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Five centuries of Stockholm winter/spring temperatures reconstructed from documentary evidence and instrumental observations

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Abstract Historical documentary sources, reflecting different port activities in Stockholm, are utilised to derive a 500-year winter/spring temperature reconstruction for the region. These documentary sources reflect sea ice conditions in the harbour inlet and those series that overlap with the instrumental data correlate well with winter/spring temperatures. By refining dendroclimatological methods, the time-series were composited to a mean series and calibrated (1756–1841; $r^2 = 66\%$) against Stockholm January–April temperatures. Strong verification was

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confirmed (1842–1892; $r^2 = 60\%$; RE/CE = 0.55). By including the instrumental data, the quantified (QUAN) reconstruction indicates that recent two decades have been the warmest period for the last 500 years. Coldest conditions occurred during the 16th/17th and early 19th centuries. An independent qualitative (QUAL) historical index was also derived for the Stockholm region. Comparison between QUAN and QUAL shows good coherence at inter-annual time-scales, but QUAL distinctly appears to lack low frequency information. Comparison is also made to other winter temperature based annually resolved records for the Baltic region. Between proxy coherence is generally good although it decreases going back in time with the 1500–1550 period being the weakest period—possibly reflecting data quality issues in the different reconstructions.

1 Introduction

"And all through the months that in other days had been beautiful with flowers the snow fell steadily, and the cold winds blew fiercely, while eyes grew sad and hearts heavy with waiting for a summer that did not come. And it never came again; for this was the terrible Fimbul-winter…" (Norse stories retold from the Eddas. Wright Mabie 1901).

In pre-industrial societies, most economic activities were dependent upon and constrained by the natural environment—including climate (Brázdil et al. 2006). Stockholm, located near 59°N, 18°E, at the interior of an archipelago in the Baltic Sea (Fig. 1), is a city where the sailing season was strongly dependent on ice-free conditions before the invention of steel hulled ships, steam engines and ice-breakers.

Swedish archives are well-known to be rich (Pfister and Brázdil 1999), and documents concerning Stockholm, the capital, are particularly abundant. Thus, with documentary evidence concerning sailing activities going back to the beginning of the 16th century (Retsö 2002; Leijonhufvud et al. 2008) and a long instrumental record of meteorological observations starting in 1756 (Moberg et al. 2002), Stockholm is well suited for studying the relationship between the sailing season and climate for a long time period.

Leijonhufvud et al. (2008) showed that the start of the sailing season each year, as deduced from custom ledgers and other documents related to harbour activities in Stockholm harbour, can be used as robust proxy variables for winter/spring temperatures, at least until the beginning of the 1870s. In that study (henceforth referred to as L08), we showed how information gleaned from the administrative records may be interpreted as a January–April temperature proxy, and how statistical methods commonly used in dendrochronology may be used to derive a temperature reconstruction back to 1692. Unlike the approach of L08 and a few other studies (e.g. Tarand and Nordli 2001), most previous studies in historical climatology use climatic indices, defined as discrete numbers on an ordinal scale, to describe climatic conditions in the past (see e.g. Brázdil et al. 2005). In the current study, we will make an extension of the L08 January–April temperature reconstruction back to the early 16th century, but also present an independent winter/spring climate series using the more traditional indexing method. Additionally, we compare these two climate records with previously published five-century long series reflecting cold-season climate conditions in the southern Baltic Sea region.

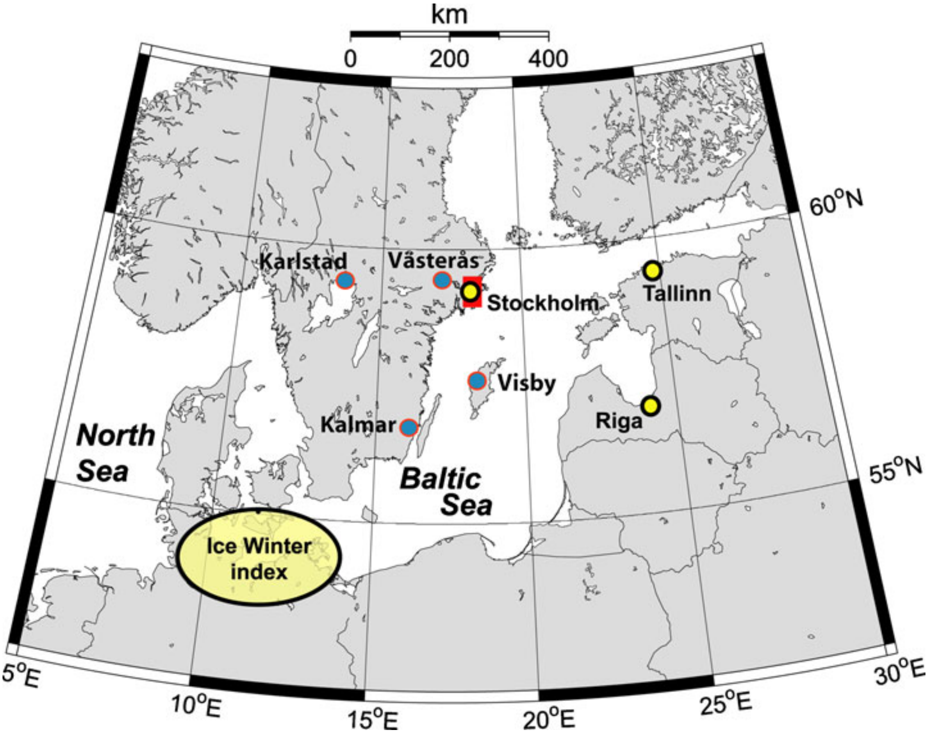


Fig. 1 Location map, showing Stockholm and other key locations discussed in the paper. Luterbacher grid box (LUT; see Section 6) shown in *red* while other winter proxy records are highlighted in *yellow*

It should be made clear that the Stockholm quantitative and qualitative winter/spring climate series developed here are based on entirely independent data. The raw data used for the quantitative reconstruction are strictly numeric, consisting of dates (days after 1st January, Gregorian calendar) that indicate the start of the sailing season, whereas the qualitative index is based on interpretation of various types of descriptive information. We regard the quantitative series as our main reconstruction (being calibrated to temperatures and consisting of continuous numeric data), whereas the qualitative index series (being uncalibrated and consisting of discrete numeric data) contributes with additional independent information.

As the qualitative reconstruction, as well as two other series within the quantitative reconstruction, are composite series, it is possible to test how well composite series from historical documents stand up against more homogenous quantitatively-derived series.

2 Start of sailing season deduced from economic-administrative sources

Stockholm, with its superior geographical location as well as being the capital, was the principal trading port in Sweden (Wikberg 2006, p. 21). The economic-

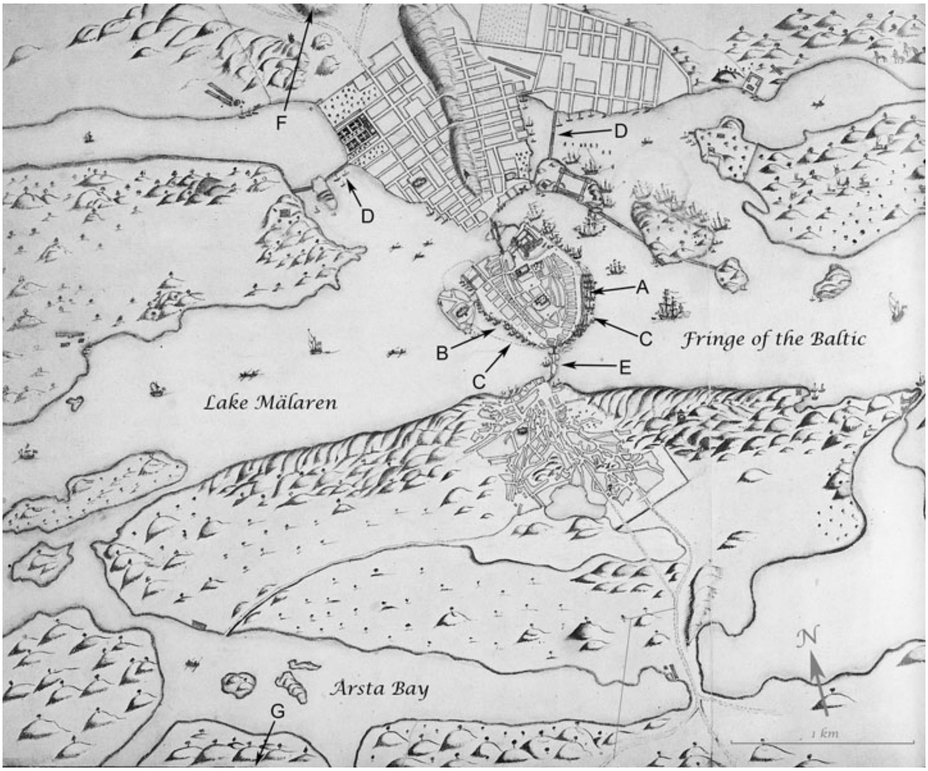


Fig. 2 Map of Stockholm AD 1642 (or possibly 1640). The central city island guards the inlet to lake Mälaren (to the west) and the innermost fringe of the Baltic Sea (to the east). Several of the harbour facilities and other important places mentioned in the text are marked: *A* the eastern harbour, *B* the western harbour, *C* the pole fence, *D* bridges; were raised, at least for larger vessels, *E* the location of the lock, built in late 1642. *F* (near upper frame) the hill where the Astronomical observatory was built in 1753, i.e. where the thermometer has been placed from 1756 onwards, *G* the Årsta manor (located slightly southwards from the letter *G*, near lower frame, close to Årsta Bay). Source: National Library, Stockholm 51:30

administrative records related to shipping and harbour activities in Stockholm contain information about most ships that sailed to and from the city, thus providing the means with which to estimate when the sailing season started each year. Figure 2 shows the physical geography of Stockholm in 1642 (1640), as well as several of the harbour facilities and other places mentioned later in Section 3.

The basic premise of this study (from L08) is simple; each documentary source is scrutinized in order to find the date that indicates when the sailing season had started for a given year. The main factor constraining sailing in spring is the ice cover of the Baltic, which is, in turn, closely related to the annual mean winter air temperature (Hansson and Omstedt 2007). For each source, a time series of dates, regarded as proxies for winter/spring temperatures, are constructed. The resulting set of time series is then used as raw data for producing the quantitative temperature reconstruction. We have transformed all relevant days into days after New Year according to the Gregorian Calendar for the whole period 1500 onwards (see Haldorsson 1996 for further explanations on the particular Gregorian calendar reform in Sweden).

