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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° × 5° 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.

Keywords Sea level pressure · Climate field reconstructions · Logbooks · Instrumental pressure series · Europe · Principal component regression

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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; Rodríguez 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 $5° \times 5°$ 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 inter-annual-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 $5° \times 5°$ 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 preparation).

This study is structured as follows: Section 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 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, Sect. 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.

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.

2.1 Data

2.1.1 Instrumental pressure series

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 supplementary online Table 1 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).

2.1.2 Wind information derived from ship logbooks

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. 2005b). 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; 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. 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° × 8° grid boxes in order to ensure a high enough data density containing meaningful wind information (see Fig. 1, left panel).

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 Sect. 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 Fig. 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° × 8° 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*).

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 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

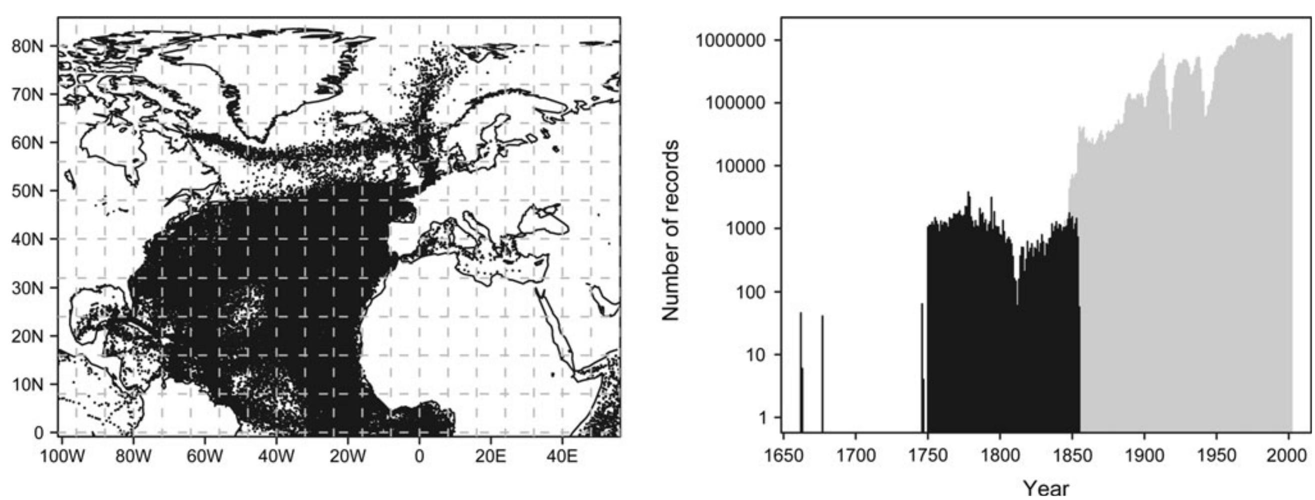


Fig. 1 *Left* location of CLIWOC records (*black dots*) for the period 1750–1855. The *grey dashed* grid indicates the 8° × 8° grid boxes over which the CLIWOC data were averaged. *Right* annual number of records from CLIWOC (*black columns*) and ICOADS (*grey columns*) 1662–2002 over the North Atlantic (100°W–50°E and 0°–90°N). Note the logarithmic scale of the number of records

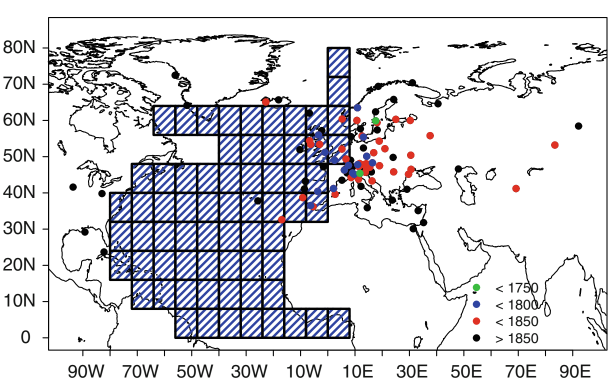
records aggregated over 8° × 8° grid boxes is spatially variable with few records north of 60°N but many records in the English Channel and along the Northwestern African and the Iberian coasts (see also Fig. 1 in the supplementary online material). This means that the true wind conditions may be assumed 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° × 8° 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 2 in the supplementary online material, 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 Fig. 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° × 8° 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° × 8° 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 Sect. 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 Sect. 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 Sect. 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° × 8° 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. 1 in the supplementary online material 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. 2 in the supplementary online material).

