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Documentary data provide evidence of Stockholm average winter to spring temperatures in the eighteenth and nineteenth centuries

L. Leijonhufvud,[1]* R. Wilson[2] and A. Moberg[3]

([1]Department of Economic History, Stockholm University, S-106 91 Stockholm, Sweden; [2]School of Geography & Geosciences, University of St Andrews, St Andrews KY16 9AL, UK; [3]Department of Physical Geography and Quaternary Geology, Stockholm University, S-106 91 Stockholm, Sweden)

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Abstract: Swedish archives provide several types of documentary sources relating to port activities in Stockholm for the eighteenth and nineteenth centuries. These documentary sources reflect sea ice conditions in the harbour inlet and correlate well with late-winter to early-spring temperatures. Instrumental measurements of temperature in Stockholm began in 1756, which allow for careful empirical assessment of the proxies from that date. After combining proxy series from several sources to derive a mean time series, calibration and verification trials are made and a preliminary January–April temperature reconstruction is developed from 1692 to 1892. This series, which explains 67% of the temperature variance, is further verified against independent temperature data from Uppsala, which go back to 1722. This additional verification of the reconstruction also assesses the quality of the early instrumental data from Uppsala, which has potential homogeneity problems before 1739 as a result of the thermometer being located indoors. Our analysis suggests that before this date, the instrumental data may be 'too warm' and need correction. Together, the documentary and instrumental data identify the post-1990 period as the warmest in three centuries. Continuing assessment of the historical archives should result in some of the documentary records being extended back into the early sixteenth century, allowing the future development of a southern Swedish winter temperature reconstruction for the last ~500 years.

Key words: Winter temperatures, climate reconstruction, documentary sources, dendroclimatological methods, Sweden.

Introduction

> After adjusting the time-series we are happy to say that the residuals are perfectly normal, thank you very much. (Paraphrasing Harry Potter).

Prior to the establishment of the first regular meteorological observations in Uppsala (1722), Lund (1740) and Stockholm (1756) (Moberg, 1998), information on past climate in southern Sweden (Figure 1) must be drawn from either non-instrumental man-made sources (eg, scientific writings, narratives, administrative records, descriptions of warm and cold spells and freezing of water bodies – see Pfister *et al*., 1999) or from proxy evidence obtained from natural archives (eg, tree-rings). Historical documentary sources are particularly valuable as they may allow the development of high-resolution (monthly to annual) reconstructions of past precipitation and temperature changes as well as providing invaluable information on extreme events such as storms, floods and other natural disasters (Brazdil *et al*., 2005). As tree-ring data normally provide proxy information for the summer (ie, growth) season, documentary sources are also invaluable as they can provide past climatic information for other seasons (ie, winter).

In this paper, we explore the potential of documentary historical sources, related to harbour activity around the city of Stockholm, as proxies of past winter temperatures. A similar approach has been described by Tarand and Nordli (2001) who used port journals, custom books, town council minutes and similar historical documents as sources of evidence for ice break-up dates in the port of Tallinn, Estonia (Figure 1). They argued that ice break-up dates was a good proxy for winter temperatures and developed a December–February temperature reconstruction back to 1500. In this study we hypothesize that it might be more correct to interpret man-made documentary sources as reflections of human behaviour, which are in turn susceptible to specific climatic phenomena, rather than to view such sources

*Author for correspondence (e-mail: Lotta.Leijonhufvud@ekohist.su.se)

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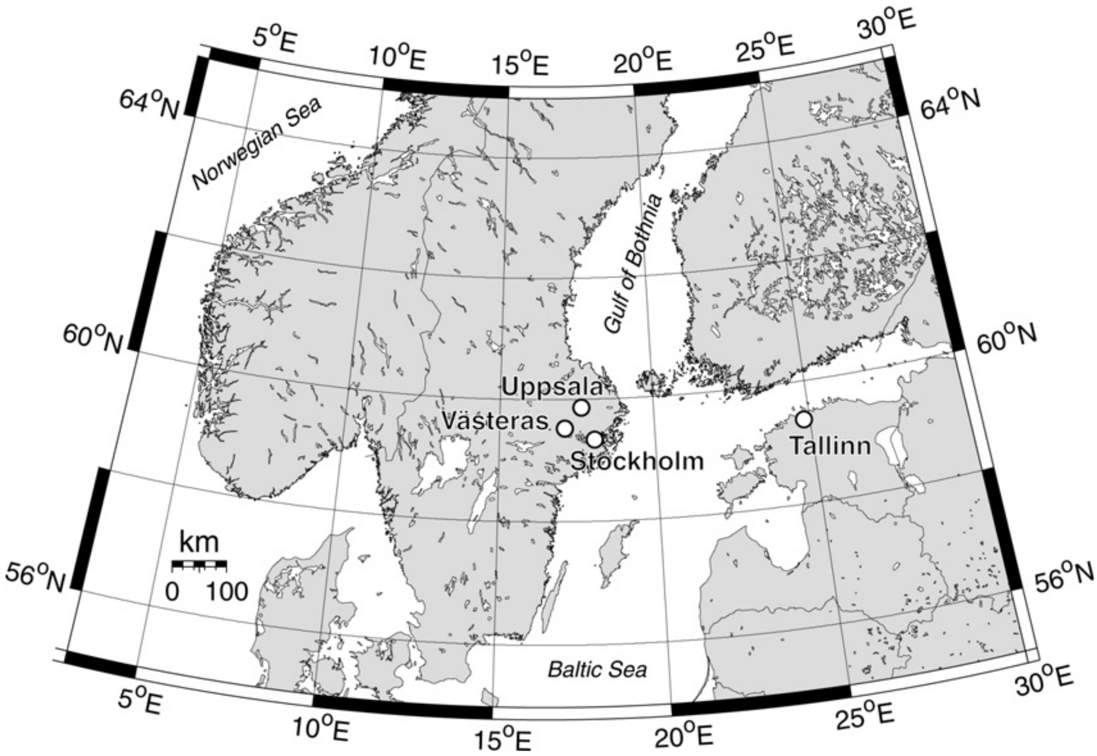

Figure 1 Location map

as direct proxies of temperature and precipitation. For example, port-journals may be used to assess the beginning of the sailing season, which ultimately cannot start until the inlet to the harbour is ice-free. However, ice-free water is a necessary, but not the only, condition for sailing. In reality therefore, man-made sources probably reflect human expectations of weather rather than the climatic conditions themselves.