The various economic-administrative sources are ordered chronologically, with the first date each year when the administration of the respective source began being taken as the basis for discrimination. The records were kept continuously throughout the sailing season. This means that, usually, when the sailing season had begun (or more correctly, when the administrative recording of sailing/harbour activities had begun), ships were recorded every day or every second day, which makes it easy to estimate the date for the start of the sailing season. In years when sailing started late in spring, the first date of entry usually contains several transactions; i.e., several ships arrived, or departed, at the same time.

The information about ship activities in various economic-administrative sources is the main indicator of the start of the sailing season used for the quantitative reconstruction in L08 and in this study. (Our qualitative index is based on other information, see Sections 3.12 and 3.14 and 4.3). Further discussion on problems related to determining the start of sailing season is provided in L08.

3 Sources: description and criticism

The source critical discussion which was initiated in L08 is continued here. As has been noted by several studies, the importance of such analyses is vital for all studies using documentary data as climatic proxies (Bell and Ogilivie 1978; Pfister et al. 1999; Brázdil et al. 2005). The L08 reconstruction, which covers the period 1692–1892, was based on data from seven different sets of administrative records. Four of the sources extend back before 1692. Two of them, the ballast and the sea passports, do not form continuous series, and have large gaps.

For the period 1502–1636 we are faced with a problem of having sources that cannot be calibrated and verified against instrumental records. This type of difficulty, is also faced in dendrochronological studies that use sub-fossil (Luckman and Wilson 2005; Wilson et al. 2007; Grudd 2008) or historical (Wilson et al. 2004, 2005; Wilson and Topham 2004; Büntgen et al. 2006) tree-ring material to extend living chronologies. In those cases, the underlying assumption is that a specific species of trees responds in a similar way to climate over time, even if the climatic regime changes. An equivalent assumption has to be made for documentary evidence. It is therefore essential that sources are carefully evaluated, in order to judge whether or not the early sources are likely to contain climatic information comparable to sources used in the calibration and verification periods. In addition to source criticism, it is also important to undertake statistical cross-comparisons among time series derived from different sources.

Sections 3.1–3.11 describe sources used only for the quantitative reconstruction. Sections 3.12, 3.13 describe sources containing information used for both the quantitative reconstruction and qualitative index. Section 3.14 describes sources used only for constructing the qualitative index. Table 1 summarizes general information about the sources used for the quantitative reconstruction. Table 2 presents correlation coefficients between each series in Table 1 and the mean of all other series having simultaneous data.

Table 1 Administrative sources with corresponding proxy labels reflecting opening of sailing season in Stockholm

Archive/source	Proxy label	Brief description	Period of coverage
RA/Lokala tullräkenskaperna	GSTA	First arrival according to Great Sea Toll ledgers	1533–1622/1664
RA/Lokala tullräkenskaperna	GSTD	First departure according to Great Sea Toll ledgers	1537–1622/1673
SSA/Stadskamreraren	TolagA	First arrival according to local import tax	1636–1841
SSA/Stadskamreraren	TolagD	First departure according to local export tax	1636–1841
RA/Stockholms vågböcker SSA/Borgmästare & Råd	Balance	Balance accounts from the great iron balance	1546–1668
RA/Lilla tullen & skeppsgårdshandl, SSA/Stadskamreraren	SaS	Diverse sources of short administrative series concerning different fees in Stockholm harbour	1620–1692
SSA/Fraktböcker	Freight	Sea freight contracts, specifying date of contract	1551–1590
SSA/Borgmästare & Råd, Stadskamreraren	Harbour fee	Harbour fees in Stockholm & Vaxholm, fees for getting through the lock of Stockholm	1608–1692
SSA/Borgmästere & Råd	Pole	Fee for the opening of the pole barricade around the city	1603–1620
RA/KoK, passdiarier and SSA, Hak	Sea passport	Insurance document for ships travelling to the Mediterranean and beyond. Stockholm is home-port	1689–1831
SSA/Hak/Sjöfolkskontrollen	Ship records	Registers of sailors leaving Stockholm	1692–1842
SSA/Hak/Huvudprotokoll	Ballast	Planks granted for ballast by the city council	1673–1734
Hildebrandsson (1915)	Västerås	Deduction for the Bay of Västerås in lake Mälaren: ‘when the lake Mälaren is so open and free of ice that the sailing season between Västerås and Stockholm has begun’	1712–1892
Berättelse angående Stockholms Kommunalförvaltning År 1894 (1896)	Off.start	Official statistics of the opening of the sailing season	1815–1892
RA/KMT registratur, KrA/Admiralitetskollegiet registratur, etc	DeSpring	Letters from the Government or the Admiralty Board describing ice conditions and the start of sailing (no continuous series of shipping traffic)	1502–1783
NMA/Årstafruns dagböcker	Årsta diary	Notes in diary when the ice break-up occurred in the Årsta bay	1793–1837

Table 2 Correlations between each proxy series as labelled in Table 1 against the mean of all other simultaneous series

	Västerås	Off.start	TolagA	TolagD	Ship records	Årsta diary	Sea passport	Ballast	SaS	Harbourfee	GSTD	Balance	GSTA	Pole	Freight	DeSpring
A. Correlations with mean of all other series																
R	0.70	0.89	0.82	0.81	0.76	0.57	0.49	0.33	0.58	0.61	0.62	0.38	0.44	0.62	0.17	0.77
P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.06	0.00	0.01	0.43	0.00
N	149	46	159	136	150	54	100	48	19	20	56	26	65	17	24	19
B. Correlation with QUAL																
R	−0.64	−0.65	−0.63	−0.51	−0.53	−0.46	−0.33	−0.08	−0.62	−0.80	−0.58	−0.37	−0.58	−0.30	−0.32	−0.74
P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.00	0.00	0.00	0.05	0.00	0.22	0.11	0.00
N	149	46	159	137	150	41	100	48	20	20	58	29	69	18	26	55

3.1 Custom ledgers: the Great Sea Toll (1533–1622 with few gaps, 1636–1673 with many gaps) and the Tolag (1636–1841 with few gaps)

Two custom ledger series, the Great Sea Toll and the *Tolag* are the longest and most complete data sources used in the quantitative reconstruction. They were levelled upon import (arriving ships) and export (departing ships). The revenues of the Great Sea Toll accrued to the Crown (Wikberg 2006, p. 17), while the *Tolag* was a municipal custom, mainly used for building activities and payment of salaries to the city's administration (Sandström 1990, p. 81). The dates for the first arrival and departure of ships after each winter documented in these sources are treated as independent proxy series, labelled 'GSTA' and 'TolagA' for first arrivals and 'GSTD' and 'TolagD' for first departures. Although both types of sources are fairly rich, it has not been possible to build complete series of sailing season start dates. There are some gaps in all four series.

The Great Sea Toll was initiated in 1533 when the Hanseatic League lost their toll-freedom in Sweden (Smith 1934, p. 111). Government administrative control ended in 1726, when it was leased to a half-private society; *Generaltullarrendesocieteten* (Wikberg Lindroth 2004). However, after 1622 only a few surviving Great Sea Toll registers from Stockholm exist, because the specifications were requested by the army as wadding for artillery and most of this record was destroyed. Some data from the port of Nyköping (~70 km south of Stockholm) have therefore been used for a few years between 1660 and 1673 in an attempt to make an inter-correlation between the calibrated and verified *Tolag* series with the older source.

An instruction to the Director-General of customs from 19 December 1636 stated that all customs were to be manned with clerks and writers, visitation officers, rowers and other servants (Smith 1950, p. 133). The circumstance that the customs employed visitation officers indicates that they did inspect the ships. 'Rowers' indicate that it was sometimes necessary to access ships not docked at the quays.

In the statutes for the *Tolag* it was stated that a city was only allowed the *Tolag* on condition that it also administrated the Great Sea Toll for the Crown (Dalhede 2005, p. 22). The administrative routines for the *Tolag* should therefore be the same as the ones for the Great Sea Toll. This suggests that if the *Tolag* picks up a climatic signal, the Great Sea Toll would do likewise. However, it cannot be assumed *a priori* that legislative ordinances were followed; Sandström (1990, p. 36) points out that the two different customs are not entirely comparable with each other. Differences stem mostly from the fact that some people set sail before they had paid; especially the *Tolag* seems to have been comparably easy to evade. This problem does not concern the present analysis as tax-evaders were accounted for with their "*restantier*"—i.e. their rest—and if they dared to return to the city the following year, they had to pay then. Most importantly for this investigation; neither the *Tolag* nor the Great Sea Toll are maintained with respect to when the captains paid their dues, but rather to when the ship arrived at the custom station (Sandström 1990, p. 87; this is obvious in most of the original documents—SSA, RA).

The registers of the Great Sea Toll are divided between import-custom and export-custom; such that there is one register for arriving and another for departing ships. The registers are written chronologically for each provenance or destination. When the last ship had arrived (or departed), a summary of how much custom had been gathered from that port was made. This practice, with separate accounts for the different ports, indicates that the custom-accounts also were made for reasons of trade statistics. If so, this heightens the value of the custom accounts as a source for climate proxy information.

The *Tolag* series begin in 1636 and end in the mid 19th century (Table 1). Because of practical problems of abstracting the *Tolag*, we did not abstract data from after 1841. Nevertheless, our *Tolag* series are sufficiently long to allow for calibration against instrumental temperature data (see L08).

As the Great Sea Toll from Stockholm ends in effect in 1622, it is impossible to check the inter-correlation between the series of sailing season derived from that source and the corresponding series derived from the *Tolag*. The few data from the Great Sea Toll that are part of the series between 1636 and 1673—where five out of nine data originate from the port of Nyköping—are too few for meaningful correlation analysis with the corresponding *Tolag* data from Stockholm. However, we assume that trading conditions, as far as they are determined by whether the sea was open or not, are similar for the two harbours. Nevertheless, there might be some differences in trading practises because Nyköping was a much smaller port than Stockholm.

The correlation between the sailing season start deduced from each of the two *Tolag* series and the mean of other simultaneous series is ~0.8 (Table 2), implying a high degree of linear coherence between data series during 1636–1841. The corresponding values for the earlier Great Sea Toll data are lower ($r = 0.62$ for GSTD, $r = 0.44$ for GSTA). This does not necessarily imply that the Great Sea Toll data are inferior as indicators of the start of the sailing season compared with the *Tolag*, but is more likely mainly a consequence of poorer quality (from our point of view) of other data sources used in the 16th century, in particular the Freight books (see Section 3.4).

3.2 Weigh books (1546–1668, with many gaps)

Weigh books are the journals which document goods that were weighed in the town's weigh house. There is a difference between the early weigh books from the 1540s, placed in KA, and the later books from the 1570s, placed in SSA; the former were kept in an attempt to track trade, while the latter were made as a foundation for taxation (Odén 1959). The earlier weigh books therefore probably have a higher source value than the latter ones.