Figure 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.

2.3 Reconstruction methodology

Multivariate principal component regression was used to reconstruct 5° × 5° resolved seasonal mean SLP fields for



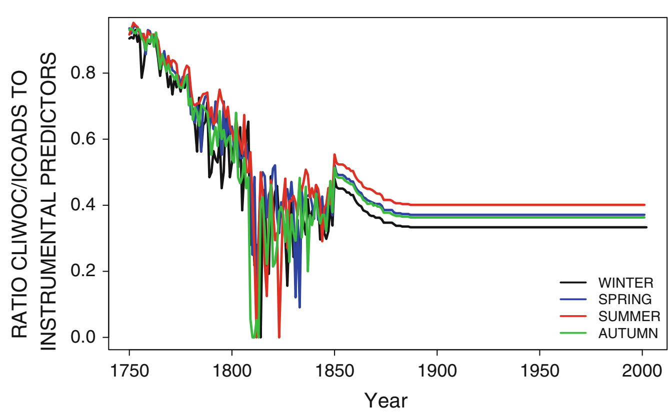


Fig. 2 *Left* complete predictor network used to reconstruct seasonal North Atlantic, European and Mediterranean SLP fields 1750–2002. The *blue shaded* grid boxes are the 8° × 8° aggregated and averaged wind information derived from ship logbooks while the *dots* represent the terrestrial instrumental 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

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° × 5° gridded instrumental SLP 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, empirical orthogonal functions (EOFs) 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 and Zwiers 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° × 8° grid boxes (due to the partly low number of available records), as well as by the large number of predictors (see Sect. 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 $-\infty$ 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 gives an overview of the data pre-processing and reconstruction methodology applied in this study.

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.