Swedish data sources for harbour activity

Table 1 lists the available historical sources for the eighteenth and nineteenth centuries that may be regarded as reflecting the beginning and end of the sailing season, and might therefore be used as proxies for temperature. Of these sources, only the 'ice break-up' (Hildebrandsson, 1915) and official statistics (*Berättelse angående Stockholms kommunalförvaltning År 1894*, 1896) have previously been published. The remaining data are only available as handwritten archival material. Shipping generated several kinds of port activities with subsequent administration. All the sources (see Table 1) below refer to different administrative procedures of the central and/or local governments with connections to shipping.

These administrative activities were carried out on a daily basis for the entire sailing season and detailed notes were made throughout this period. At the end of the year a chronological summary was made in a ledger (cf. Odén, 1960). Many of these ledgers are preserved and are easy to work with since they are chronologically ordered. Historians have utilized these books for decades to try to estimate trade volumes and assess issues related to smuggling and exemptions from taxes – and other dues and fees. The latter problem does not concern this study, since privileged people were still recorded in the ledgers, though not with the value of their imported or exported goods, but only when they arrived or departed. Smuggling is also likely not a problem since it is easier to avoid the attendance of the authorities in a crowd, rather than arriving as the first ship of the season.

Administrative proceedings were generally carried out more or less immediately before the time of the actual journey. Some, such as the payment for imported goods were generally made very close to arrival, since the merchants were not allowed to unload their ships until their accounts had been settled (Smith, 1950). Others, such as the sea passports, could be organized well in advance of a planned journey.

Once the documentary-based data had been obtained, the sailing dates were transformed to the number of days after 1 January, adjusting for differences between the Julian and the Gregorian calendar. (See Haldorsson (1996) for further explanations on the Gregorian calendar reform in Sweden.) In a few select cases, some problems were noted on the decision whether a particular date should represent the end of the autumn sailing season, or if it should be interpreted as marking the start of the spring sailing season. Usually, there is a gap in the accounts of at least 2 months, eg, the 'last ship' arrived in late January and the 'first ship' arrived in late March. The ship arriving before the gap has been regarded as the last ship of the previous season, even though it has been recorded for the same year as the ship we have regarded as the 'first ship' of the season. However, when there has only been, for example, one month between the 'last' and 'first' ship, it is very difficult to assess which ship was the last of sailing season and which was the first. These problems are generally connected with very mild winters; probably with open water all year round. We are well aware that this causes certain arbitrariness in the data set, which may influence the empirical relationship with temperature.

Ship records

Ship records were drawn up in the city's Chamber of Commerce and could be arranged well in advance of the planned travel. They were made for the control of people and to prevent criminals from leaving the country. The dated protocols are standardized and specify which people would go on a particular journey. The protocol would later be shown to the harbour-master. A copy was made and saved in the archives of the Chamber of Commerce and these copies were, at the end of the year, hardbound.

Table 1 Proxy data from different kinds of administrative records for the eighteenth and nineteenth centuries used in the reconstruction

Archive/source	Variable label	Brief description	Reflecting	Period of coverage
SSA, Hak, Sjöfolkskontrollen,	Ship records spring	Registers of sailors leaving Stockholm in the spring	Opening of sailing season	1692–1841
Skeppsprotokoll & Skeppsinlagor	Ship records autumn	Registers of sailors leaving Stockholm in the autumn	Closing of sailing season	1692–1841
SSA, Stadskamrerarens Verifikationer	First arrival (*tolag*)	Arrival of ships in the spring according to the Stockholm municipal custom registers	Opening of sailing season	1636–1841
Tolags-	First departure (*tolag*)	Departure of ships in the spring according to the Stockholm municipal custom registers	Opening of sailing season	1636–1841
Journaler	Last arrival (*tolag*)	Arrival of ships in the autumn according to the Stockholm municipal custom registers	Closing of sailing season	1636–1841
	Last departure (*tolag*)	Departure of ships in the autumn according to the Stockholm municipal custom registers	Closing of sailing season	1636–1841
SSA, Hak, Huvudprotokoll	Ballast	Planks granted for ballast by the city council	Opening of sailing season	1673–1734
RA, KoK, Passdiarier; SSA, Hak, Inkomna sjöpass	Sea passports	Insurance documents for ships travelling to the Mediterranean and beyond. Stockholm is home-port	Opening of sailing season	1689–1831
Hildebrandsson (1915)	Ice break-up	In Västerås: 'when the lake Mälaren is so open and free of ice that the sailing season between Västerås and Stockholm has begun'	Opening of sailing season	1712–1892
Berättelse angående Stockholms	Official statistics – begin sailing	Official statistics of the opening of the sailing season	Opening of sailing season	1815–1892
Kommunalförvaltning År (1894, 1896)	Official statistics – end sailing	Official statistics of the closing of the sailing season	Closing of sailing season	1815–1892

The proxies we are using are 'the beginning' and 'the end' of sailing season. Different administrative routines have captured these events differently. The various series are labelled in accordance with their original names in the archives.
This paper focuses on calibration and vertification of documentary data, which is why we have not extended the temperature reconstruction before 1692, when the ship records series begin.

The ship records series begin on 29 May 1691 and end in 1841. Since the decision to draw lists of departing sailors was made on 22 May 1691, the start of the sailing season for that year cannot be determined by the ship records (SSA, Handelskollegium, Sjöfolkskontrollen, Skeppsprotokoll, 1691). The ship records form a complete series from 1692 to 1841 without any gaps.

Tolag

Tolag was instituted by the Crown in 1636 as a duty on goods transported by sea – though some land-transported goods also paid the duty – to pay for port-facilities. It was generally granted to a city under condition that the city also collected *Stora sjötullen* (the major import–export toll) for the Crown (Dalhede, 2005). Only the towns that were allowed to have foreign trade could levy the *tolag*. (Etymologically, the word is probably a variant of the old Germanic words of 'tull' (Swedish), 'toll' (English) and 'zoll' (German).) It was levied as percentages of the value of the goods.

The structure of the *tolag*-registers is similar to that of the ship records, though less organized. The registers were made to ensure that duties were paid. At the top of the page there is almost always a date, which has been interpreted as the date when the ship arrived/departed because, not uncommonly, there are also dates along the margin, which clearly refer to the day when payment was actually made. The ships were numbered, where the first ship most often also had the earliest arrival (departure) date. When this was not the case, the earliest date was chosen as the start of the sailing season. This situation, that ship number 1 might not have the earliest arrival date, probably occurred because of a delay between the date when the custom officers went off to inspect an arriving ship to assess how valuable its cargo was, and when the captain actually presented himself at the custom-office.