In 1604, King Karl IX commanded that weighing should occur in immediate connection with the paying of duties when goods were exported and imported. However, the use of the balance was not only a duty, but also a privilege and merchants could be forbidden the use of the balance as punishment for crimes (Odén 1959). These properties of the weigh books render them suitable for establishing the beginning of the sailing season.

From a practical point of view, however, it turned out to be difficult to work with the weigh books. The hand-writing of the records is cramped, so it is not certain that it has been possible to ascertain correctly whether a certain person has “bought, “sold”, “exported” or simply “weighed” his goods. Furthermore, the city law stated that not only goods for export or import should be weighted, but also goods which were sold in the city. This implies that goods sold in the city might later have been exported, but we cannot know when or how this occurred

(Odén 1959). These circumstances reduce the value of the documents as a source for climate proxies. Nevertheless, sailing season dates derived from the weigh books (labelled ‘Balance’) show a reasonable correlation ($r = 0.38$, Table 2) with the mean of other simultaneous series. The weigh books are important for obtaining data for the years 1626, 1630 and 1668, when no other data exist.

3.3 Short administrative series (1620–1692, with many gaps)

Short administrative series (labelled ‘SaS’) is a composite series consisting of information from several short and broken sources of economic-administration. The SaS series is, in its construction, similar to the ‘DeSpring’ series described in Section 3.13, and the placement of data in one or the other are in some cases arbitrary and judged mainly from practical considerations. However, all data in this data-set originate from administrative routines and have a specific and well-defined start of the sailing season. Although it would have been possible to split this information into several series, it was preferable to compose them into one because otherwise this would have resulted in a series consisting of only a few values, and sometimes only one single value. Such a situation would have made the quantitative analysis approach of L08 and the error assessment very difficult. It would of course have been possible to not include these composite series, but then information would have been lost, both from years when other data exist, but also from years when there are no other data at all, except for from an isolated source. Such is the case for 1685, when the only data available comes from an account of fees for opening bridges in the city (See Fig. 2, label ‘D’). The correlation between SaS and other simultaneous series is 0.58 (Table 2), which indicates a reasonable degree of similarity in the few years ($n = 19$) of overlapping data. This shows that a composite series from historical documents work well as a climatic indicator.

3.4 Freight books (1551–1590, with gaps)

Freight books are a series from the latter half of the 16th century, containing contracts of sea freights. They begin in 1551 and end in 1590, with gaps 1564–1568 and 1577–1584. In general, the notes in these books were made later than the Great Sea Toll, indicating a different administrative routine. The correlation between the ‘Freight’ series and other simultaneous series is poor, $r = 0.17$, which casts some doubt on the inclusion in the quantitative reconstruction. However, these data do provide information for the year 1551, which is not represented by any other historical source.

3.5 Harbour fee (1608–1692, with many gaps)

Harbour fees are sorted among the verifications in *Stadskamrerarens arkiv* at the city’s archive—as are the *Tolag* records. The data used here actually consist of two types; harbour fees from Stockholm and Vaxholm (the outer harbour some 20 km north-east of Stockholm) and lock fees from the lock of Stockholm. Fees from the harbours of Stockholm sometimes distinguish between the eastern and western harbour (See Fig. 2, labels ‘A’ and ‘B’). We have chosen fees from the eastern harbour, because they were paid a few days earlier than the ones from the western harbour (SSA, *Stadskamrerarens arkiv*, *Verifikationer* 1641, 1644). In principle, these data could have been added to the SaS series, but since there are data from several years simultaneously, it was convenient to develop a separate series from the harbour fees (labelled 'Harbourfee'). From 1608 to 1623, the series comprise data concerning fees paid for passage through the lock of Stockholm. At that time, there was no actual lock, but boats were dragged upstream against the flow of the channel between the Baltic and the lake Mälaren. (See Fig. 2, label 'E'). For the latter period, 1636–1681, data are true harbour fees. The last datum, 1692, concerns the lock fee (i.e. when there was a lock.). The correlation of Harbourfee with other series is quite strong ($r = 0.61$, Table 2) for the 20 years of overlapping data.

3.6 Pole penny (1603–1620, complete)

Stockholm was surrounded by a defence blockade of piles in the waters surrounding the main city island (See Fig. 2, very faint dots in water indicated by label 'C'). These piles were connected with bars, which could be raised to allow incoming (departing) ships to enter (leave) the harbours. This procedure has generated a short, but well-preserved, series of data from the early seventeenth century, called *pålpenning* (pole penny). The time series (labelled 'Pole') is complete 1603–1620. Its correlation with the mean of other series is $r = 0.62$ (Table 2).

3.7 Drafts of Sjöpass ("Sea Passports") (1689–1706 scattered values, 1733–1831 nearly complete)

From 1665, there exist drafts of sea passports in the main archive of the National Board of Trade, RA. The documents are very well preserved and begin with the form that should be used for the passports. They are written in Latin. The passports specify; (1) a date, (2) who the captain was and where he came from, (3) the ship's name and its capacity, (4) from which harbour the ship was sailing from and where it was sailing to, and (5) what goods it brought. The passport is signed with the same date as was given in the very beginning of the letter.

The main problem with these drafts as indicators of the start of the sailing season is that there were few passports issued. We have not been able to include any of the very first drafts still existing, because there were very few of them and the few existing ones were issued in the middle of the sailing season (in the summer months). The first year, which may contain relevant climatic information, as well as being consistent with the calibrated and verified sea passports, is 1689. During 1733–1831 the data series (labelled 'Sea passport') is nearly complete. Its correlation with the mean of other series is relatively modest ($r = 0.49$), but highly statistically significant being calculated for 100 overlapping years.

3.8 Planks granted for ballast (1673–1734, nearly complete from 1689)

As described in L08, records of planks (or 'wood') may be found among the main records of proceedings of the Chamber of Commerce, SSA. The application for ballast could be made well in advance of a planned journey, as was also the case for the sea passports. The number of ships is fewer than those registered in the *Tolag* and ship-records accounts. The correlation between the series ('Ballast') derived from this source and the other simultaneous series is 0.33, making this one of the weaker contributors to the common signal. Further information is provided in L08.

3.9 Ice break-up in Västerås (1712–1892, complete)

A series of deduced ice break-up dates for the lake waters outside the town of Västerås, covering the period 1712–1892, has been developed by Hildebrandsson (1915). Västerås is located at a bay of Lake Mälaren, ~90 km west of Stockholm. Although this published series does not relate directly to port activities in Stockholm, it is included in our quantitative reconstruction (and L08) because it is strongly correlated with Stockholm temperatures in all months from January to April (see Fig. 2 in L08 and their associated extensive discussion concerning this source). The correlation between this series (here labelled 'Västerås', also to enhance that this series probably does not so much reflect ice break-up as the name implies, but rather the beginning of the sailing season in Västerås) and the mean of other simultaneous series is quite strong, $r = 0.70$.

3.10 Official port statistics (1815–1892, complete)

As described in L08, official port statistics on the beginning of the sailing season are published in a series of the City Council's Working Committee (Berättelse angående Stockholms Kommunalförvaltning 1894). This data series (here labelled 'Off.start') is complete for the period 1815–1892, and correlate with the other simultaneous series at the high level of $r = 0.89$. See L08 for further information.

3.11 Ship records (1692–1841, complete)

Ship records were drawn up in the city's Chamber of Commerce, SSA, and could be arranged well in advance of the planned travel. The data series (labelled 'ship records') are complete for the period 1692 to 1841 and correlates at high level of $r = 0.76$. See L08 for an extensive description and discussion of this source.

3.12 Descriptive sources I—The Årsta Diary (1793–1837, nearly complete)

The diary kept by Lady Märta Helena Reenstierna, concerns her daily life for nearly 40 years at the Årsta manor, just to the south of Stockholm (See Fig. 2, label 'G'). She made more or less daily descriptive weather observations, not only because she was interested in the weather but because she was dependent upon climatic conditions for the manorial management. Among these notes, c. 14,500 weather observations, are information on the ice break-up in the Årsta Bay. Notices of ice break-up occur for nearly every year. Information from the Årsta Diary is used both to derive a time series of ice break-up dates 1793–1837 (labelled 'Årsta diary'), which is included in the quantitative reconstruction, and as a contribution to the qualitative index series.

The diary observations on ice break-up may be regarded as being similar to scientific observations of ice break-up. As they were written by the same chronicler they constitute the most consistent data set used in this study. Nevertheless, the correlation between the Årsta diary ice break-up dates and observed January–April temperatures for Stockholm is lower than that between the start of the sailing season as suggested in some other series available for the period 1793–1837. (TolagD correlates at $r = -0.91$ and Ship records at $r = -0.70$ with JFMA temperatures, compared to $r = -0.52$ for the Årsta diary). The correlation between the Årsta diary ice break-up dates with the “ice break-up” series from Västerås, is 0.58. This relatively low correlation is probably a consequence of the fact that the series from Västerås reflect the start of sailing season in the western part of lake Mälaren, while the Årsta series is a series of true ice break-up in the easternmost part of the lake. As was shown earlier, the series from Västerås has an excellent correlation with Stockholm winter temperatures.

The correlation between the Årsta diary ice-break up series and the mean of the other simultaneous series contributing to the quantitative reconstruction is $r = 0.57$, which is comparable to some of the early series derived from economic-administrative sources.

Additional descriptive climatic information from Lady Reenstierna’s diary, was used to construct the qualitative index series. However, any one particular piece of information was never used for both series, in order to guarantee full independence between the two reconstructions. For example, entries in the diary such as ‘very mild today and the lake has become open’ are only used for the quantitative reconstruction, whereas keywords relating to the diarist’s perception of temperature (e.g. ‘cold’, ‘very cold’, ‘mild’ etc.) entered the database used to derive the index.

3.13 Descriptive sources II—descriptive spring data (1502–1637 with gaps, 1652–1783 very sparse)

None of the administrative-economic records described above provide any information before 1533. Hence, to extend the quantitative reconstruction back to the earliest 16th century, it is necessary to deduce the start of sailing season from a variety of other sources. For this purpose, a dataset labelled ‘DeSpring’ (descriptive spring data) was developed. Among the series used for the quantitative reconstruction, this is the most distinct of the datasets. DeSpring has similarities to the SaS series, both being composite series, but unlike the SaS, DeSpring does not originate from economic-administrative routines. Therefore, the start of the sailing season might not be determined as directly as is the case with most of the administrative sources.

Governmental letters used in these series consist of requests that ships should set sail to or from Stockholm that are made by an official, for example, the King or Regent. A key expression is *första öppna vatten*, i.e. ‘first open water’, referring to the break-up of ice in the archipelago in the spring. Together with the dating of the letter in which the key expression occurs, the first dated mentioning of actual shipping provides an approximation of the onset of the period of navigable waters to and from Stockholm, and hence the reopening of the sailing season.

