et al. (1999)
RR-Hungary (I)	Budapest			Rácz (1999)
TT-Hungary (I)	Budapest			Rácz (1999)
TT-De Bilt	52.1	5.2	8	Vose et al. (1992); Peterson and Vose (1997)
RR-Kew	51.47	−0.32	5	Vose et al. (1992); Peterson and Vose (1997); Wales-Smith (1971)
TT-Berlin	52.5	13.4	50	Vose et al. (1992); Peterson and Vose (1997)
TT-Uppsala	59.88	17.6	21	Bergström and Moberg (2001)
PP-Uppsala	59.9	17.6	14	Bergström and Moberg (2001)
RR-Podehole	52.8	−0.1	3	Vose et al. (1992)
RR-Hoofdorp	52.3	4.7	4	Vose et al. (1992)
TT-Tornio[b]	65.50	24.08	~2	Vesajoki et al. (1995); Holopainen (2000)

[a]October to May Predictor
[b]Haparanda (Sweden; 65.8°N; 24.2°E; 6 m elevation) has been taken as a reference station for the model calibration in the twentieth century

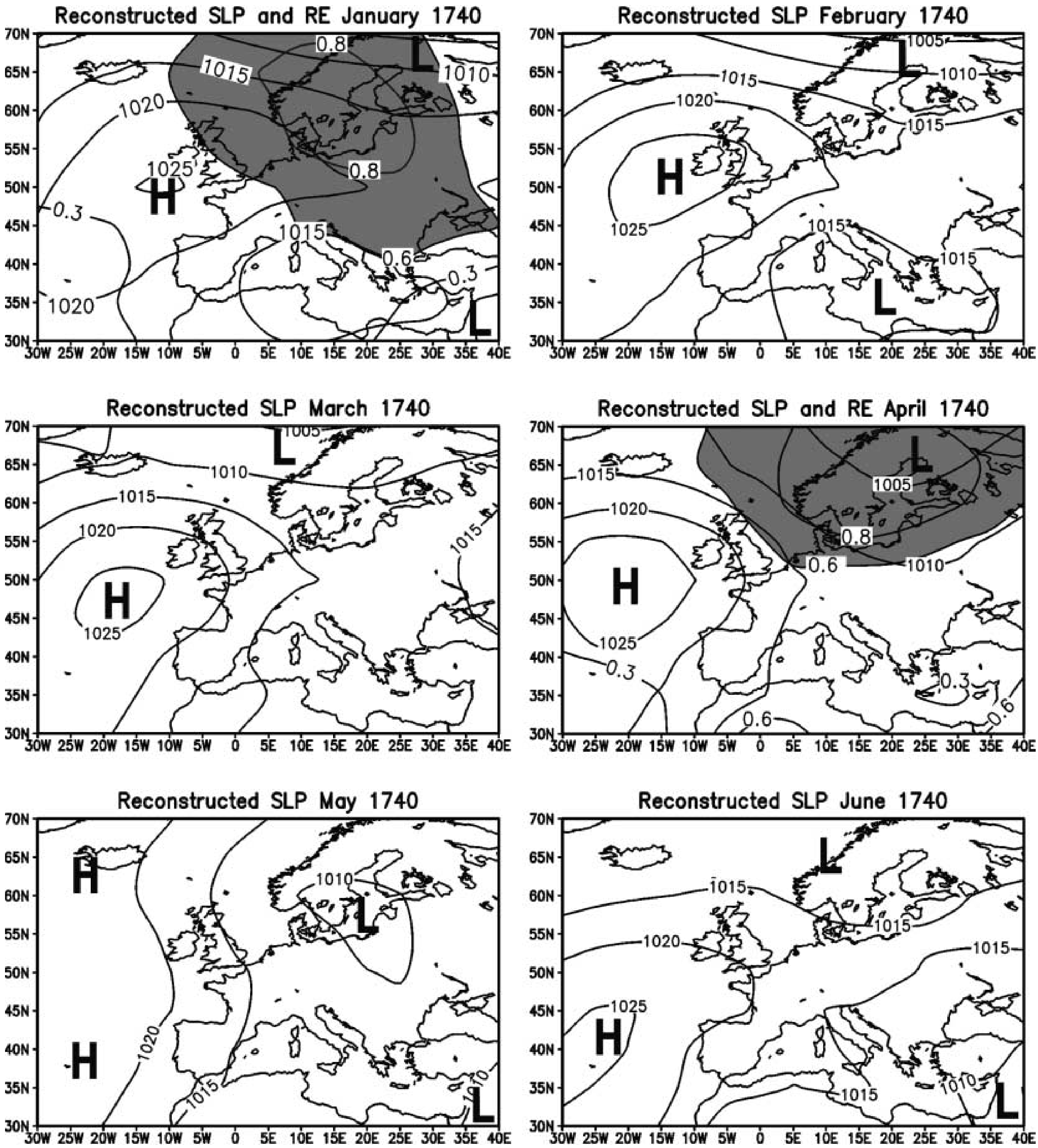

Fig. 4. Reconstructed monthly SLP fields for the year 1740. The contours of the isobars are drawn at 5 hPa intervals. Areas with values of RE ≥0.6 (indicating very skillful reconstructions) for the four central months of each season (i.e. January, April, July and October) are *hatched*

performance, as presented in Fig. 2, clearly shows that the winter reconstructions have predictive skill. Although none or only one to two predictors are available in the NW, SW and NE sector, the RE is of the order of 0.2 to 0.5, this indicates that remote predictors can significantly contribute to skillful SLP reconstructions. As for the other seasons, there are some sectors which do indicate meaningful reconstructions (such as SW).