Sea passports

The National Board of Trade, *Kommerskollegium*, was founded in 1651 and was given the task of supporting trade, shipping and industry. Over the centuries it has produced huge archives among which is a collection of 'sea passports' that functioned as a kind of insurance against piracy in the Mediterranean. From 1665 there exist drafts of sea passports and from 1739 there are diaries for all issued sea passports. The drafts are not so well preserved, or there were never many of them. The diaries, however, are more comprehensive and are presented as long, chronological tables. It is therefore only necessary to find the first passport with the home-port of Stockholm for a particular year.

The homeport is the most critical issue for using sea passports as a source for identifying the beginning of sailing season in Stockholm, because it is not certain that the homeport was the same as the sailing port. Sometimes this difference is apparent when a sailing port was explicitly stated. However, such a practice may vary over time, as well as the diligence of the diary-keeper.

Another problem with sea passports is that they were issued to, and required by, only part of the foreign trade and not necessarily by those merchants setting sail at the very beginning of the sailing season. Since they were mainly issued for longer – and therefore more perilous – journeys, it seems reasonable to assume that the captains, and shareholders of the cargo, tried to limit the risks as much as possible. One such risk that they could minimize was to start the journey when there was no doubt that ice-free conditions occurred along the route.

The sea passport diaries are available until 1831, after which there was an administrative re-organization and they were combined with privileges of tax-exemptions. Because of this administrative change for the archive, as well as weak empirical correlations with temperature (see Figure 2), we stopped the collection of this data source from 1832. However, we considered it worthwhile to investigate the sea passports, because they go back further in time and may be a complimentary source for the seventeenth century for later work.

Planks granted for ballast

Planks granted for ballast by the City Council constitute a much shorter series, but the archive begins in the early 1670s. There are

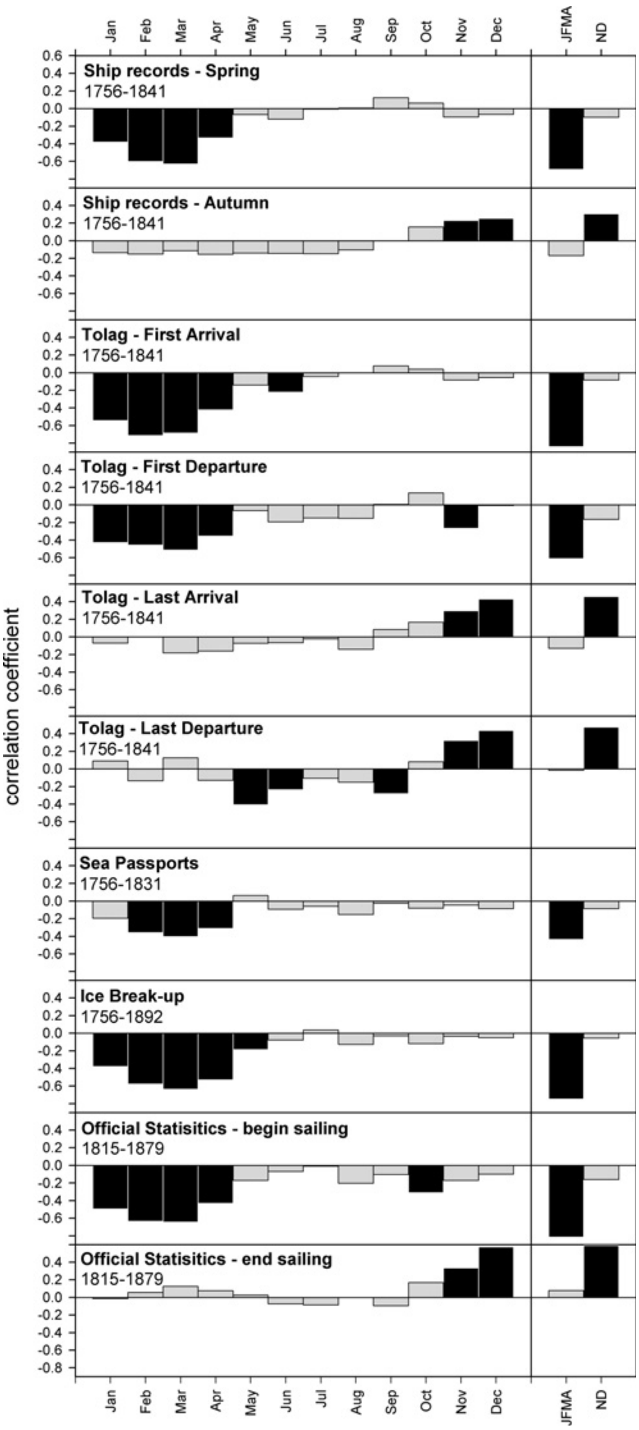

Figure 2 Correlation analysis between the documentary records and monthly temperature series from Stockholm (Moberg *et al*., 2002). The analysis results (calculated over different periods) are shown from January to December as well as for mean temperatures for January–April (JFMA) and November–December (ND). Significant (95% CL) correlations are highlighted in black

some gaps in the mid 1670s and during most of the 1680s. Between 1689 and 1734, only two years are missing; 1708 and 1709. These records of planks (or 'wood') can be found among the main records of proceedings of the Chamber of Commerce. This source features similar problems to the sea passports. The number of ships is fewer than those registered in the *tolag* and ship records accounts. The application for ballast could be made well in advance of a planned journey, as was also the case for the sea passports. The ledgers are otherwise similar to the other sources; chronologically ordered, with the account running over the calendar year, and the first applicants applying for allowance to take wood as ballast sometime after New Year.

Ice break-up

We used 'ice break-up' data from Västerås, a town situated on lake Mälaren *c*. 90 km west of Stockholm (Figure 1). These data were published in 1915 (Hildebrandsson, 1915) and are probably less like scientific observations of the natural phenomenon of ice break-up but similar in character to the newly collected data reflecting the beginning of the sailing season. Hildebrandsson used data published earlier by Hülphers (1765, 1793). For the first period, 1712–1752, they are based on notes from diaries from the 'seamen's' guild, which, according to Hülphers, 'are completely trustworthy' (Hülphers, 1765, our translation. We have translated *båtsman* as 'seaman'). It is not clear what the seamen's guild meant by 'open water'. Are these observational notes that there was no ice on the lake, or do these notes rather reflect the circumstance that some of their members were ordered to be put to sea?

For the period 1753–1793, the dates refer to Hülphers's observations. He states that ice break-up is 'the time when the lake Mälaren is so open and free of ice that the sailing season between Västerås and Stockholm has begun' (Hülphers, 1765, our translation), but no similar declaration is made for the notes for the period 1766–1793 (Hülphers, 1793). In this study we assume that Hülphers used the same observational criteria for the later period as he used for the former one. Between 1794 and 1835, observations were made by J. Widell, Master of Balance (probably the iron balance in Västerås) and from 1835 by the Master of Balance O. Norelius (manuscript part of the Hildebrandsson paper). This implies that the construction of the 'ice break-up' series makes them more closely related to our other sources and being therefore more indicative of man's dependency on climatic conditions rather than the natural proxy 'ice break-up'.