This type of source does not necessarily include a chronological sequence of naval activities, such as those related to economic administration. Neither do they provide a daily sequence of general weather observations, such as the Årsta diary. Information derived from the various sources is used both for the quantitative and the qualitative reconstructions. To some extent it has been arbitrary to which of those two datasets a particular piece of information was assigned. As with the Årsta diary, however, the same item of information is never used in both datasets.

Perhaps surprisingly, the correlation between DeSpring and the mean of other series in the quantitative dataset is quite strong ($r = 0.77$). The correlation, however, is estimated from only 19 common years, so it is difficult to judge whether the high value is fully representative, but it is another indication that composite series from documentary sources work.

The quantitative DeSpring series has most of its data in the period 1502–1637 and only very few scattered values for 1652–1783. It could, in principle, have been possible to construct a much longer quantitative DeSpring, but that would have left too few pieces of evidence to allow the qualitative index series to be constructed in some periods. As we attempted to develop two independent reconstructions, we decided to let DeSpring remain incomplete rather than optimize the information entering the quantitative reconstruction.

3.14 Descriptive sources III—information used only for the qualitative index

Most of the data used to derive the index series stem from observations relating to winter and spring climatic conditions in Stockholm and its vicinity. However, information relating to other parts of south-eastern Sweden, especially from the coastal regions and the Lake Mälaren valley, has also been used. In some cases, data from towns as far southwards as Kalmar (~400 km from Stockholm), and Visby (~200 km southeast) and as far westwards as Karlstad (~300 km) have been included (Fig. 1). The use of data from such distant places is justified by instrumental observations, which indicate that winter and spring temperatures between Stockholm and other stations within this area are very highly correlated. For example, Stockholm January–May (JFMAM) temperatures correlate with Kalmar, Visby and Karlstad instrumental temperatures for the period 1890–2001 at $r = 0.97$ (as calculated from data in Tuomenvirta et al. 2001).

Figure 3 shows the amount of information forming the basis for the qualitative index in each year during 1502–1860. Compared to the earlier part of the period for which data are collected, the density of data grows substantially after the mid 18th century. This is because of a general upsurge in the number of journals and other publications. One useful source for the latter half of the 18th century

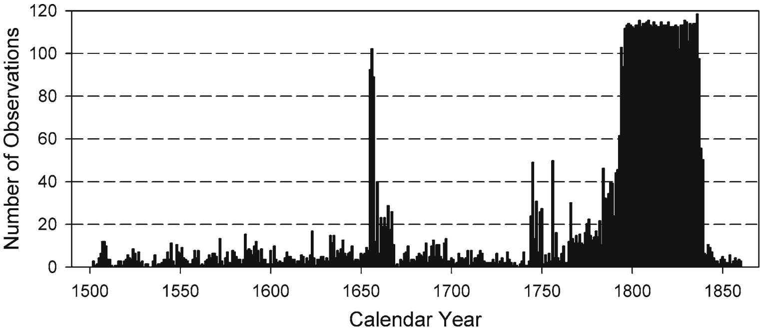


Fig. 3 Number of observations forming the basis of the qualitative index

is the meteorological observation diary from the old astronomical observatory in Stockholm, which not only contains the instrumental temperatures used to derive daily temperature and air pressure records back to 1756 (Moberg et al. 2002), but also many pieces of descriptive information. The very high values (>100) during 1793–1841 mainly stem from the Årsta diary (see Section 3.11), revealing that this is an exceptionally rich source. The amount of observations per year in earlier periods is more modest, typically being less than 10, but for some years and periods peaking to around 50 or even 100 observations.

The preserved Chancery Registers of the central administration, containing mostly outgoing correspondence, begin in 1521 (Konung Gustaf den förstes registratur 1861–1916). Prior to this year, the preserved archives of the Sture regents—mostly containing incoming correspondence—have been used. In both bodies of administrative correspondence, the climatological proxy data are mostly associated with transport and communication, particularly sea transport.

Despite the great importance to Sweden's foreign trade of ice break-up, its exact date for a particular year is almost never stated in these older sources. At best, they provide either a date before which the ice is certain to have obstructed shipping, or a date on which shipping is certain to have started. Hence, only a time-span during which the break-up of the ice is certain to have occurred can be deduced. This implies that some data in the index could have been included in the quantitative DeSpring series. However, most data forming the foundation for the index, can not be expressed parametrically (interval or ratio scale) but only at an ordinal (index) scale.

From 1560 to about 1720, the outgoing letters of the King and the Government are an important source, though available only in archival form (*Riksregistraturet*, RA). The correspondence of the Board of the Admiralty (*Amiralitetskollegiets registratur, Krigsarkivet*) has also been consulted. Official reports to the Government, in particular from the provincial governors, are indispensable, especially in years of crisis when governors had to call upon support from the Government (*Kollegiers m.fl. skrivelser till Kungl. Maj:t*, RA).

Towards the end of the 16th century, the making of weather annotations appears to have become somewhat more widespread, at least among the clergy. These observations were seldom recorded on a daily basis, or they have not been preserved in that format. Rather, they focus on extreme events such as harvest failures, floods, famines and plagues, but also present summary statements on weather on a seasonal or annual basis. Several examples of such annotations are found in Gustaf Utterström's pioneering essay on historical climatology in Sweden (Utterström 1955). However, qualitative descriptions of Stockholm winters presented by Utterström for the period after the mid 18th century are derived from instrumental measurements (Liliequist 1943), and thus cannot be used for the qualitative index constructed here.

In addition to the Årsta diary, a few other diaries have also been used (Rosenhane 1995; Hausen 1880). The newspaper, *Post och inrikes tidningar*, reported on ice conditions and sailing at the Sound (Öresund) as well as at Dalarö in the southern part of the Stockholm archipelago for considerable periods during the 18th century. For the period 1840–1860, the most important source is a public database of medical history (*Medicinhistoriska databasen*). In particular, the reports of the provincial doctors often contain good weather descriptions. Even though a large number of these reports are not used, their quality clearly surpasses the average of the qualitative statements as a whole over the period 1500–1860. Finally, qualitative information has been found in a large number of publications on local history, military history, agricultural history, etc. (Among others, Allén 1965; Edman 1985; Ekman 1783; Collmar 1960; von Dalin 1761–1762; Palme 1942; Strömbeck 1993; Waaranen 1863–1864; Barkman 1939; Zettersten 1890; Swederus 1911; Ekström 1949; Gullander 1971; Bååth 1916; Utterström 1957).

4 Reconstruction methods

Sections 4.1, 4.2 describe the method for constructing the quantitative temperature reconstruction, whereas Section 4.3 explains how the qualitative index series is derived.

4.1 Derivation of a dimensionless composite of the sailing season series

The L08 study provided quantifiable evidence that the dominant climate signal of the historical series of the start of the sailing season during the 18th/19th centuries is January–April temperatures. Figure 4a plots the time series for all the individual sources. The mean inter-series correlation (MIC; also called RBAR) (Wigley et al. 1984) between the proxy records over the 17th–19th centuries is 0.65 highlighting the generally strong common signal between the series. Although it is not possible to compare the pre-1756 data to instrumental data, the strong correlation between the proxy records in this period, together with the fact that there is a strong correlation between the proxies and instrumental data in the period of overlap, implies that the proxies on average portray a similar winter temperature signal. The MIC for the 16th century is, however, markedly weaker. This is partially related to the non-continuous nature of the historical series used over this period, but also because the Freight series is included in the reconstruction. Excluding this series, implying that 1551 would become a gap, would increase MIC to 0.35. For the reconstruction, we include the Freight data in the knowledge that it is not a particularly strong proxy, but adjust the error bars (see later) accordingly to represent the weaker common signal between the proxy records for this period.

Although similar common longer-term trends may be observed in the various proxy series (Fig. 4a), differences in year-to-year variance exist between the individual records. For example, over the period 1817–1841, the standard deviation of the time series ranges from 14.1 days (Västerås) to 22.2 days (TolagA). L08, in their analysis, recognised these source-related differences, and when compositing the source time-series together, normalised the data to z-scores (zero mean and standard deviation of one) prior to averaging. As the multiple historical sources cover different periods (see Section 3 and Table 1), such an approach could theoretically reduce the amount of low-frequency information gleaned from the final composite series. Figure 4b presents the mean time-series of all the historical source time-series after they have been normalised to their respective period of coverage (hereafter referred to as the 'simple' composite series). It is clear that compared to the raw data (Fig. 4a),