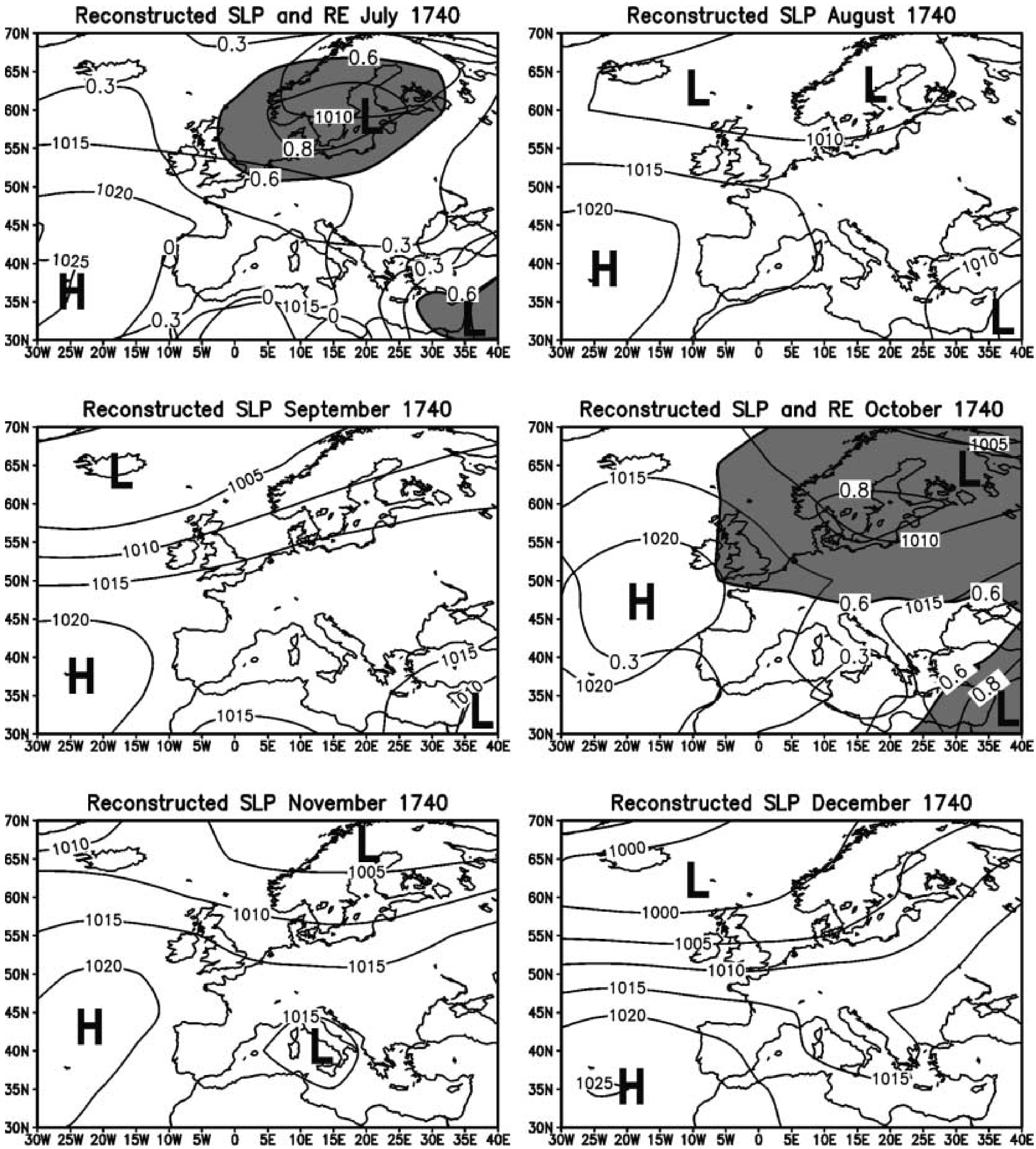

Fig. 4. (Contd.)

Mostly, however, the RE values are low. This shows the limitations of good spatial SLP reconstruction, both in season and area. It is surprising that the CE sector which incorporates most of the predictors, does not show the highest values throughout the whole period. Obviously, especially for the pre-1659 period, it seems more important to have one single predictor from an area with a significant connection to the atmospheric circulation, than several predictors from rather close locations that share similar climate characteristics. Indeed, backward elimination technique revealed that the Western Baltic Sea Ice Index (Koslowksi and Glaser 1999) and the reconstructed precipitation over Andalusia (Rodrigo et al. 2001) are among the most important predictors for the