Differences between this 'ice break-up' series and the custom-books from Stockholm may to some degree depend on natural differences in ice-conditions between the two towns. Hülphers noted that there can be large differences in ice conditions on lake Mälaren, and that the bay at Västerås has a later ice break-up date than, for example, the narrow passes close to Stockholm, which were open longer (Hülphers, 1765).

Official port statistics

The official port statistics on the beginning and end of the sailing season are published in a series of City Council's Working Committee and begin in 1815. The original notes were taken from the Harbour Master's Office (*Berättelse angående Stockholms kommunalförvaltning År 1894*, 1896). This statistic is interesting as it makes a distinction between sailing season and open water; the sailing season is usually shorter than the number of days with open water. The number of days of open water, or, rather, the number of days of ice, may be regarded as a natural proxy variable for winter temperatures. We have chosen not to include the number of days with ice in the reconstruction as that source is intrinsically different from the others that we use, and focus only on the beginning and end of the sailing season.

Assessment of the historical sources as climatic proxies

Empirical correlation analysis between each documentary source and monthly mean temperature values from Stockholm, based on instrumental data from Moberg *et al*. (2002), was undertaken over the respective common period between each source and the

Table 2 Interproxy correlations

	SRS	TFA	TFD	SP	IBU	BS
BA	0.28* (41)	0.35 (16)	0.55** (24)	–	0.30 (23)	–
SRS		0.78** (15)	0.91** (81)	0.47** (94)	0.63** (130)	0.84** (27)
TFA			0.89** (70)	0.63** (77)	0.73** (100)	0.90** (26)
TFD				0.67** (47)	0.58** (75)	0.97** (25)
SP					0.39** (94)	0.32 (17)
IBU						0.80** (65)

Correlations are made over the period of maximum overlap between bivariate pairs. The number of observations are denoted in parentheses. Significance levels are * 90% and ** 95%. BA, ballast; SRS, ship records (spring); TFA, *tolag* (first arrival); TFD, *tolag* (first departure); SP, sea passports; IBU, ice break-up; BS, official records (beginning of sailing season).

instrumental data to quantify how well each documentary time series may reflect monthly mean temperatures throughout the year. Figure 2 presents the results and shows that significant (95% confidence level) inverse correlations are found with January–April mean temperatures for the ship records (spring (–0.69)), *tolag* (first arrival (–0.84) and departure (–0.61)), ice break-up (–0.75) and the beginning of sailing date in the official statistics (–0.82). A weaker (–0.44), but still significant, correlation is also found with the sea passport data. The other data sets reflect late-autumn temperatures at the end of the sailing season but generally cohere more weakly with the instrumental data. We decided therefore to concentrate our study on late-winter to early-spring proxies to derive a reconstruction of winter (January to April) temperature.

The ship records (spring), *tolag* (first arrival and departure), ice break-up, the beginning of sailing season in the official statistics and the sea passport data essentially reflect the timing of the ice break-up in the spring. The reason that these data correlate best with a broader seasonal window (ie, January–April) is most likely related to the fact that the thickness of the sea ice reflects the severity of winter conditions. However, it should also be recalled that man-made sources reflect, above all, human behaviour, and this behaviour may reflect climatic conditions in a more varied and subtle way than only the physicality of ice thickness. Hence, the man-made sources analysed here may better reflect 'cold', but not 'severe' winters than actual observations of ice break-up would, because man is more flexible and may react faster to changing conditions than natural proxy-variables. This is also the main criticism regarding man as a climatic proxy. One of the very distinctions of humans is our flexibility to overcome the elements.

The plank ballast data could not be assessed in the proxy/climate correlation analysis (Figure 2) as their end date (1734) is before the beginning of the Stockholm instrumental data (1756). Therefore, to quantify whether the ballast data are a valid proxy for winter temperatures, they are compared with the other proxy series using correlation analysis. The resultant correlation matrix (Table 2) shows that in general, the ballast data correlate relatively weakly with the other proxy series. Despite the generally lower correlations portrayed by the ballast data compared with the other historical proxies (Table 2), we include them in the following preliminary reconstruction as a methodological challenge in the knowledge that more sixteenth and seventeenth century data will be generated from other historical sources with similar features. Ongoing data collection will enable better assessment of these data in the future.

A preliminary winter temperature reconstruction 1692–1892

Generating a mean time series

The varying lengths and different start/end dates of the different documentary sources, as well as the multiple missing values in each series represent a problematic situation – but very typical of documentary sources – for the development of a continuous reconstruction of winter temperature for Stockholm. The simplest solution is to average the series together. Figure 3A shows each series after being standardized to z-scores (zero mean and unit standard deviation) and highlights the generally high interseries coherence that was quantified in the correlation matrix (Table 2). Although the simple mean of the individual series (Figure 3B) expresses relatively narrow error bars, the time series is potentially biased for two reasons. First, the time series variance is likely variable through time as an artefact of the changing number of constituent series (Figure 3C) which influences the variance (Osborn *et al*., 1997). Variance will be relatively high for those years where replication (number of historical series) is low compared with those years where replication is high. Second, a Kolmogorov-Smirnov (KS) test for normality, using the Lilliefors significance correction, indicates that the data are negatively skewed at the 95% confidence level. This is because the observational values (ie, the dates) cannot have a normal distribution since the observation of the start of sailing season can only occur if there is no ice, which in turn occurs if temperatures are above 0°C for sufficient time. To correct for these biases, the variance of the time series was first stabilized using a simple scaling procedure outlined in Osborn *et al*. (1997) by using the following equation:

$$Y(t) = X(t)\sqrt{\frac{n(t)}{1 + [n(t) - 1]\,\bar{r}}}$$

where $X(t)$ is the simple mean value at time t, $n(t)$ is the number of series at time t, is the mean correlation between all pairs of time series and $Y(t)$ is the adjusted mean value at time t.

To normalize the distribution of the data, a constant was added to each annual value so that they were all positive, and the resultant values squared. Figure 4A compares the simple mean series to the variance adjusted mean series after the time series have been normalized. Qualitatively, there is little difference, with the largest adjustment being made for the 1863 value. However, the KS test of the distributions (Figure 4B and C) shows that the adjusted time series is now normally distributed and will not violate any assumptions for the regression based reconstruction. The variability of the time series, represented by a moving 31-yr variance plot (Figure 4D), indicates the changes that the variance correction has made. We show later that the variance in the adjusted proxy record better tracks the actual variance changes expressed by winter temperatures since the mid-eighteenth century.