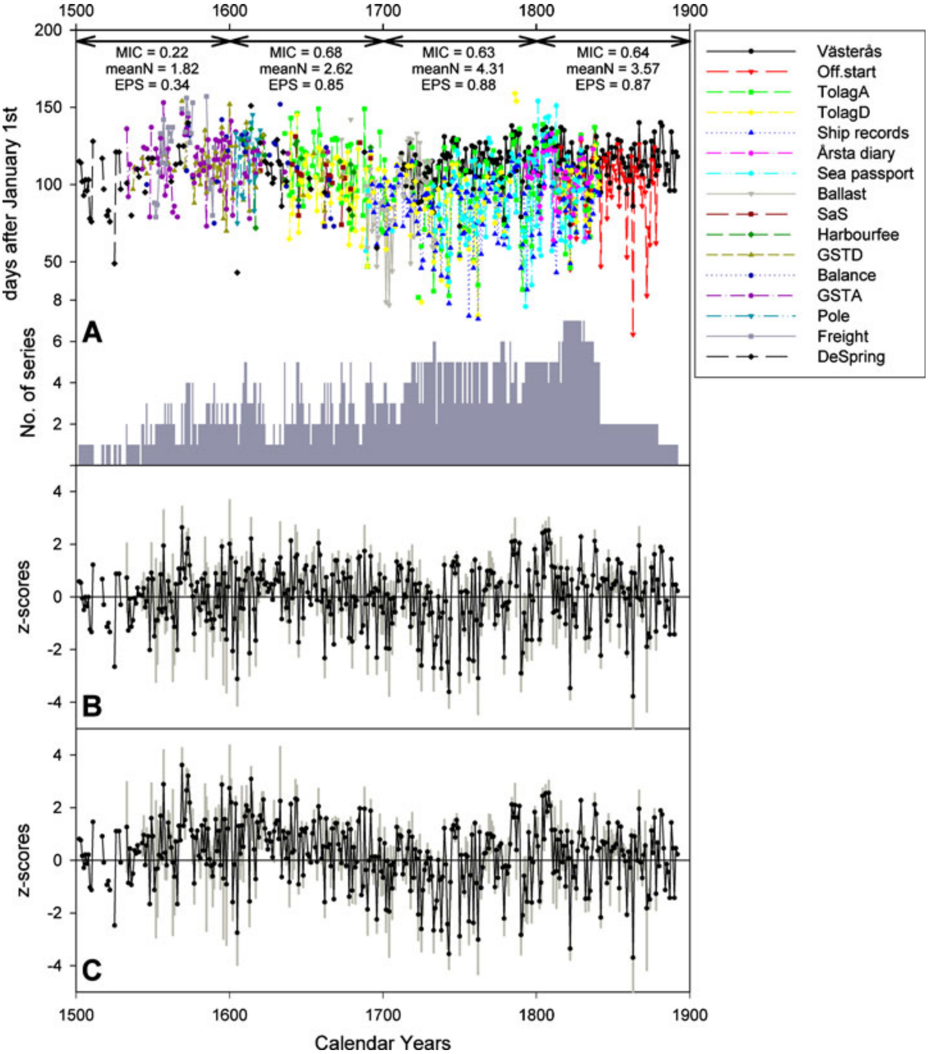


Fig. 4 **a** Individual raw data series with replication histogram. *MIC* mean inter-correlation between all possible bivariate pairs; *meanN* the average number of historical proxy sources per century, *EPS* Expressed Population Statistic (see Section 4 for details). Due to the discontinuous nature of many of the series, correlations were only calculated using data with three consecutive values. The final mean correlation value was weighted relative to the number of observations in each bivariate pair for each century—so allowing greater weight to a correlation derived from more observations. **b** Simple mean of normalised series with 2 sigma error envelope. The raw data have individually been transformed to z-scores with respect to their own period as well as the variance being stabilised using the Osborn et al. (1997) method (see main text). **c** As (**b**) but the raw data have been transformed to modified z-scores using the evolutive normalisation approach (see Section 4)

potential longer-term low-frequency information has been lost as the 'level' of each of the individual historical time series have been adjusted towards the long term mean of zero.

In order to attempt to capture as much low frequency information as possible from the data, an evolutive approach to time series normalisation was therefore employed; the final composite series was derived using the following steps:

The historical source data were ordered relative to their end dates (i.e. Västerås first, Off.start second and so on until the final series—Freight—see Table 1). The Västerås data were normalised to z-scores over their full period (1712–1892). The next series (Off.start) was then transformed in order to have the same mean and standard deviation as the Västerås data over their period of overlap (1815–1860).

This same procedure was undertaken for each historical time series going backward in time, but the transformation of each series was always relative to the mean and standard deviation of all preceding transformed time-series for the years of greatest overlap. Due to this procedure, each individual transformed proxy series (except the first one—Västerås) was allowed to have a mean value different from zero and a standard deviation that was not equal to one. Hence, they are not pure z-score series, but rather ‘modified’ z-scores—in contrast to the ‘simple’ approach which forces each transformed proxy series towards zero mean and unit variance. Consequently, the evolutive approach better allows preservation of long term variations in climate mean and variance.

Once all the constituent historical time series had been normalised to modified z-scores, they were averaged together to derive the final mean composite series. Following similar procedures detailed in L08, to minimise variance artefacts due to the changing number of observations through time (see Fig. 4a) as well as the change in common signal, the variance of the final mean composite series was adjusted using the following equation (Osborn et al. 1997):

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

where $X(t)$ is the simple mean value at time t, $n(t)$ is the number of series at time t, $\bar{r}$ is the inter-series correlation between all pairs of time series (MIC), and $Y(t)$ is the adjusted mean value at time t. As a slight refinement to the original L08 method, and following suggestions outlined in Frank et al. (2007), the MIC for each century (Fig. 4a) was utilised so that the weaker common signal between the historical archives would not bias (downwards) the variance of the final mean series in the 16th century.

The final, dimensionless, composite mean series is shown in Fig. 4c. Unlike the reconstruction of L08, (which at its corresponding step was found to differ significantly from a normal distribution, determined by a Kolmogorov–Smirnov test for normality and the Lilliefors significance correction), the final composite series was found to be normally distributed, so no further transformation of the time-series was deemed necessary for further analysis. From Fig. 4c, the final composite series shows more low frequency variability compared to the ‘simple’ version (Fig. 4b). Spectral analysis (not shown) reveals that there is more spectral power at frequencies >∼100 years in the ‘evolutive’ version.

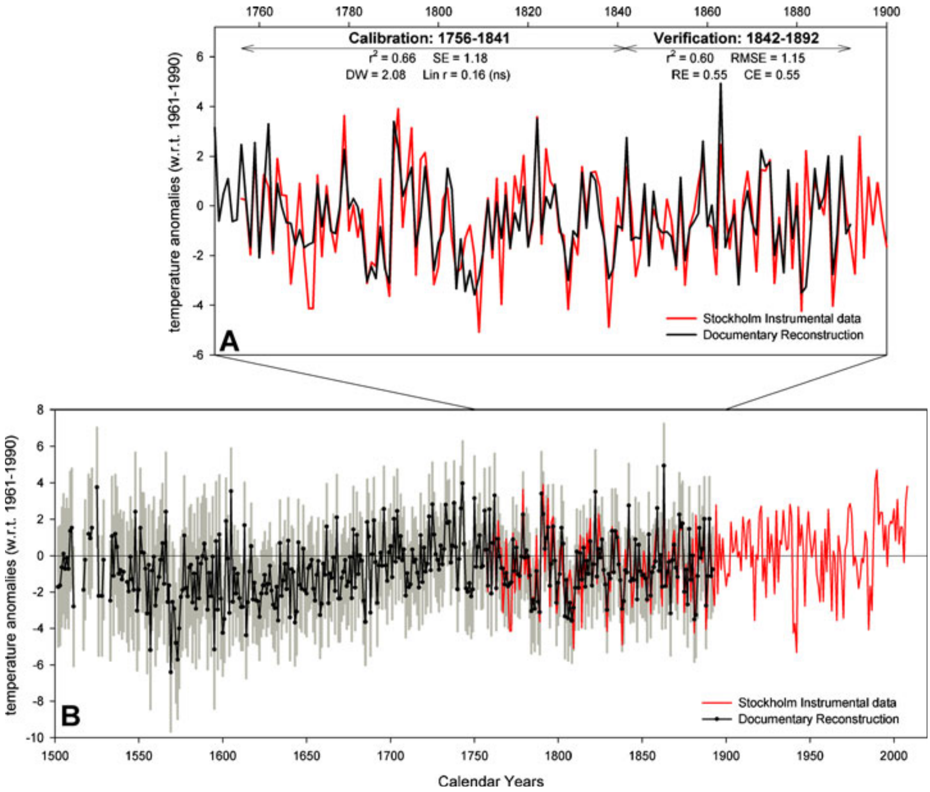


Fig. 5 **a** Calibration (1756–1841) and verification (1842–1892) against Stockholm JFMA temperatures. *DW* Durbin Watson statistic (Durbin and Watson 1951) measuring autocorrelation in the model residuals; *Lin r* is the linear trend of the residuals measured by the correlation between the residual values and time. *RMSE* root mean square error. *RE* reduction of error statistic, while *CE* the coefficient of efficiency (Cook et al. 1994). **b** Full reconstruction with 2 sigma (i.e. 1.96 multiplied by the SE of the estimate from the calibration and error modelling) error bars (see text for details on derivation)

4.2 Calibration/verification and error bar estimation for the quantitative reconstruction

The final dimensionless composite series was calibrated (using ordinary linear regression) against January–April (JFMA) mean Stockholm temperatures (Moberg et al. 2002) over the period 1756–1841, while model verification, using the square of the Pearson's correlation coefficient (r^2), the reduction of error (RE) statistic, and the coefficient of efficiency (CE) (Cook et al. 1994), was made over the 1842–1892 period. For consistency's sake, these calibration/verification periods are the same as in L08. Unsurprisingly, as the data sets used since the 18th century in this study are similar to those used by L08 (except for the addition of the Årsta diary data), the calibration results are comparable to the original study, with the regression model explaining 66% of JFMA temperature variance (Fig. 5a) and the model residuals showing no autocorrelation (DW= 2.08) or long term linear trend (Lin $r = 0.16$). Verification results are also highly robust, similar to L08, with $r^2 = 0.60$ and RE/CE $= 0.55$.

As the early proxy time series do not overlap with the instrumental data it is impossible to quantify the calibration/verification error prior to 1756. However, it is important to make some estimate of the decrease in reconstruction confidence back in time. To achieve this, we hypothesised that the MIC between the proxy records provides an estimate of the common signal between the series. Therefore, as the MIC is lower in the 16th century than later centuries, the common signal is weaker and therefore the confidence of the reconstruction must therefore be reduced over this period. In addition to the MIC, a further factor that needs to be taken into account is the number of historical proxy variables included for any particular period. Following Wigley et al. (1984) this issue may be considered as a signal-to-noise ratio problem. When the signal (as measured by the MIC) is high, then only relatively few series are needed to derive a robust mean function. When the MIC is low (as in the 16th century), then more series are theoretically needed. The appropriateness of averaging a sample of proxy records together to represent the theoretical population time-series can therefore be quantified using both the number of proxy sources (n) and the MIC to calculate the Expressed Population Statistic (EPS—Wigley et al. 1984). In simple terms, the EPS can be thought of as an empirical assessment of how the average of a sample of time-series correlates with the theoretical population time-series. The derivation of the EPS may be described as dividing the signal by the total variance (signal + noise). The EPS is calculated using the following equation:

$$EPS(t) = \frac{n(t)\bar{r}}{n(t)\bar{r} + (1 - \bar{r})} \approx \frac{signal}{total\,\text{variance}}$$

where EPS(t) is the Expressed Population Statistic at time t, $n(t)$ is the number of series at time t and $\bar{r}$ is the inter-series correlation between all pairs of time series (MIC). For this study time t relates to mean estimates calculated over each century (see Fig. 4a).

To estimate the decrease in confidence of the reconstruction back in time, the seven historical proxy records (Västerås, Off.start, TolagA, TolagD, Ship records, Årsta diary and Sea passport) that cover the 1756–1841 period were analyzed and white noise was added to the data prior to normalising and compositing. This was done multiple times, steadily increasing the amount of noise added to the individual proxy records (10%, 20%, up to 90%). By adding noise, it is possible to model the decrease in signal strength (as measured by the EPS). For every level of noise, a new composite series was derived and calibration tests made against JFMA Stockholm temperatures over the period 1756–1841, to analyse how the calibration r^2 decreases and the standard error (SE) of the estimate increases with increasing amount of noise added.