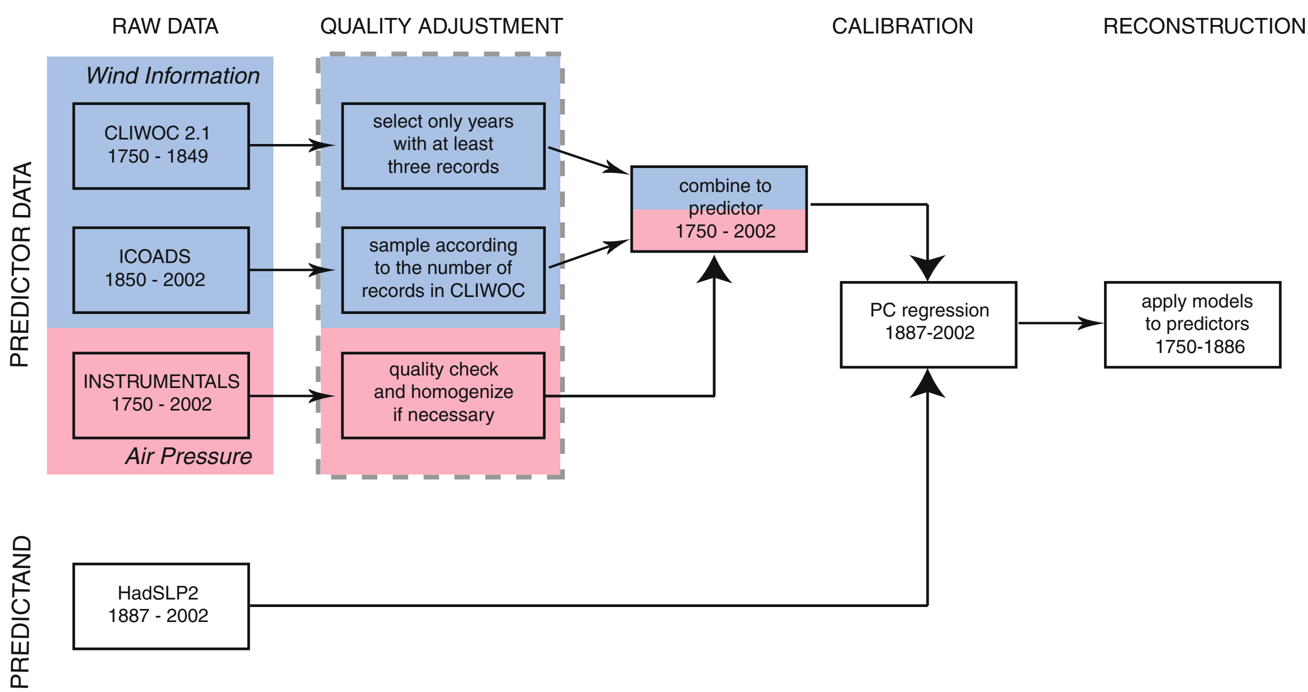


Fig. 3 Scheme for the data pre-processing and reconstruction methodology applied to reconstruct seasonal North Atlantic, European and Mediterranean SLP fields back to 1750. The predictor data (wind information derived from logbooks, *blue* and instrumental pressure series, *red*) were pre-processed to 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

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.

3.1 Overall model performance

Figure 4 presents the performance of the seasonal reconstructions expressed as RE scores averaged over three subregions (northeastern and southeastern North Atlantic and continental Europe) as well as over the entire grid (40°W–50°E and 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.

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 Fig. 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