Calibration and verification

As the seven historical series are not continuous and there is no common period of overlap, calibration was made over the period represented by the greatest number of series while allowing a reasonable overlap with the instrumental data from Stockholm. Calibration to January–April temperatures was therefore made

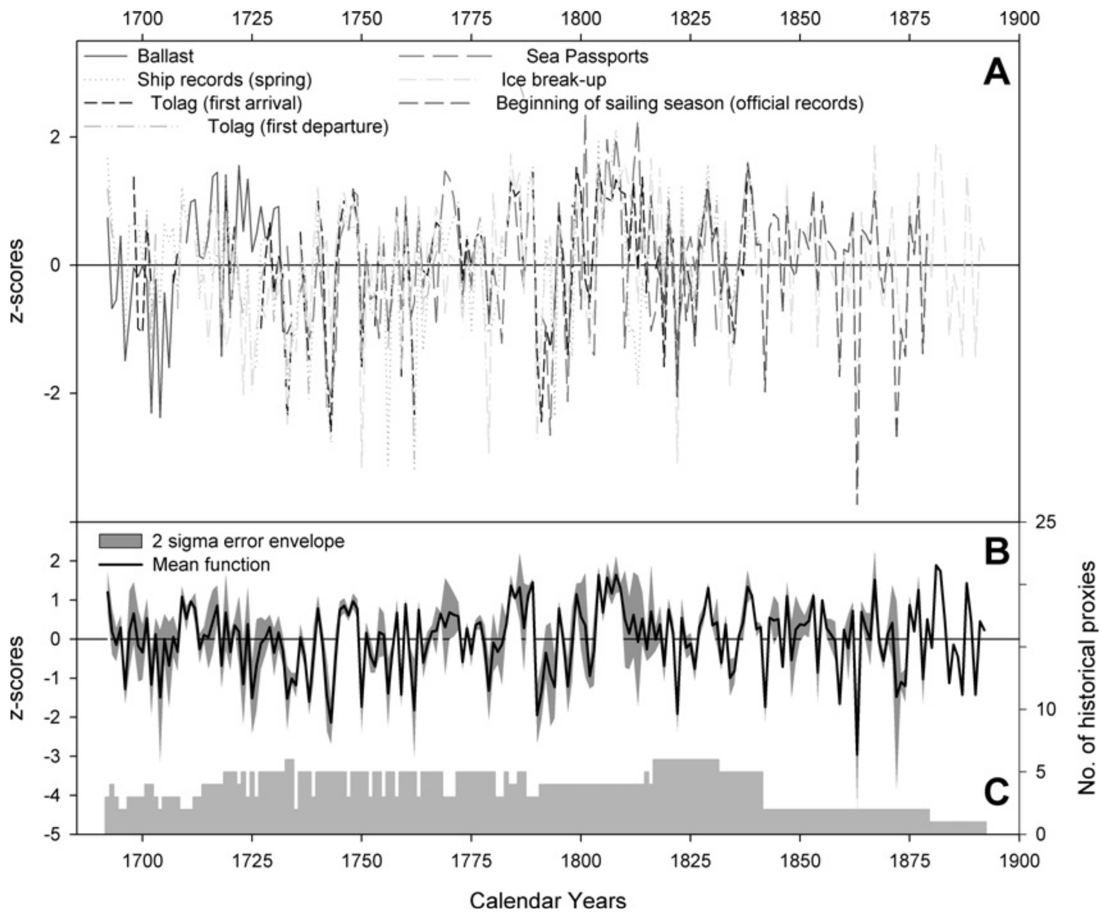

Figure 3 (A) Individual historical proxies after standardization to z-scores. (B) Mean of historical series with 95% error envelope. (C) The histogram denotes the number of records through time

over the 1756–1841 period, with the Stockholm instrumental data starting in 1756, and proxy replication being approximately five documentary series up to 1841 (Figure 3C). Model verification was made over the 1842–1892 period, which is represented by only two proxy series (ice break-up data and official records (beginning of sailing season)). Additional verification is made over the 1722–1755 period (having approximately five documentary series) using instrumental data (Bergström and Moberg, 2002) from Uppsala (located ~65 km north from Stockholm; Figure 1). The correlation between the Uppsala and Stockholm January–April mean temperature series is 0.99 for the period 1756–2006, with Stockholm temperatures being on average ~0.7°C warmer than Uppsala.

This additional period of testing is particularly useful as it allows stringent testing of the final reconstruction, using independent data, outside the period used to evaluate the proxy series (Figure 2) as well as assessing the influence of the inclusion of the Ballast data. The reconstruction is verified using the square of the Pearson's correlation coefficient (r^2), the reduction of error (RE) statistic, and the coefficient of efficiency (CE). These statistics are commonly used in dendroclimatology (Cook *et al*., 1994) and are measures of shared variance between the actual and modelled series. RE and CE are usually lower than the calibration and verification r^2. A positive value for either statistic signifies that the regression model has some skill. CE provides the more rigorous verification test. To test the robustness of the decadal to long-term signal in the reconstruction, assessment of the residual autocorrelation in the regression model was also employed using the Durbin-Watson statistic, as well as by calculating the linear trend (lin R) of the regression residual time series. See, for example, Wilson *et al*. (2006) for a recent explanation of the RE, CE and DW statistics.

Figure 5A presents the calibration results of the adjusted mean series to Stockholm January–April temperatures. Over the calibration period (1756–1841) the proxy explains 67% of the instrumental variance and no trends are observed in the regression model residuals (DW = 2.06 and lin R = 0.16). Verification (1842–1892) is also excellent with RE and CE well above zero at 0.56. The root mean square error (RMSE = 1.13°C) which defines a 95% error envelope around each annual value of ~2.3°C indicates not only the high variance of winter temperatures but that despite the high calibration r^2, the reconstruction does not model well the extreme annual values.