Figure 6 shows the derived modelled linear relationship between the EPS and calibration r^2 (6A) and between the EPS and standard error of the regression estimate (6B) for each noise level. Using these near linear relationships, the decrease in calibration r^2 and increase in SE prior to 1756 was estimated relative to the EPS calculated for each century (see Fig. 4a). Over the calibration period (1756–1841), the EPS is 0.89 (SE = 1.18°C; $r^2 = 0.66$). In contrast, during the 16th century, the EPS is 0.34 which equates to an estimated r^2 of 0.34 and a SE of 1.67°C. The full reconstruction with its 2 sigma error estimates is shown in Fig. 5b.

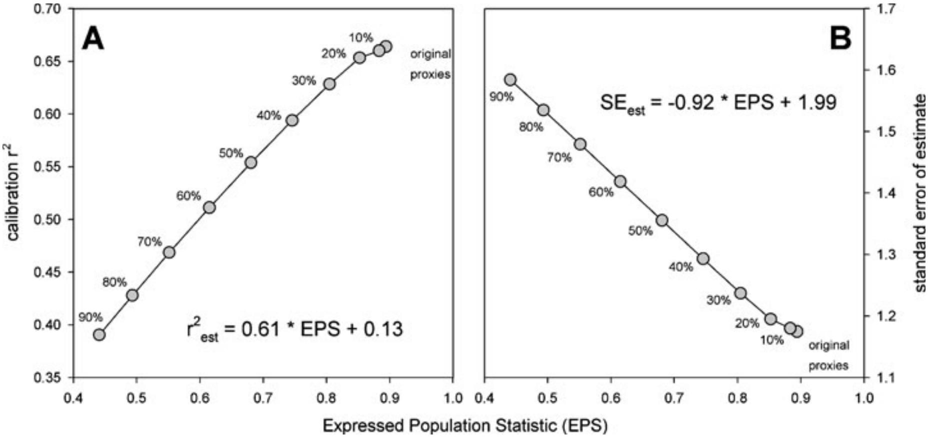


Fig. 6 Error modelling to derive error estimates. Percentage values denote how much random white noise was added to the individual proxy records. **a** Relationship between the EPS and the calibration r^2. **b** Relationship between the EPS and the calibration standard error of the estimate. The linear regression equations between the variables is shown

4.3 Construction of a qualitative temperature index series on an ordinal scale

To derive a separate index for winter/spring temperature conditions in Stockholm and nearby locations in south-eastern Sweden, we used a variant of the traditional indexing approach in historical climatology. At the core of the method is the search and extraction of keywords from a digital text database that holds all the available information from sources described in Sections 3.12 and 3.14. Descriptive climate information from all sources was extracted through cross-tabulating selected keywords, or combinations of keywords, relating to the various authors' perception of temperature (e.g. 'cold', 'very cold', 'mild', etc.). An example of another linguistic marker for winter weather conditions is *menföre* or *oföre*, which refers to inappropriate conditions for land surface transport (too little snow for sledges). When it occurs in letters in the first months of the year it actually describes early thaw (See Retsö 2002).

The descriptive information extracted for a particular winter/spring season is subjectively interpreted and transformed into an index value, defined on a widely-used seven-point ordinal classification (−3 extremely cold, −2 very cold, −1 cold, 0 normal, +1 warm, +2 very warm, +3 extremely warm) (Brázdil et al. 2005). Our index roughly conforms to a normal distribution, which is close to the real distribution of seasonal mean temperatures, but differs from the distribution normally used in index-constructions (e.g. Pfister 1992). It should be made clear that the mapping of information onto the index scale is subjective; due to the disparate sources and types of information, it has not yet been possible to define an objective algorithm for translating the descriptive information to an index scale.

The total number of observations (Fig. 3) is about 7,300, with the data density being much higher in the last ~100 years of the study period (1502–1860). Hence it is likely that the quality of the index, in terms of reflecting average winter to spring temperatures, improves in the later part of the series.

5 Comparisons between Stockholm reconstructions

In this section, the occurrence of warm and cold decades and single years in the quantitative reconstruction, extended to the present by a combination with instrumental data is briefly analysed. The qualitative index series is then analysed. This is followed by a discussion of similarities and differences between the two series. For practical purposes, the quantitative reconstruction (as defined in Section 5.1) is henceforward labelled as QUAN and the qualitative index as QUAL.

5.1 The full reconstruction based on quantitative data (QUAN), AD 1502–2008

To derive a continuous reconstructed time series for the period 1502–2008, the time series obtained by linear regression in Section 4.2 was scaled to have the same mean and variance as the instrumental JFMA temperatures over the 1756–1892 period. The instrumental data were then spliced onto the proxy record to allow an effective representation of Stockholm winter temperature for the last 500 years (Fig. 7). The instrumental temperatures are taken from Moberg et al. (2002), being updated through April 2008 with recent data obtained from the Swedish Meteorological and Hydrological Institute, corrected for the urban heat island effect as in Moberg et al. (2002).

Of the five warmest non-overlapping complete decades in the whole QUAN record, four are within the 20th century (1989–1998 (1st), 1999–2008 (2nd), 1930–1939 (4th) and 1905–1914 (5th)); the most recent 20-year period 1989–2008 thus stands out as the longest and warmest period of the whole 500 years. Within this most recent period are three of the ten warmest years on record (1990 (2nd), 1989 (5th)

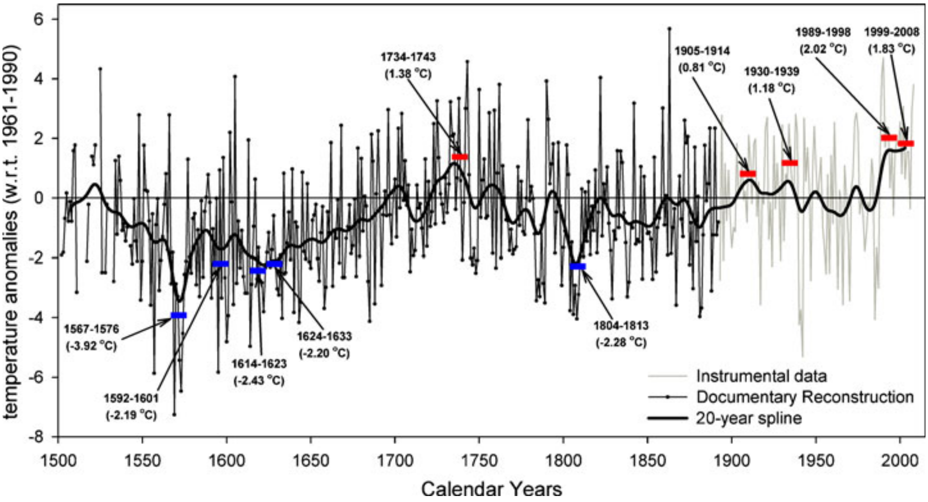


Fig. 7 QUAN—full Stockholm winter temperature reconstruction. Instrumental data have been spliced onto recent period after the reconstruction was appropriately scaled to have same mean and variance over the 1756–1892 period. The five warmest and coldest non-overlapping decades are shown—analysis made for all decades with at least seven values per decade. *Smoothed line* is a 20 year spline

and 2008 (10th)—see Table 3 and Fig. 7). Interestingly, the warmest reconstructed year is 1863, which the proxy data have markedly over predicted (Fig. 5a) compared to the instrumental data. The extreme nature of this year in L08 was diminished by their transformation of the composite data-set to reduce skewness in the data (see Fig. 4 in L08). Such a transformation could not be statistically justified in this present study due to the extended length of the full composite series.

The coldest decade in QUAN is 1567–1576 in which four of the coldest years are found (1569 (1st), 1573 (2nd), 1572 (5th) and 1574 (9th). The early 17th century has two complete cold decades (1614–1623 (2nd) and 1624–1633 (4th), with 1592–1601 (5th) further highlighting how cold the ~1560–1650 period was. The 3rd coldest decade is 1804–1813, which is roughly centred on 1809 which L08 discussed in great detail. Outside of the very cold 16th–17th centuries, the next coldest years are 1942 (6th) and 1940 (10th) highlighting the extremity of this period during the second world war.

As a result of to the calibrated error (>2.3°C) in the reconstruction (Fig. 4b) caution is advised when comparing such extreme years. For example, at the 95% C.L. there is no statistical difference between the 10 warmest years and likewise for the 10 coldest years (Table 3).

5.2 The qualitative index series (QUAL), AD 1502–1860, and comparison with QUAN

In contrast to QUAN, which depicts a notable degree of low-frequency variability, QUAL mainly depicts high- and mid-frequency variability (Fig. 9, first and second panels). One reason why much of the low frequency information appears to be lost in

Table 3 Ten coldest/warmest JFMA seasons in QUAN (temperature anomalies in °C from 1961–90 average)

Rank	Year	Value
10 coldest years		
1	1569	−7.26
2	1573	−6.47
3	1557	−5.87
4	1595	−5.83
5	1572	−5.43
6	1942	−5.32
7	1614	−4.96
8	1600	−4.81
9	1574	−4.53
10	1940	−4.24
10 warmest years		
1	1863	5.68
2	1990	4.71
3	1743	4.58
4	1525	4.33
5	1989	4.11
6	1605	4.08
7	1822	4.04
8	1790	3.93
9	1762	3.81
10	2008	3.80

QUAL is likely that contemporary observers' assessments of the severity of winters relate to their own lifetime's experience (Glaser et al. 1999). In a warm period, the observers may perceive some winters as cold, even though the same winters would not be described as cold if they had appeared in a cold period. The effect of this is that the index values are forced towards a zero average, even if climate itself deviated from the long-term average during long periods (Fig. 9).

Although QUAN by construction has advantages over QUAL in the low-frequency domain, the descriptive sources used in QUAL can potentially contain information that the administrative-economic ones used in QUAN cannot capture, or may capture wrongly (as e.g. in the record-warm year 1863 mentioned in Section 5.1).

Figure 8 shows how strongly both QUAL and QUAN correlate with Stockholm monthly temperatures for January to May during 1756–1860. Both series correlate most strongly ($r \sim 0.6$–0.7) with temperatures in February and March. QUAN's third strongest month is April ($r \sim 0.5$; QUAL correlates notably less), while QUAL's third strongest month is January ($r \sim 0.5$). Both series show their weakest correlations in May ($r \sim 0.2$)—the QUAN correlation not being significant at the 95% C.L. The stronger correlation for QUAL, compared to QUAN, with January temperatures is likely because QUAL can better include information from the early part of winters, whereas the information in QUAN focuses on the start of the sailing season, which generally occurred in March or April. This is reflected by the stronger correlation between QUAN and April temperatures. Perhaps surprisingly, both series have virtually identical strong correlations with both JFMA and JFMAM temperatures ($r \sim 0.8$), explaining about 64% of the seasonal temperature variability. The correlation between QUAL and QUAN is substantially weaker, being $r = 0.59$.