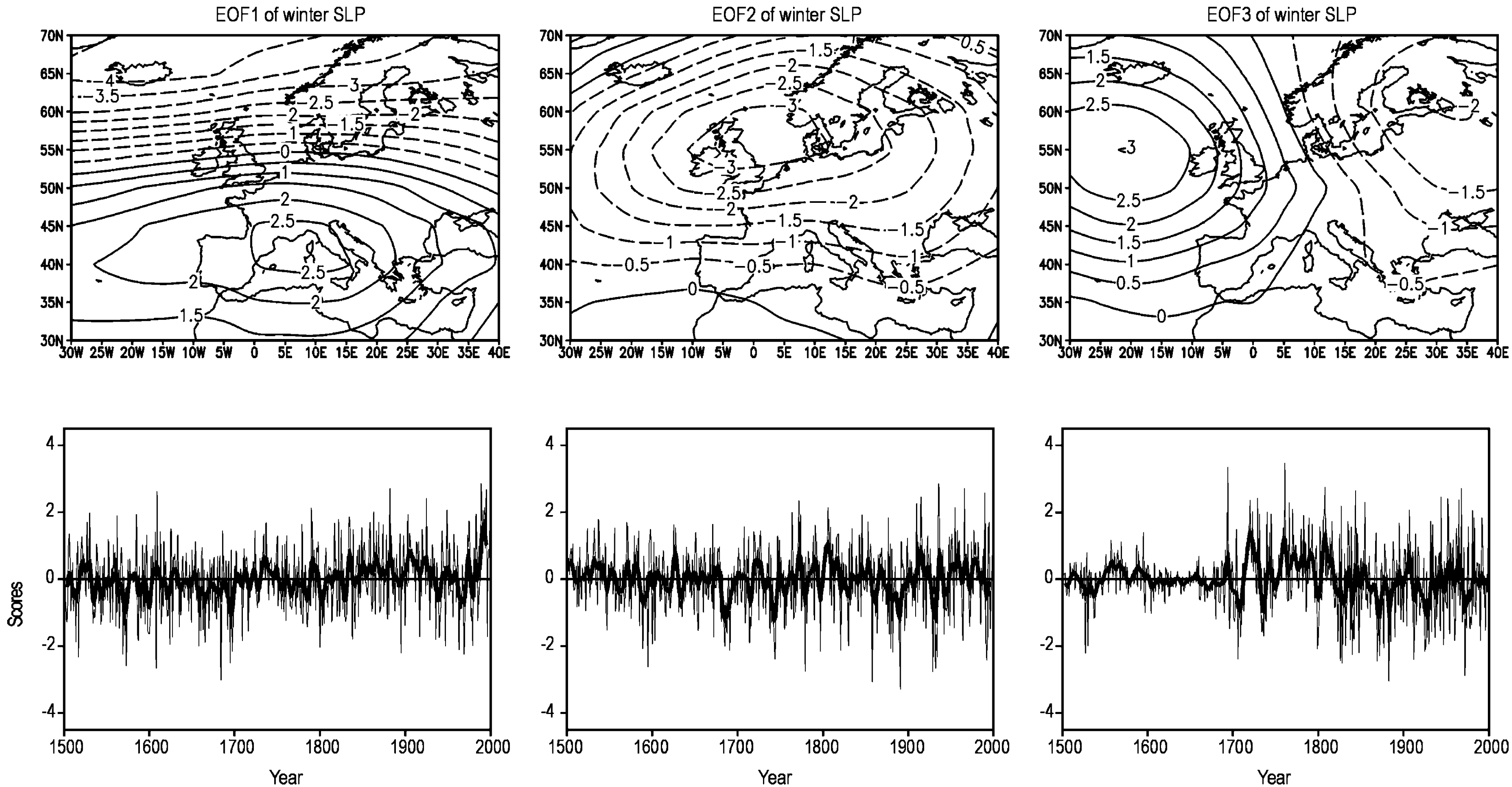

Fig. 5. Top: patterns of the first three EOFs of winter SLP anomalies 1500–1999 (anomalies in hPa; contour interval 0.5 hPa). The last nine winters are reanalysis data (Kistler et al. 2001). The first EOF accounts for 55%, the second 23% and the third EOF 17%, respectively, of the winter SLP variance. *Solid lines* indicate positive values, and *dashed lines* mark negative values. Below: corresponding normalized time components (scores) of the first three EOFs. The *thick line* is the 9 point low pass filtered time series. For clarity of the figures, the monthly (DJF) scores for the post 1659 period were averaged to one seasonal winter value for the respective years

winter season SLP reconstructions prior to 1659. They account for for a substantial amount of variance over central/northern Europe and of southwestern Europe, respectively.

The Central England Temperature (CET, Manley 1974) is the most important predictor for the monthly pre-LMM reconstructions from 1659 to 1669, when station pressure series are lacking. This single predictor explains a significant amount of variance over the eastern North Atlantic as well as parts of Western, Northern and Central Europe (not shown). Station pressure predictors are most important for large-scale SLP reconstructions. The earliest station pressure series was available for Paris from spring 1670 to 1713 (Legrand and Le Goff 1992, Slonosky et al. 2001b) and for London from 1697 to 1708 (Slonosky et al. 2001b). All the sectors in Fig. 2 show a rapid increase of the RE values, and thus a better model performance. After the Paris series was unavailable the reconstructions became less reliable (Fig. 2); however, they are still meaningful until the next pressure series (1722, Uppsala, Sweden; Bergström and Moberg 2001) could be included. In the following decades increasing station pressure predictors became available (Jones et al. 1999; Slonosky et al. 1999: see electronic supplementary material at http://dx.doi.org/10.1007/s00382-001-0196-6) which led to excellent monthly reconstructions in all sectors presented in Fig. 2.