Independent instrumental data from Uppsala of winter temperatures also indicates strong coherence with the reconstruction (Figure 5B). Over the period 1842–1892, similar verification results are obtained to those using the Stockholm instrumental data (Figure 5A). Verification over the period 1722–1755 is more problematic because of known homogeneity issues. Before 1739, Uppsala temperatures were measured indoors in unheated rooms, as well as the data from 1732–1738 being recorded 170 km away from Uppsala itself (Moberg *et al*., 2000; Bergström and Moberg, 2002).Verification was therefore made by splitting the period into two equal length periods (1722–1738 and 1739–1755). Over the later period, verification is excellent (RE = 0.59, CE = 0.58). However, over the 1722–1738 period, although RE remains positive, the CE value is negative (–0.07) indicating loss in coherence between the reconstructed and actual temperature data. These poor results reflect the higher temperature values in the measured data compared with the reconstruction over this period, suggesting

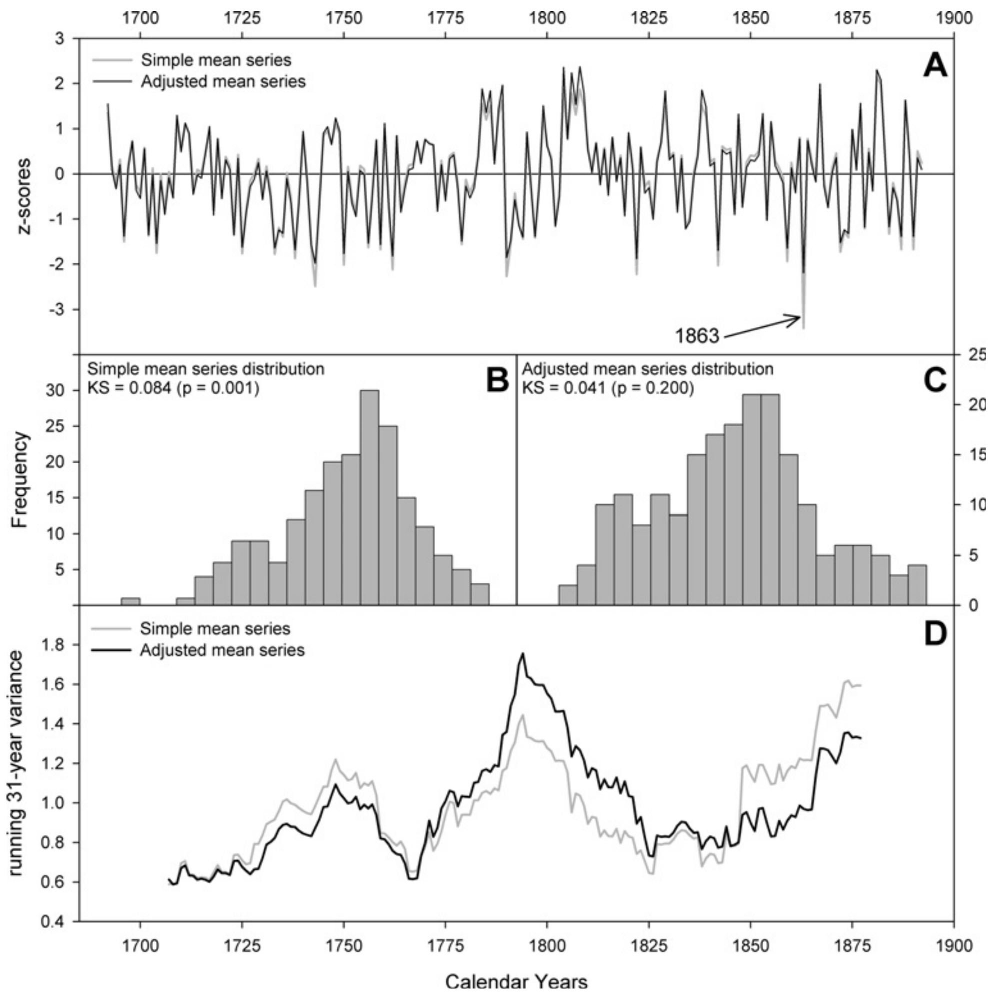

Figure 4 (A) Comparison of the simple and adjusted (for variance and normality) mean series. Both series have been standardised to z-scores. Histograms denoting the data distribution of the simple (B) and adjusted (C) mean series. KS, Kolmogorov-Smirnov test value (with significance *p* value). (D) Running 31-yr variance plots for the simple and adjusted mean series

potential problems with the early Uppsala temperature series. However, as this was a relatively warm period (in particular according to the instrumental data), defining the start of sailing season as a proxy variable for temperature is problematic because the sailing season might have been continuous throughout the year.

A final assessment of the reconstruction is made by comparing the variance through time of the reconstruction and instrumental series. As detailed earlier, the variance of the mean proxy record was stabilized to take into account the change in replication through time. Figure 5C shows running 31-yr plots calculated from each time series after they had been standardized to the 1756–1892 period. The variance trends over this period are generally the same. Importantly, the period of higher variance around 1800 and the late-nineteenth century observed in the instrumental data, is picked up by the reconstruction. If the uncorrected simple mean series (Figure 3A) had been used to generate the reconstruction, then the variance would incorrectly have been higher at the end of the nineteenth century compared with around 1800. This justifies the variance correction applied.

Discussion

The purpose of this paper has been to test whether different documentary sources of port activities from Stockholm might be used to verify and reconstruct past winter temperature. We hypothesized that the different documentary sources – port records, tax ledgers and so on – detailed the beginning of the sailing season, which in turn depended on ice break-up in the inlet to the harbour of Stockholm. Ice break-up is itself related to winter temperatures. By combining information from seven historical sources, we developed, using methods commonly used in dendroclimatology, a well-verified reconstruction of winter temperatures from 1692 to 1892 explaining well over 60% of the winter temperature variance in calibration and verification periods from 1739 to 1892. Our analysis therefore supports the theory that administrative routines concerning port activity reflect winter temperature, at least in the period analysed.

An important feature of this record is that it expresses annually resolved information for the winter season, which is distinctly lacking in the more widely explored tree-ring based proxies, which generally represent summer conditions (some Scandinavian examples are Lindholm and Eronen, 1995; Kirchhefer, 2001; Eronen *et al*., 2002; Grudd *et al*., 2002; Helama *et al*., 2002, 2004). Despite the fact that our reconstruction does not capture extreme years particularly well (the 95% error estimate for each year is ~2.3°C), it is nevertheless robust and explains more variance than is generally captured from tree-rings and other annually resolved proxies (eg, corals in tropical regions; Wilson *et al*., 2006). The rather large error estimate results partly from a high variance of the winter temperatures themselves, but it also reflects the ambiguities of human responses to climatic events.