It is tempting to investigate how much the predictive skill of winter/spring temperatures can be increased by combining QUAN and QUAL in a multiple regression approach. This was tested (i.e. with QUAN and QUAL as predictors and Stockholm temperatures as the predictand) for 1756–1860 and observed 78% explained temperature variance for JFMA and 77% for JFMAM, with both predictors being highly significant in the model. Hence, there is a potential for improving the reconstruction skill by combining the two series. This is not attempted here as the two series clearly have different properties in the frequency domain. The discrete nature of QUAL

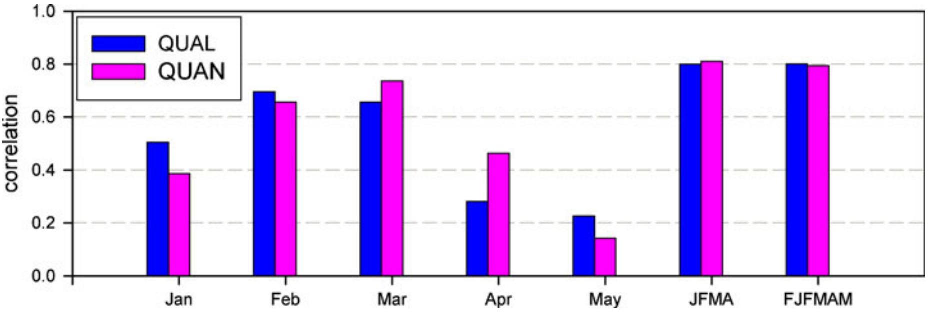


Fig. 8 Correlations between instrumental Stockholm January to May temperature, 1756–1860 and the QUAL and QUAN reconstructions. Correlation 95% significance level = 0.19

and the continuous nature of QUAN is another difficulty from a technical point of view. However, these preliminary results are encouraging.

6 Comparison of QUAN and QUAL with similar series

Despite the strong calibration and verification results of the quantitative reconstruction (Fig. 5), and the similar strong correlations with instrumental data for the qualitative index (Fig. 8), no true validation of our datasets can be made prior to 1756. However, cross-comparison of the two independently derived series QUAN and QUAL, and comparison of both of them to other winter temperature proxy records for the Baltic region will provide some estimate as to the robustness of our reconstructions, especially if strong coherence is identified with independent data. Figure 9 compares our reconstructions with several other winter related proxy reconstructions (see Fig. 1 for their locations):

The relevant 0.5 × 0.5 degree grid box (18-18.5E/59-59.5N) from the Luterbacher et al. (2004) temperature reconstruction for the December–May season for Europe. Hereafter referred to as LUT.
The Tallinn December–March temperature reconstruction (Tarand and Nordli 2001). Hereafter referred to as TAL.
The Riga ice break-up date series (Jevrejeva 2001). Hereafter referred to as RIG.
The end of winter ice break-up data for the western Baltic (Koslowski and Glaser 1995). Hereafter referred to as IWB.

Overall, the inter-proxy comparison of the Baltic winter temperature related series (Fig. 9), broadly show (after some disagreement in the early 16th century) cool conditions from ~1550–1700 (QUAN shows ~2°C cooler than the 1961–1990 reference period), a warm pulse from ~1710–1750, another cool period from ~1760–1900, a short warm period in the early 20th century and marked warming over the last two decades, which in QUAN are the two warmest decades over the last five centuries.

Running 31-year correlations between all of these series are shown in Fig. 10. These running correlations do not only provide information about the quality of our new reconstructions, but they also tell us something about the reliability of the other four series, as all six are compared against the five others in a similar manner.

QUAN and QUAL correlate quite strongly against each other, which nicely validates the high-frequency coherence between these two independent proxy series representing Stockholm temperatures. Notably, the correlations from the late 16th century to the mid 17th century ($r \sim 0.6$–0.8) are as high, or even higher, than in the QUAN calibration period. However, when comparing the longer-term trends between the time series (Fig. 9), QUAL shows distinctly less low frequency information than QUAN, which is likely to be related to limitations of the derivation of historical indices in capturing secular-scale information as briefly discussed in Section 5.2.

Comparison with LUT is particularly interesting, as this gridded series should represent the Stockholm region (Fig. 1). From ~1900 to the present, QUAN and LUT agree well ($r > 0.8$). These strong correlations are certainly a result of the fact that both series are constructed from instrumental data in this period. The correlations are also high from ~1750 to 1900 ($r \sim 0.6$–0.8). However, LUT data for

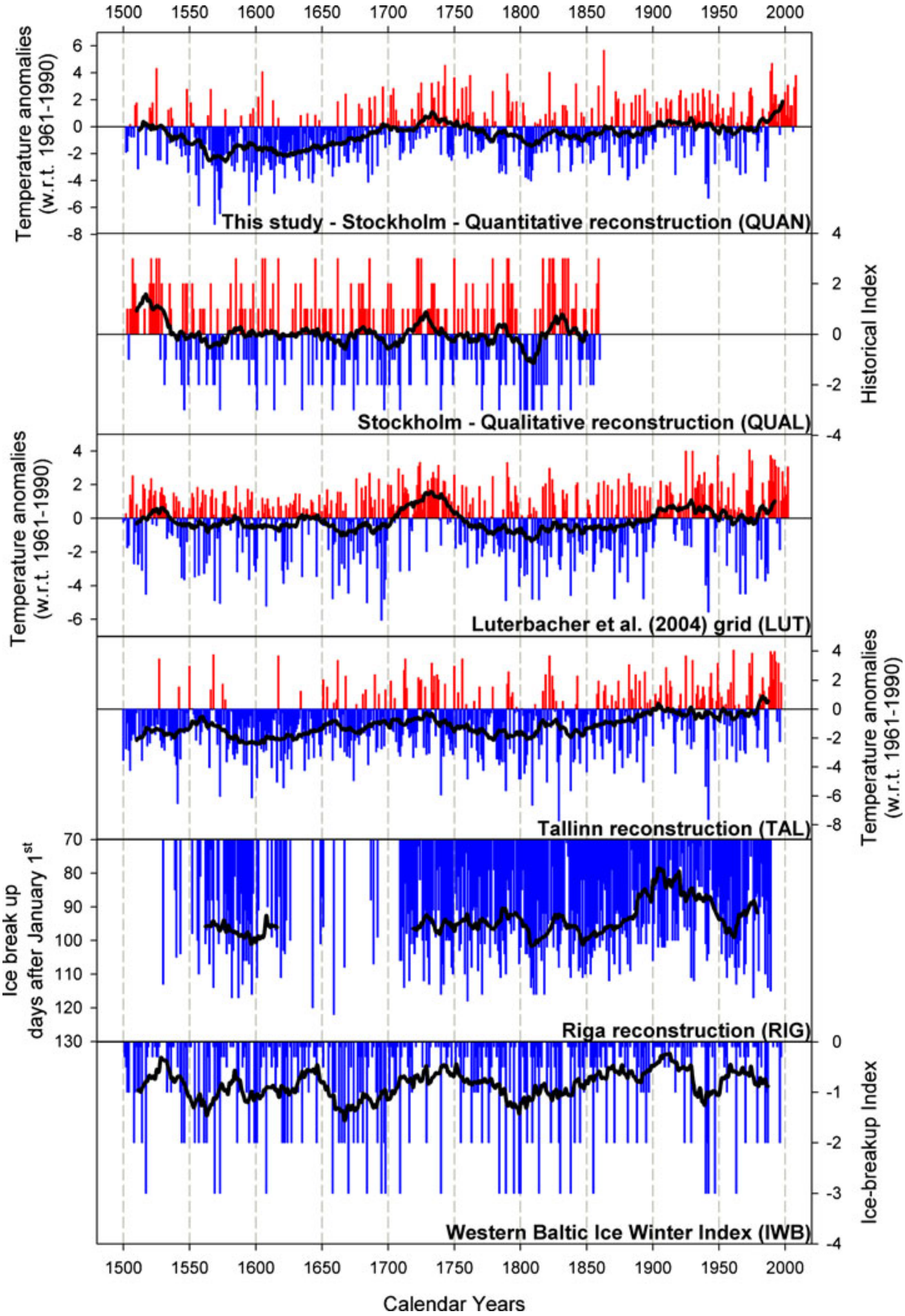


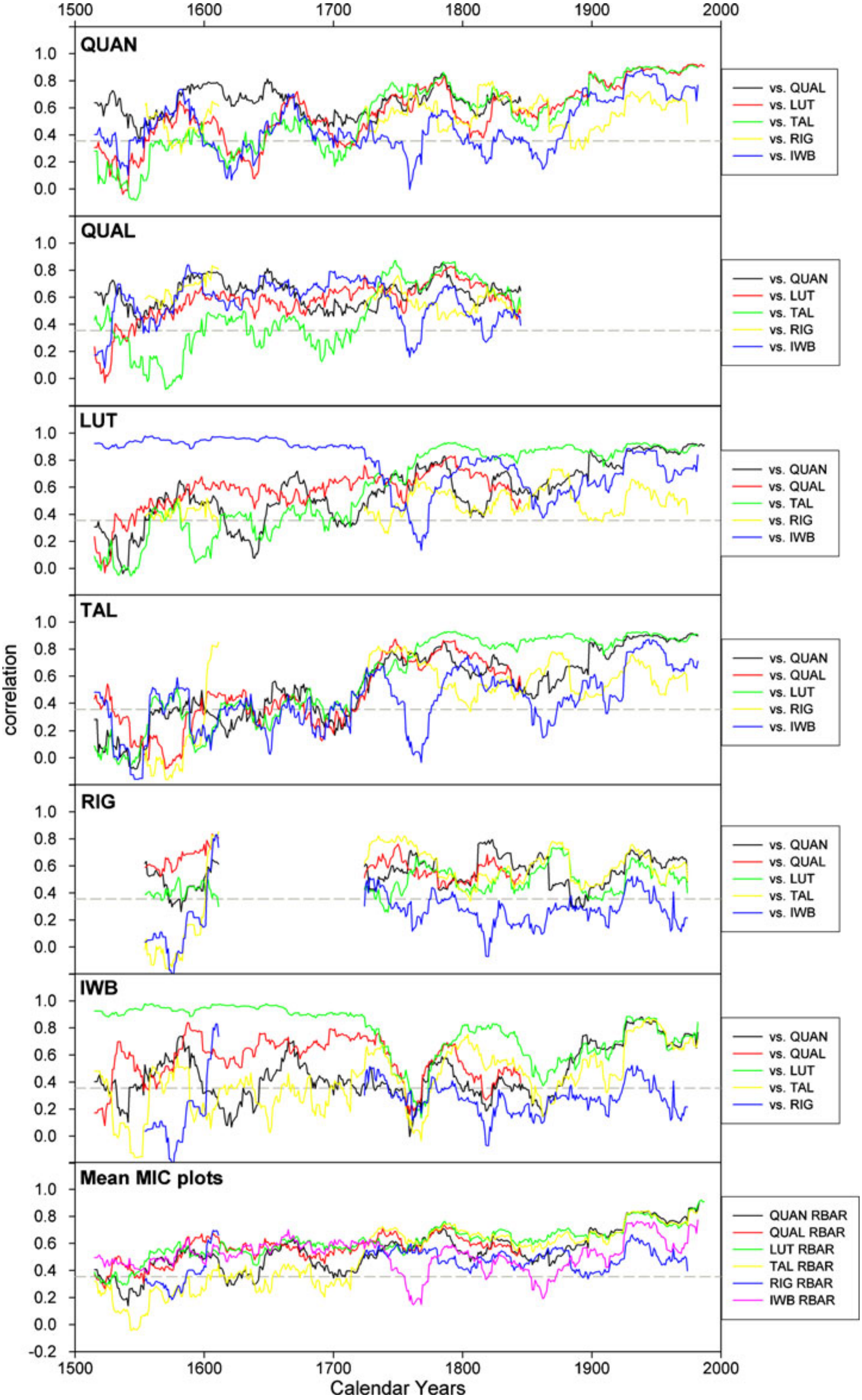
Fig. 9 Stack plot comparing the Stockholm reconstruction with other winter temperature reconstructions around the Baltic. *Smoothed black series* are a moving 21-year average