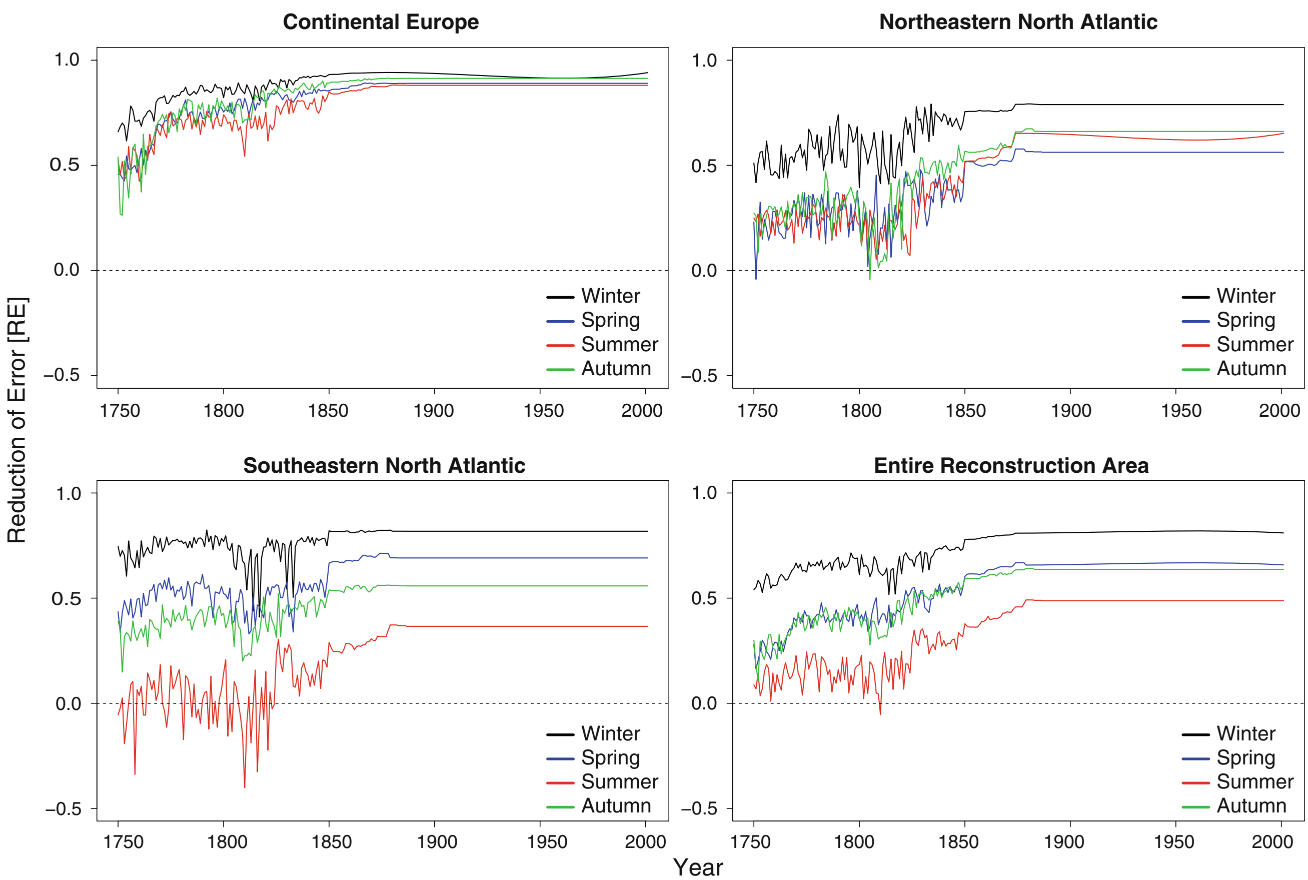


Fig. 4 Seasonal evolution of RE skill scores 1750–2002 averaged over continental Europe (10°W–25°E and 40°N–60°N; *top left* panel), the marine region of the northeastern North Atlantic (40°W–0° and 50°N–70°N; *top right* panel), the marine region of the southeastern North Atlantic (40°W–0° and 20°N–45°N; *bottom left* panel), and for the entire reconstruction area (40°W–50°E and 20°N–70°N; *bottom right* panel). Positive values indicate higher skill than climatology

representation of the SLP field over the reconstruction area even with a spatially and temporally limited predictor network. We subsequently focus only on winter.

3.2 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 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. 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. 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. 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