Reconstructions are based on the assumption of stationarity in the statistical relationships derived during modern calibration periods. This assumption seems reasonable in view of interannual variabilites, which exceeds differences in mean climatic states between different periods. Thus, the regression-type relationships derived from our SLP reconstructions are almost entirely based upon high-frequency relationships (Luterbacher et al. 2000). This assumption also applies to most of the existing paleo reconstruction studies (Jones et al. 1998; Luterbacher et al. 2000). Probability density functions of circulation change with time, but it is assumed that the relations between the variables such as pressure, temperature and rainfall do not significantly change with time (Luterbacher et al. 2000). Therefore, longer time scale variability is relatively small (Luterbacher et al. 2000). However, Slonosky et al. (2001a) and Jacobeit et al. (2001a) recently wrote about decadal scale variability of the correlations between climate and atmospheric circulation. Therefore, the relationships between the climatic predictor data and the atmospheric circulation may not be stable over time, i.e. local temperature and precipitation do not always respond in the same way to the circulation.

In order to ensure that the model verification results, as presented in Figs. 2 and 3), are not statistical artefacts of small sample sizes of the fitting and verification periods within the twentieth century, we performed similar analyses with the fitting period 1931-1990 and the verification period 1901-1930. The results did not change significantly, thereby indicating the stable quality of our reconstructions (not shown). Considering the decadal variability in pressure, experiments have also been conducted with 20- and 25- year calibration periods that were then verified with the remaining years. Similar reconstruction skills have been achieved for these experiments, which improves the confidence of our final reconstructions.