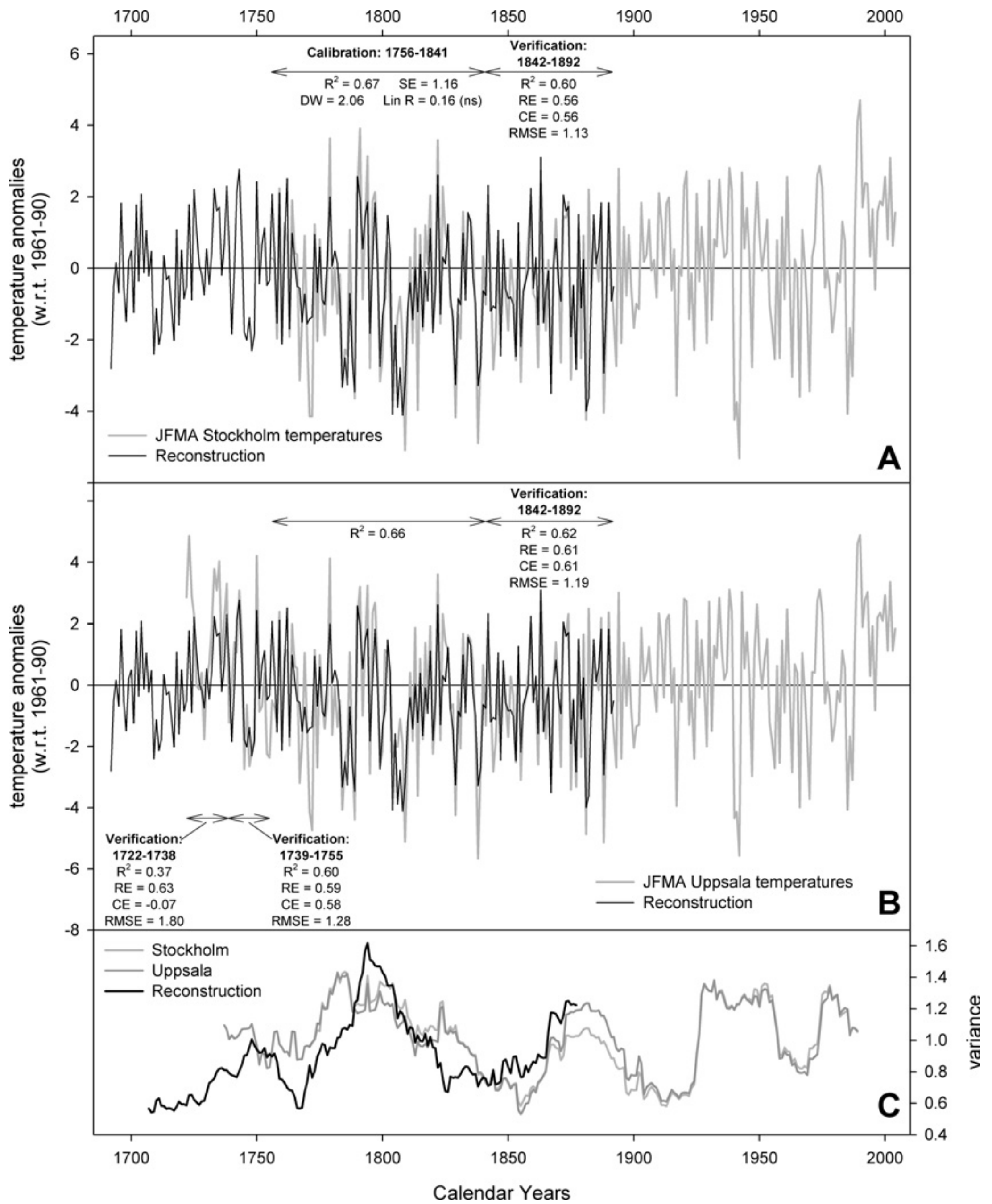

Figure 5 (A) Calibration and verification against Stockholm JFMA temperatures. Lin *R* is the linear trend of the residuals measured by the correlation between the residual values and time. RMSE, root mean square error. (B) Extra verification against Uppsala temperatures. (C) Moving 31-yr variance plots for the reconstruction and instrumental time series. The series have been standardized to the 1756–1892 period

The subtleties of human reactions to climatic conditions can sometimes be very obvious in the historical sources. For example, the reconstruction does not capture the extreme cold measured temperature values of 1809 well. According to the ship records from 1809, the first three applications for sailing from Stockholm were made on 21 January, 18 February and 8 April, but not until 25 April did the sailing season (as we have interpreted it) begin (SSA, Handelskollegium, Sjöfolkskontrollen, Skeppsinlaga 1809). Comparing the application entries with changes in Stockholm temperatures, the fluctuations in daily temperatures from January to April 1809 were as follows. On 20 January temperatures increased from −22°C to −6°C. On 21 January, the first date of application, temperature was −9°C. On 22 January, however, the temperature dropped to −12°C. A similar situation occurred a month later: on 14 February, a fortnight-long cold spell was broken, with temperatures between −20°C and −10°C, and temperatures increased to be marginally above 0°C. This mild weather continued for eight days, after which temperatures once more fell to −18°C. The end of March was also extremely cold with temperatures down to −16°C. On 6 April, the temperature was −1°C, and the next day it was above zero. Then it was warm for a few days and on 11 April the temperature again dropped down to between −5 and −10°C. This, final, cold spell continued for close to a week, and on 17 April temperature rose to 0°C and there were no more cold spells for that year (according to the daily temperature data from Moberg *et al*., 2002).

The detailed example above indicates that a dramatic increase in temperatures (as happened in January, February and early April) allowed people's hopes to be raised and they began to prepare for the sailing season. The different reaction time, from only