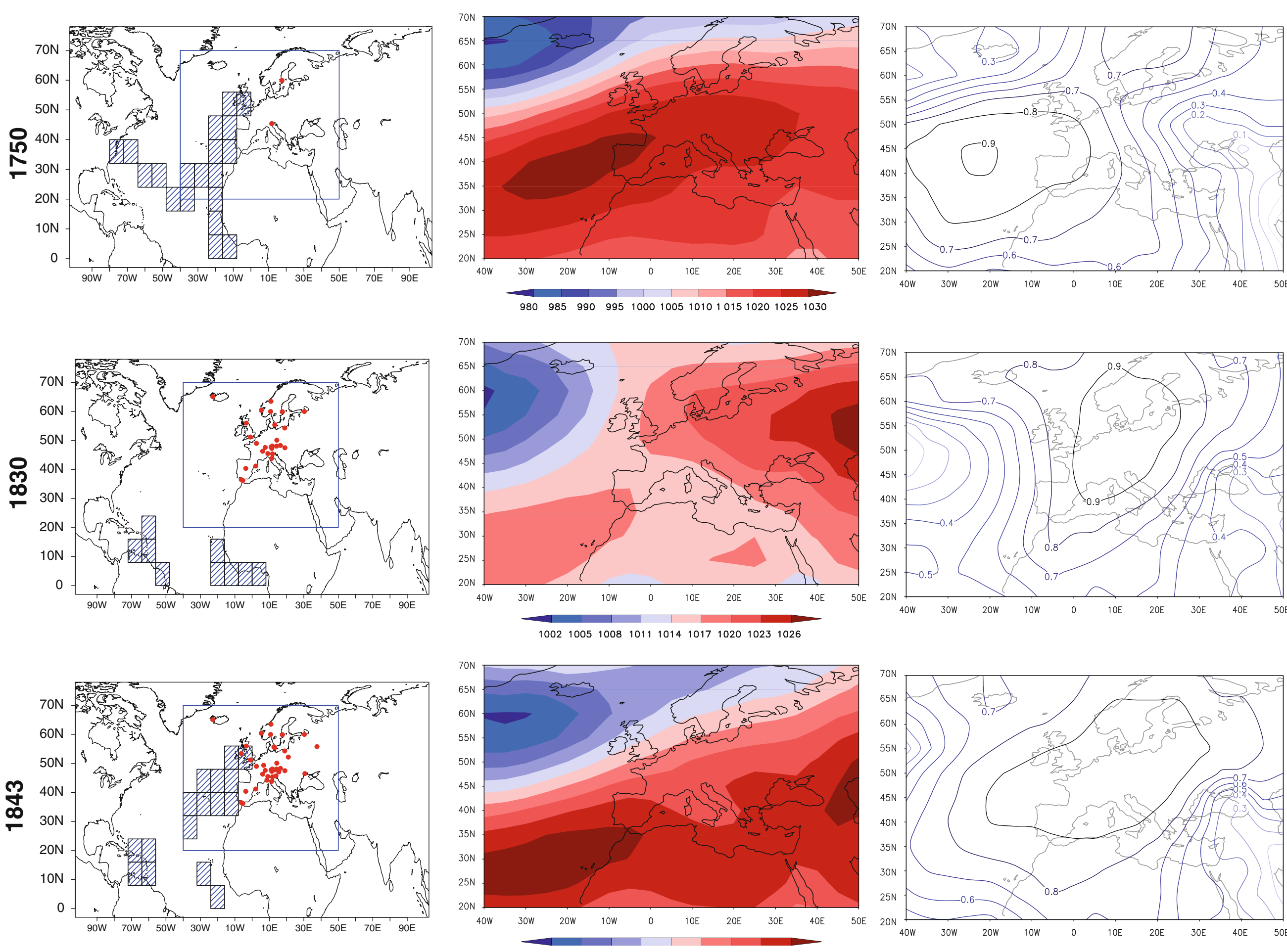


Fig. 5 *Left* predictor network (*blue shaded* boxes denote CLIWOC wind information, *red dots* refer to instrumental pressure series, *blue frame*: reconstruction area); *middle* Reconstructed SLP field; *right* Reconstruction skill expressed as RE values calculated during the verification period 1965–2002 for winter 1750 (*top row*), 1830 (*middle row*), and 1843 (*bottom row*)

available for the winter of 1830 (Fig. 5, middle row). The reconstruction for this winter mostly relies on instrumental pressure time series but hardly any information from CLIWOC (Fig. 5, middle left panel). It shows a strong Western Russian high (Fig. 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. 5, middle right) with RE values in the range of 0.2–0.6. 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.

As an example of a spatially well-distributed predictor network over the sea and the continent, Fig. 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. 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. 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.

3.3 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 5 indicated that the use of CLIWOC information does indeed improve the reconstruction skill over the entire North Atlantic. To emphasise this improvement, Fig. 6 presents the time series of the reconstructed SLP (using instrumental pressure series only and additionally with CLIWOC data), each averaged over four 5° × 5° grid boxes located south of Iceland and over the Azores, along with the associated skill scores.

Figure 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. 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.

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

To evaluate our SLP reconstruction, Fig. 7 shows the correlation between this study and the SLP reconstruction by Luterbacher et al. (2002) at each 5° × 5° grid box over the winters of the period 1750–1850 for the common reconstruction area (30°W–40°E and 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