Additionally, no notable changes in the regression results were found when applying different EOF truncations in the predictor and predictand fields (not shown).

4.2 Synoptic analyses and dynamical aspects of the year 1740

The two examples of monthly (1740) and seasonal (1573) SLP reconstructions clearly showed the potential that only a few predictors can have: in this study, they provided reliable estimates of past circulation. However, a mean seasonal winter SLP field for 1573 (Fig. 3) cannot generally capture the within-season's climate variability and may not indicate extreme climatic conditions within a specific season. It is interesting to note that the subjective reconstruction of Jacobeit et al. (1999) shows similar patterns.

Reconstructed SLP fields enable and facilitate the search for and the comparison with analogues. Information from the station collective and the constraint to similar pressure patterns work as a filter and exclude a local circular argument. January and February 1740 provide a good example, because negative temperature anomalies over wide parts of Europe are normally due to cold advection from northwestern Russia. The analogue with January 1987 shows that other circulation patterns without an anticyclone over the northeast are also possible. Interestingly, the SLP reconstruction of January 1987 with the available predictors for winter 1740 is very similar to the observations (not shown).

A stable ridge over and slighly east of the Rockies and a second ridge over the eastern Atlantic dominated mid- and upper tropospheric flow. The corresponding troughs extended from the Canadian Archipelago down to Labrador and to the Black Sea. The ridge over the eastern Atlantic led to stable high SLP over the British Isles.

The Canadian Arctic is the source region of air masses which feed the western North Atlantic storm tracks. Buzzi (1999) showed that Greenland is a significant barrier for the Arctic air to the west of it. Cold air mostly flows around the ice-shielded island, which regularly produces flow splits. A blocking ridge builds up downstream and damps further cyclonic development. Circulation causalities over neighbouring regions can therefore be linked with the perimeter of the reconstructed SLP fields, which otherwise is not possible.

It seems that stationary atmospheric circulation patterns during winter and spring 1740 significantly conditioned SSTs and marine boundaries along the European

Atlantic coasts. This is due to cold offshore winds, which may have sustained significant fluxes of sensible and latent heat over the Bay of Biscay and the western Mediterranean Sea. The centre of the subtropical high was approximately 20° of latitude north of the climatological position around Madeira.

4.3 EOF analysis of winter SLP 1500–1999

The EOF patterns of winter SLP 1500–1999 (Fig. 5) largely correspond to the first three January circulation patterns derived by T-mode PCA (Jacobeit et al. 2001b) from the reconstructed SLP grids from 1780 onwards (Jones et al. 1999). The main difference occurs with EOF 3. It explains much more variance (28%) in the January analysis since 1780 (Jacobeit et al. 2001b) thus exceeding the pattern which corresponds to EOF 2 in Fig. 5. This pattern is possibly due to different temporal resolutions (seasonal versus monthly) and to the fact that the reconstruction skill decreases for the earlier parts of the extended period that was considered here (see Fig. 2). This reduced skill is also responsible for the lower variances of EOF 2, and, which is even more conspicious, of EOF 3 prior to the mid-seventeenth century (Fig. 5), when there were fewer data available to constrain the spatial patterns.

Remarkably, most differences from subjective maps from the sixteenth century (Jacobeit et al. 1999) also occur for winter seasons with SLP patterns associated with EOF 3. Thus, restricted information might also be responsible for the early lack of cold winter pressure patterns with an anticyclonic centre over the Baltic region. These are patterns which dominated the 'Little Ice Age' winter seasons in the subjective maps (Jacobeit et al. 1999). However, the reconstructed SLP fields for the cold winter of 1740 and the SLP patterns of 1987 indicate that coldness over Europe is not necessarily connected with an anticyclone over Scandinavia/western Russia.

5 Conclusions

Principal component regression analysis was applied to early instrumental time series (pressure, temperature and precipitation) and documentary proxy data to reconstruct monthly SLP fields for the eastern North Atlantic-European area dating back as far as 1659. Seasonal estimates were obtained from 1500–1658. The reconstructions are based on the assumption of stationarity in the statistical relationships that were derived during modern calibration periods.