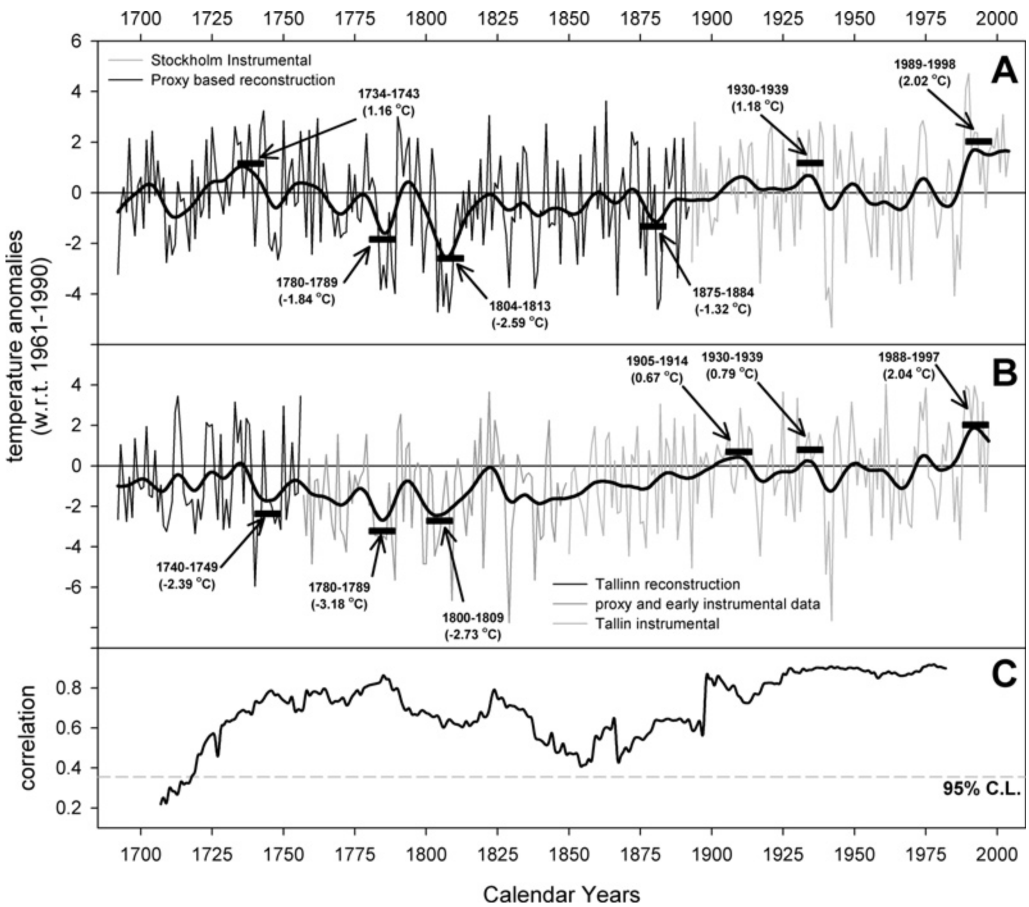

Figure 6 Comparison of the Stockholm (A) and Tallinn (B) documentary-based winter temperature reconstructions. The post-1892 data (light grey) for the Stockholm series are the instrumental data. The Stockholm reconstruction was scaled to have the same mean and variance as the instrumental data over the 1756–1892 period before this splice was made. For the Tallinn reconstruction, the 1757–1849 period (dark grey) is a combination of proxy and early instrumental data, some of which come from Stockholm and St Petersburg. From 1850, the data (light grey) are exclusively Tallinn instrumental data. The bars denoted the three warmest and coldest decades in each record. (C) Running 31-yr correlation coefficient between the Stockholm and Tallinn reconstructions

a few days during early winter to more than a week in mid-April, might be explained by a psychological feature that people become hardened when a winter seems to continue endlessly as it did in 1809.

However, in 1809 the ice in the Stockholm archipelago probably took longer to break-up, because the first arriving ship, according to the *tolag* journals, did not arrive in Stockholm until 8 May 1809. Continuing work is focusing on such extreme years in the hope that such information could be incorporated into the reconstruction to allow better modelling of such events.

Figure 6 compares the Stockholm reconstruction with the series from Tallinn (Tarand and Nordli, 2001). As with the Stockholm reconstruction, the Tallinn series is made up of differing constituent series through time (Tarand and Nordli, 2001). Prior to 1757 the reconstruction is made up purely of data from historical sources (ie, ice-break data in Tallinn port). Between 1757 and 1849, the reconstruction is an amalgam of both historical sources and early instrumental data from Tallinn, Stockholm and St Petersburg. Finally, after 1850, the data are exclusively instrumental from Tallinn.

After around 1900, when both the Stockholm and Tallinn series (Figure 6A and B) consist of local instrumental temperature data, they correlate at between 0.8 and 0.9, as revealed by running 31-yr correlations (Figure 6C). This defines the strongest correlation that can be expected for the proxy parts of the series. Over the 1692–1892 period as a whole, the two series correlate at 0.61. The running correlations, however, show that the coherence is variable through time (Figure 6C). Prior to ~1720, the correlations become weak and even non-significant, suggesting problems with one or both of the proxy series, which cannot at this time be resolved. The next period of lower coherence is from ~1830–1890. Notably, these lower correlation values occur during the calibration period of the Stockholm reconstruction (which was well correlated with local temperatures, Figure 5A) and may thus possibly reflect problems in the data used by Tarand and Nordli (2001) in this period. Correlations between the two records are, however, generally high (> ~0.7) in the second half of the eighteenth century. Unfortunately, the fact that instrumental Stockholm temperatures are included in the Tallinn series in this period complicates the interpretation of the comparison of the two series.

When taking into account the instrumental data, both reconstructions agree almost exactly concerning the two warmest decades on record: they are 1989–1998 (1988–1997 in the Tarand and Nordli (2001) record) and 1930–1939 (Figure 6A and B). The two coldest decades approximately coincide; 1780–1789 (both records) and 1804–1813 (1800–1809 in the Tarand and Nordli (2001) record). The strong coherence between the two records and the general similarity in decadal and long-term trends indicates a common broad-scale pattern of temperature change and variability in the Baltic region from the late seventeenth to the late twentieth centuries. In general, Stockholm winter temperatures fluctuated around the 1961–1990 mean level until ~1770, followed by a general decline until the early nineteenth century. Temperature was then generally below the 1961–1990 level (with some decadal variability) until the early twentieth century, when warming brought levels up to the 1961–1990 average. A recent rise in temperature around 1990 caused the last one and a half decades to be the warmest period over the last three centuries. These broad-scale trends mirror surprisingly well similar trends noted for large scale temperature reconstructions (eg, Moberg *et al*., 2005; D'Arrigo *et al*., 2006; Wilson *et al*., 2006, 2007).

Conclusion

The focus of this paper has been to test rigorously documentary sources of port activities in Stockholm as possible climatic proxies. Although documentary sources reflect man's behaviour – as opposed to natural proxy variables (eg, tree-rings), which are more directly influenced by climate – we have shown a strong coherence between the sources and instrumental temperature data. The strongest coherence with winter temperatures was found with the ship records (spring), *tolag* (first arrival and departure), ice break-up, the beginning of sailing season in the official statistics and the sea passport data, which all reflect the timing of the ice break-up in the inlet to the Stockholm harbour. These historical data were combined to derive a preliminary reconstruction of January to April mean temperatures back to the late seventeenth century, which together with modern instrumental data show that post-1990 temperatures for this season have been warmer than any other period of similar length in the last 300 years. The reconstruction calibrates strongly (67%) against the instrumental record and indicates that these kinds of documentary sources work very well as proxies for late winter to early spring temperature. As some of these sources, above all the *tolag*-records, go well back into the seventeenth century, as well as other similar sources existing back into the sixteenth century, future work will focus on extending the reconstruction so that annually resolved information on Stockholm cold-season temperatures can hopefully be reconstructed for the last ~500 years.

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