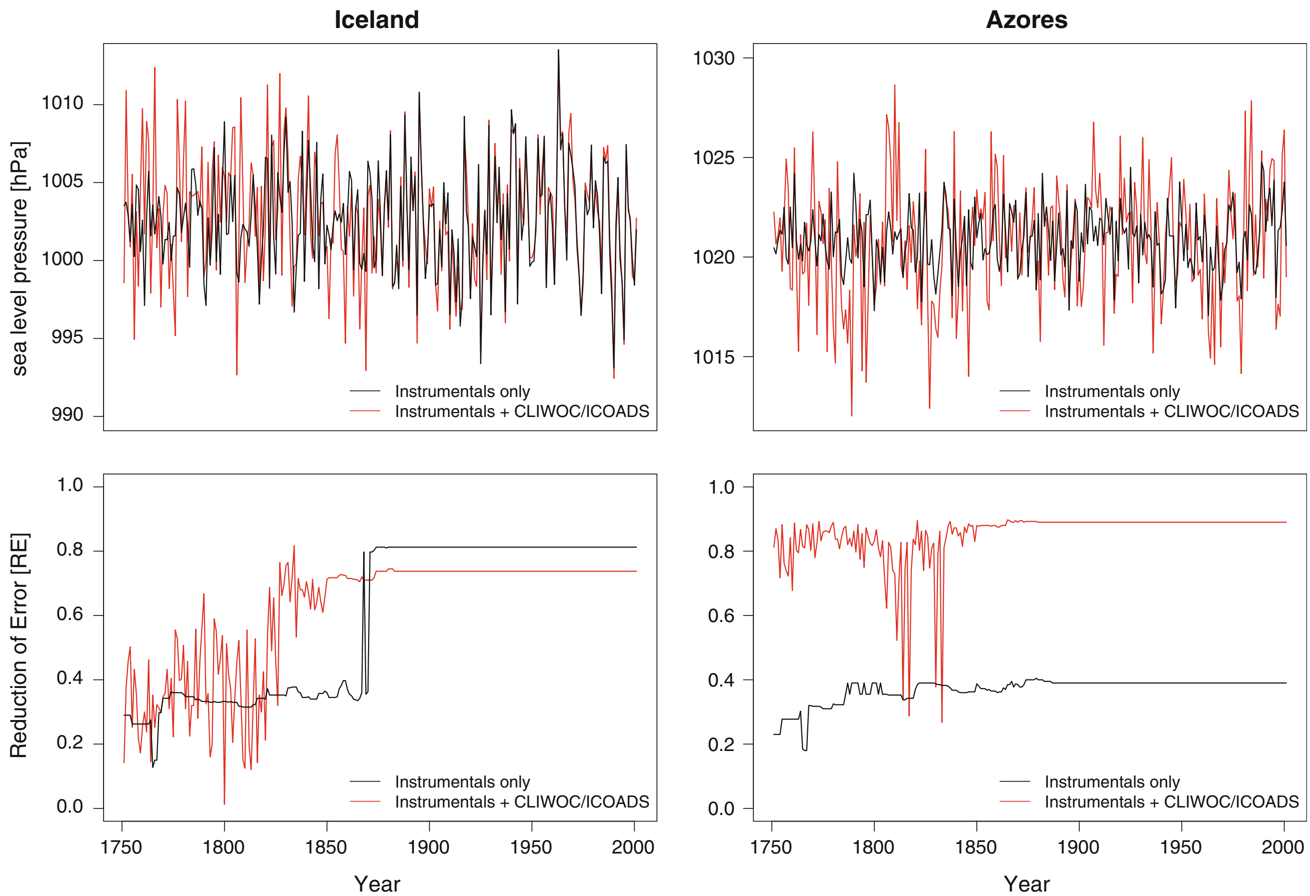


Fig. 6 Reconstructed winter SLP (*top*) and corresponding RE scores (*bottom*) each averaged over four grid boxes located south of Iceland (*left*, grid boxes centred at 17.5°W and 62.5°N) and the Azores (*right*, grid boxes centred at 27.5°W and 37.5°N) 1750–2002. The *black line* is the reconstruction based on instrumental pressure records only, the *red line* additionally includes ship log data

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. 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 south-eastern 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 (Fig. 8 for winter; for the other seasons see Figs. 3–5 in the supplementary online material). For summer, a correlation coefficient of 0.35 ($p < 0.1$) was found for Liverpool (Fig. 4 in the supplementary online material). 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