the chosen grid point are expected to be dominated by the Stockholm temperatures after 1756, i.e. from the time when LUT includes instrumental Stockholm data. Hence, the high correlations in this period add no new information about QUAN compared to our own calibration/verification results.

Correlations between QUAN and LUT are generally weaker before the mid 18th century. For three periods, the first half of the 16th century, and the first decades in the 17th and 18th centuries, coherence is insignificant. Given the strong correlations between QUAN and QUAL in these periods, the simultaneous low correlations between QUAN and LUT cast doubts on the reliability of the early LUT data, which are exclusively derived from proxy data before 1659. Notably, no data in LUT comes from sites nearby Stockholm before 1722, when the Uppsala temperature series of Bergström and Moberg (2002) is included. The weak correlation between QUAN and LUT before the late 17th century may thus be because there is too little information from this area in LUT to provide a good estimate of Stockholm temperatures. On the other hand, simultaneously with the insignificant QUAN/LUT correlation in the early 17th century, the correlations between QUAL and LUT are significant. Interestingly, the QUAL/LUT running correlations are at a relatively stable level of $r \sim 0.6$–0.7 from around 1600 to 1750, suggesting that there is relevant information concerning Stockholm winter/spring temperatures in LUT also before the inclusion of the Uppsala temperatures. These results from the comparison of QUAL, QUAN and LUT are counter-indicative, and hence difficult to interpret.

The inclusion of Uppsala temperatures in LUT, however, can explain why LUT portrays warmer temperatures than QUAN around the 1730s (Fig. 9). L08 suggested that Uppsala temperatures may be biased ‘too warm’ prior to 1739 due to the thermometer being located indoors (in un-heated rooms; see discussions also in Moberg et al. 2000, 2002). In the 17th and 16th centuries there is a clear deviation between cooler reconstructed temperatures in QUAN compared to near 1961–90 average temperatures in LUT. The LUT series is, interestingly, strongly weighted towards IWB (see high correlations in Fig. 10) and the Low Countries winter reconstruction (Shabalova and van Engelen 2003; running correlations analysed but not shown) before ∼1750, which both infer temperatures near the 1961–90 average; hence explaining the character of long-term trends in the first half of the LUT series. This suggests that LUT may possibly suffer from the kind of low-frequency problems which seems inherent in our QUAL series, and perhaps in many other index-based reconstructions. The different long-term trends depicted in the various historical proxies point to a need for better assessing the reliability of these trends, considering both the raw data used and the methodology for development of climate reconstructions.

TAL, which is derived from similar sources as QUAN—port records portraying the start of the sailing season (although using a simpler technique, Tarand and Nordli 2001)—agrees with QUAN concerning cooler temperatures during the 16th and 17th centuries. Despite the similar low-frequency trends, there is a distinct weakening in a common signal seen as generally insignificant correlations between QUAN and TAL during the first half of the 16th century and also around 1600 and 1700. The two series show strongest correlations after ∼1750, but in this period TAL is constructed from instrumental data (including Stockholm and St Petersburg temperatures). The almost complete deterioration of correlation between QUAN and TAL for the first half of the 16th century may reflect the use of economic-administrative sources in


QUAN
vs. QUAL
vs. LUT
vs. TAL
vs. RIG
vs. IWB
QUAL
vs. QUAN
vs. LUT
vs. TAL
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vs. TAL
vs. IWB
IWB
vs. QUAN
vs. QUAL
vs. LUT
vs. TAL
vs. RIG
Mean MIC plots
QUAN RBAR
QUAL RBAR
LUT RBAR
TAL RBAR
RIG RBAR
IWB RBAR
correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
1500
1600
1700
1800
1900
2000
Calendar Years

◀ **Fig. 10** Running 31-year correlations between the different proxy records shown in Fig. 6. The lower panel is the mean (MIC) of the correlation in each of the *upper panels*. The *horizontal grey dashed line* denotes the 95% C.L

this period (Tarand and Nordli 2001) while such data do not exist for Stockholm for this period. On the other hand, the independent QUAN and QUAL series correlate quite strongly in this period, which suggests that it is possibly TAL that is based on less detailed proxy data in this period. Generally, the problem with TAL is that it only uses one datum for each year; i.e. it is a single composite series. Again (as with LUT), there is some counter-indicative information as correlations between QUAL and LUT are significant (although rather weak) in the first few decades.

Running correlations between QUAN and RIG are overall quite similar to those between QUAN/LUT or QUAN/TAL, although the long term trends of the RIG series (Fig. 9) appear quite different compared to all other series—with inferred warmth peaking in the early 20th century. The RIG series seems fraught with difficulties (e.g. large gaps) and more archival research appears to be needed in order to develop a more robust temperature reconstruction for Riga.

Weak coherence between QUAN and the IWB record is also noted in the early 16th century. However, compared to the other proxy records, this weak coherence continues up to the mid-19th century. In the 20th century, the correlation between IWB and QUAN (i.e. instrumental Stockholm JFMA temperatures) varies between 0.6 and 0.8. The weak coherence between QUAN and IWB might to some (or large) extent be because ice/climatic conditions in the south of the Baltic being rather different compared to those in the Stockholm area. The highest correlation between QUAN and IWB occur in the 1930s and 40s, which were quite extreme periods (very warm in the 1930s and very cold in the 1940s). After the 1950s, temperature fluctuations were not that large, and correlation falls.

Finally, the bottom panel of Fig. 10 shows the average mean inter-series correlation (MIC) for each of the six series against the other five. Overall the correlations are weaker in the early part of the series, and increases towards the end; hence indicating a general decrease in data coherence backwards in time. This most likely reflects a general decrease of data quality—in all series—in the earlier period.

7 Discussion and conclusion

How well do the data discussed in this paper portray five centuries of winter/spring temperature in the Stockholm region? One difficulty with the custom ledgers is that the sheer volume of trade falls as they go back in time. The total number of vessels registered in records is more than 700 in the late 18th and early 19th centuries, but drops to ca. 100 in the 16th century (RA, *Lokala tullräkenskaper*, SSA, *Stadskamrerarens arkiv*, *Tolagsjournaler*). Clearly, the more trade, the more likely it is that the first ship will have come (or left) the Stockholm harbour as soon as the water was ice-free. On the other hand, the number of ships do vary even within the calibration period, where harbour activity during the mid 1780s and the Napoleonic wars (early 19th century) was dramatically lower than the decades preceding and following these years.

Whilst economic-administrative records show when the sailing season began, they cannot tell to what degree factors other than climatic ones influenced the start of the sailing season. For example, the year 1569, which according to Table 3 was the coldest year for the past 500 years, may not have been really that cold. Sweden was at war with the Danes during that time, and the start of the sailing season being put back to late in spring could partly be a consequence of military activity. The descriptive information used to derive QUAN confirms that 1569 was likely to have been a cold winter, but not necessarily extremely cold (index value $= -2$).

We have assumed that the timing of the start of the sailing season was at its earliest possible date in order to ensure that the season's length was as long as possible, thereby allowing for maximum profit from trade conducted by individual ship owners and captains. We are, however, dealing with human beings and it might be argued that considerations other than purely economic ones might contribute to the selection of the first sailing date, for example religious festivals or other events that might preclude sailing on otherwise propitious days. Such considerations might also be more valid as one goes back to less secular times. Fortunately there is no evidence to sustain this argument since the running correlations between QUAN and QUAL (Fig. 9) do not show any trend over the full span of the record, which could otherwise have been suspected to be the case.

Comparison between QUAN and QUAL shows reasonable coherence, with generally strong correlations (Fig. 9) between the two series. However, our results indicate problems with the index approach for capturing the low frequency trends in winter temperatures. The index appears to have its relative strength in the estimation of inter-annual variations. We have also presented a tentative analysis that indicates that an improved reconstruction could be developed by combining the QUAN and QUAL data, but future explorative work must take into account differences in spectral properties of the different data-sets.

Another important result concerns the use of composite series; SaS, DeSpring and most particularly QUAL, which are constructed from a variety of sources. We have been fortunate to have had access to continuous series of data that stretch over centuries and which we also, for good reasons, may assume to have been prepared in similar ways throughout time, e.g. the *Tolag*, the Great Sea Toll, and ship records. Analyses between the composite series and the more homogenous ones, like the *Tolag* or the Great Sea Toll, show that the former series are in agreement with the latter ones, although QUAL has limitations in capturing low frequency. However, our analyses support the validity of composite series from historical documents; something that would be very hard indeed to propose in other branches of paleoclimatology.

Our quantitative reconstruction displays both high and low frequency variability. The low-frequency variations are in broad agreement with other winter temperature reconstructions from the Baltic Region (Tarand and Nordli 2001; Luterbacher et al. 2004). Our data indicate the 16th and 17th centuries as a prolonged cold period, while the 20th/21st century seems warmer. Four of the five coldest periods occurred in the 16th and 17th centuries, while four of the five warmest periods occurred in the past century. These data strongly indicate that the past 20 years form the warmest period of the past half millennium. Although there have been other warm periods, particularly the 1730s, which might have been as warm as it is today, but they were not as prolonged as the recent warm period.

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