The verification results from the twentieth century illustrate that the regression equations contain good predictive skill for the majority of grid points, especially in winter. The large-scale monthly and seasonal winter SLP reconstructions from 1500 onwards are reliable. For winter, only a small number of predictors is needed in order to achieve skillful reconstructions, even at the fringes of the grid. Even sparce documentary proxy data in the earlier period are useful and provide considerable information to reconstruct SLP pressure fields prior to 1659. With increasing data availability, reconstruction skill improves, and allows for meaningful monthly scale reconstructions since 1659.

For spring, summer and autumn, the seasonal reconstructions are less reliable. Monthly SLP reconstructions for these seasons show skill only since the beginning of the eighteenth century, when pressure series became available.

Station pressure series are the most important predictors accounting for large amounts of SLP variability over the grid. For the seasonal reconstructions, the western Baltic Sea Ice index (Koslowski and Glaser 1999) and the reconstructed precipitation in Southern Spain (Rodrigo et al. 2001) are the most important predictors.

The SLP fields of the years 1573 and 1740 demonstrated that the extended winter coldness over Europe might be related to different large-scale SLP patterns.

The EOF analysis of the 500 year winter SLP reconstruction reproduced three well known patterns with the most important dipole pattern representing European zonal flow, similar to the NAO pattern. This pattern is very frequent at present, and the steep upward trend at the end of the twentieth century is unprecedented.

For the pre-1659 period, the variance of the reconstructed SLP patterns is reduced, mainly due to the concomitant reduction in original data. EOF 3 (meridional flow pattern) seems to be most affected including SLP patterns with westward extended Russian high-pressure influence.

These extended SLP grids are also important for all kind of climatic analyses that deal with natural variability on time scales reaching from months to decades or centuries. This not only includes studies of European circulation dynamics extended further into the historical past but also applications within interdisciplinary research domains. For instance, flood frequencies and their long-term variability, investigated in the context of European scientific cooperations by historians and hydrologists, will be analyzed in terms of concomitant variations in climate conditions, thereby attempting to determine distinct climatic regimes favouring the occurrence of high or low flood frequencies on decadal to centennial time scales. This will only be possible with atmospheric grids (also on the 500 hPa level with similar reconstruction skill) that are reconstructed for several centuries. These (reconstructions on different levels) are now available, in a first step, for the North-Atlantic-European region dating back to 1500.

These reconstructions can further be compared with model-generated SLP reconstructions of natural and forced (external and internal) variability for the last centuries.

Acknowledgements This work was mainly supported by the FLOODRISK project, funded by the Swiss National Science Foundation (SNF), grant 11-52786.97 and the associated EXTREME 1500 project (Hydrological extremes in Central Europe since 1500), funded by the German Science Foundation (DFG). In its last phase, the support of the Swiss NCCR climate programme is also acknowledged. The authors are grateful for the predictor data available from various sources (GHCN2, NCAR, the IMPROVE, ADVICE, FLOODRISK and other projects). We would also like to express our thanks to the following persons, who kindly provided their valuable instrumental time series and/or reconstructed proxy data, through which our reconstructions were made possible: PD Jones (UK data, pressure series); V Slonosky (pressure series), C Pfister (Swiss data), R Glaser and G Koslowski (German data and Western Baltic Sea Ice Index); R Brazdil (Czech data); L Racz (Hungarian data); P Frich and T Schmith (Danish wind data); R Touchan (S Jordan data); FS Rodrigo, M Barriendos and J Martin-Vide (Spanish data); MJ Alcoforado (Portuguese data); RD D'Arrigo and H Cullen (Turkish data); JE Wallevik, H Sigurjonsson, A Ogilvie and T Jonsson (Icelandic data); H Bergström and A Moberg (Swedish data); H Vesajoki, J Holopainen and A Drebs (Finnish data); I Auer, R Boehm and W Schöner (Austrian data), E Cook (reconstructed NAO). The three reviewers made useful comments and suggestions and helped to improve the quality of the study. Many thanks go also to Barbara Schichler (University of Bern) for proofreading the English text. The reconstructed SLP and 500 hPa fields are available from the World Data Center for Paleoclimatology and NOAA Paleoclimatology Program http://www.ngdc.noaa.gov/paleo/pubs/luterbacher2002 and from the MEDIAS-France homepage http://medias.obs-mip.fr/slp.

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