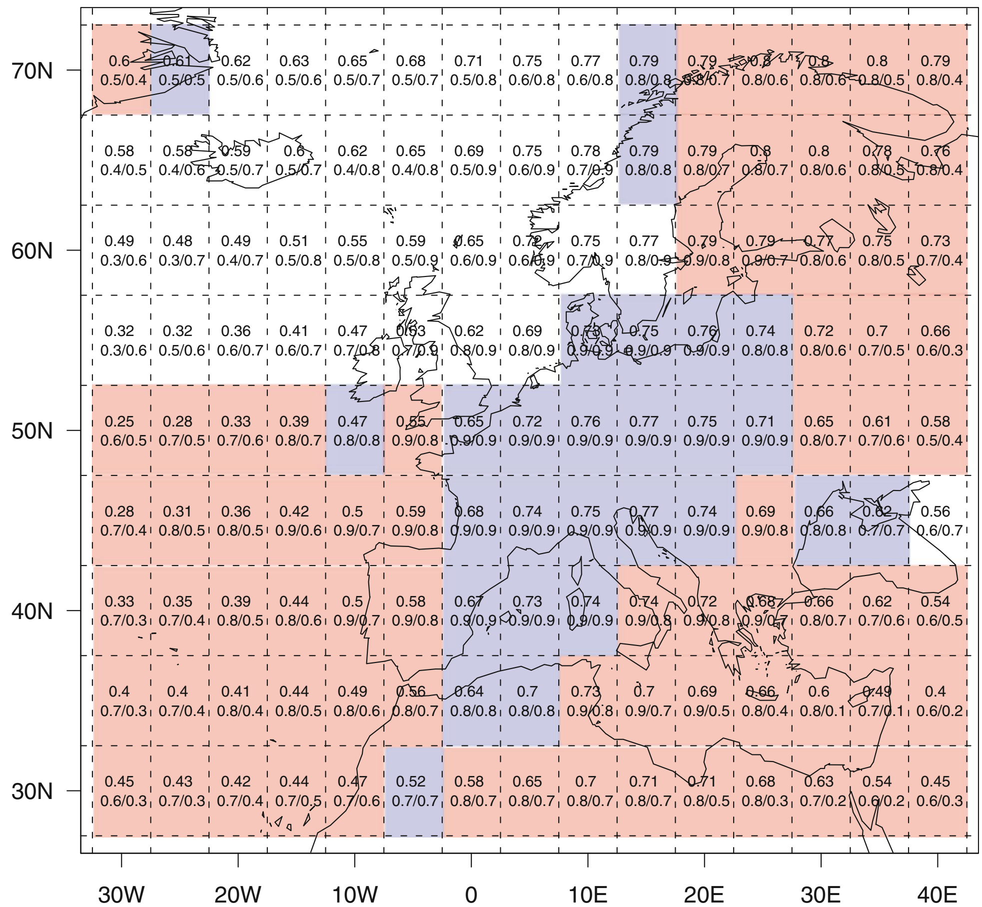


Fig. 7 Comparison of the spatial skill of the reconstruction from this study and Luterbacher et al. (2002) during the winters of the overlapping period 1750–1850. Each 5° × 5° grid box shows at the top line the correlation values and at the bottom line the mean RE skill of this study (*left*) and Luterbacher 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

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. 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.

4 Conclusions and outlook

Combining North Atlantic wind information derived from logbooks and instrumental pressure series from continental Europe and adjacent regions, a 5° × 5° 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 preparation).

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

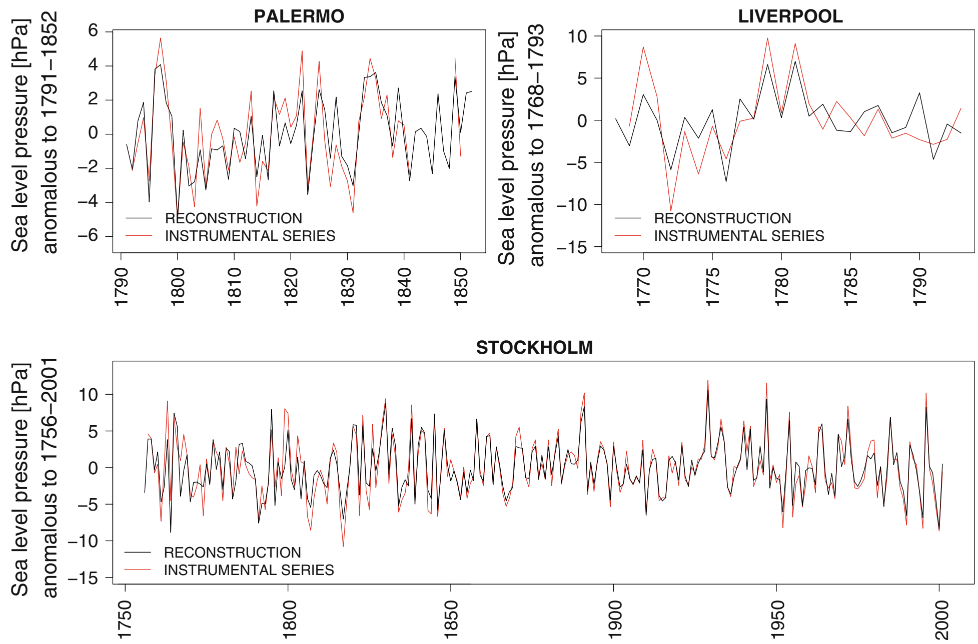


Fig. 8 Winter mean SLP from independent instrumental pressure series (*red lines*) and as reconstructed at the corresponding 5° × 5° grid box (*black lines*) for Palermo (1791–1852; Barriendos et al. 2009), Liverpool (1768–1793; Woodworth 2006), and Stockholm (1756–2001; Moberg et al. 2002). The correlation coefficients are 0.87 (Palermo), 0.76 (Liverpool), and 0.92 (Stockholm), all significant at the 99% significance level

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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