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Reconstructed drought variability in southeastern Sweden since the 1650s

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ABSTRACT: In this study, we present the first regional reconstruction of summer drought for southeastern Sweden. The June–July standardized precipitation index (SPI) was reconstructed over the period 1650–2002 based on *Pinus sylvestris* L. tree-ring width data, where the reconstruction could account for 41.6% of the total variance in the instrumental record over 1901–2002. Our reconstruction suggests an overall wet 18th century and a dry 19th century. The most outstanding pluvial phase in the pre-instrumental period took place in the mid-1720s and lasted over 50 years, while multi-decadal periods of below average moisture conditions were reconstructed in the 1660s–1720s, 1800s-early 30s, and in the 1840s–50s. Several of these dry spells have previously been found in reconstructions from Sweden and Finland, indicating that our reconstruction reflects large-scale moisture anomalies across eastern Fennoscandia. Comparison of the SPI estimates with mid-tropospheric pressure patterns suggests that summertime drought is associated with positive pressure anomalies over British Isles and the North Sea, while an eastward movement of the Icelandic low-pressure systems over the western part of central Fennoscandia results in wetter than normal June–July conditions over the region of interest.

KEY WORDS dendroclimatology; southeastern Sweden; SPI; drought reconstruction

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1. Introduction

Multi-proxy temperature reconstructions have improved our understanding of past climate variability, and helped us to put the recent warming and scenarios of future climate in a historical context (Jones and Mann, 2004). Over northern Europe, precipitation has increased by 10–40% during the 20th century, and increased precipitation in Fennoscandia over the past decades has caused climate in the region to become more oceanic (Hanssen-Bauer and Forland, 2000). However, climate models indicate that future precipitation increases are predominantly expected in winter, while summers are expected to be drier (Rummukainen *et al*., 2004; Folland *et al*., 2009). Summer droughts may have a devastating environmental and socioeconomic impact by reducing water availability, hence affecting the agricultural and water supply economical sectors severely (Fink *et al*., 2004).

Tree-ring data from trees growing in environments where climate is the major growth-limiting factor can be used as a powerful tool for developing long-term, annually resolved series of past climatic events, such as drought (Fritts, 2001). Numerous tree-ring width and maximum latewood density chronologies from temperature sensitive trees exist throughout the northern high latitudes (Schweingruber *et al*., 1993; Schweingruber and Briffa, 1996; Briffa *et al*., 2001, 2002), which have been widely used to reconstruct past temperatures. However, comparatively few efforts have been made to provide tree-ring based precipitation reconstructions for this region. Dendroclimatological studies have shown that conifers growing in southern Fennoscandia may be limited by water availability (Lindholm *et al*., 1997, 2000; Linderholm *et al*., 2003), and the use of tree rings as proxies for precipitation and drought have been explored with various success (Helama and Lindholm, 2003; Linderholm *et al*., 2004; Linderholm and Molin, 2005; Helama *et al*., 2009; Jönsson and Nilsson, 2009). Given the considerable impact of future changes in the precipitation pattern over Scandinavia on terrestrial ecosystems (Crawford, 2000), there is still a strong need for high-resolution paleo-data on precipitation and drought for the region and more work on moisture-sensitive species and sites is required.

In this study, we examine the potential of using tree-ring data from sites where the tree growth is, in general, not restricted by water availability to reconstruct regional drought. Five existing tree-ring chronologies from the Stockholm region of southeastern Sweden together with two newly developed Scots pine (*Pinus sylvestris* L.)

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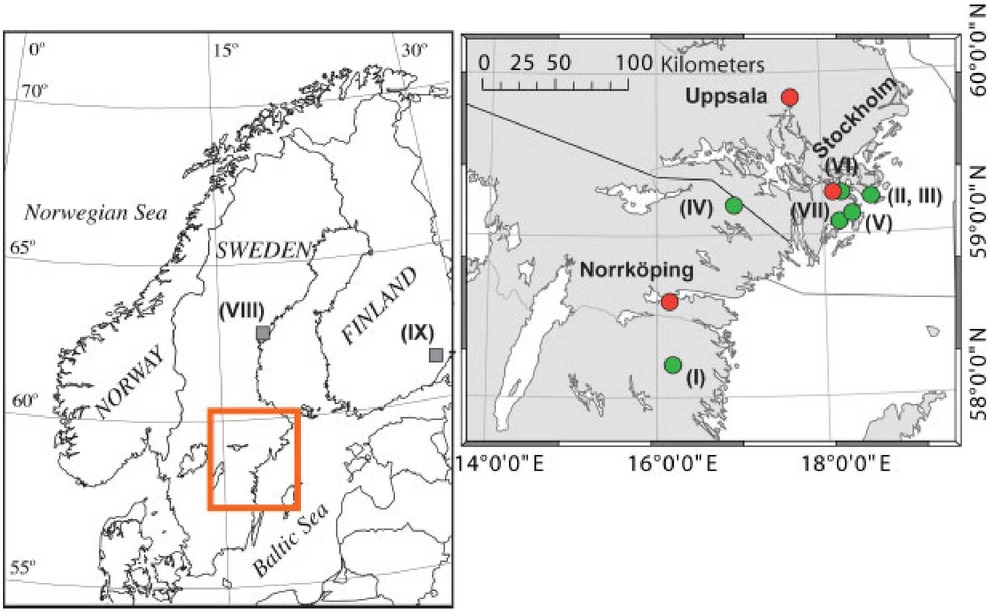

Figure 1. Map of the study area located in the counties of Östergötland, Södermanland and Stockholm in southeastern Sweden. Samples of *P. sylvestris* used in the drought reconstruction were collected in Ekhultebergen (I), Kaptensudden (II), Nämdö (III), Putbergen (IV), Sisshammar (V), Stockholm (VI), and Tyresta (VII) sites. The SPI reconstruction was compared to independent tree-ring based precipitation reconstructions from east-central Sweden (VIII; Jönsson and Nilsson, 2009) and southeastern Finland (IX; Helama *et al.*, 2009).

chronologies from well drained xeric sites, were used to develop the first regional high-resolution summer (June–July) drought reconstruction for the last 350 years. The final reconstruction was compared to the large-scale atmospheric circulation in order to identify synoptic modes that trigger regional extremes of dry and wet conditions.

2. Methods

2.1. Study region and tree-ring data

The study region covers the area between 58.14–59.20N and 16.25–18.14E in southeastern Sweden (Figure 1). The region belongs to the hemiboreal forest belt (Sjörs, 1965), and climate can be characterized as sub-continental where average January and July temperatures at Stockholm meteorological station are −2.8 and 17.1 °C, respectively, and the average total annual precipitation is 540 mm (1961–1990; Swedish Meteorological and Hydrological Institute, SMHI). Scots pine tree-ring width chronologies from seven sites in the study region were used for drought reconstruction. The tree-ring data comprises of two newly compiled chronologies and five existing chronologies downloaded from the International Tree Ring Data Bank (ITRDB, www.ncdc.noaa.gov/paleo/treering.html).

To yield reliable tree-ring based drought reconstructions, it is important to base the prediction on drought-sensitive trees, for example from those growing at xeric sites, where the radial growth is most likely limited by moisture availability (Fritts, 2001). To meet this condition, two well-drained xeric sites were selected in the studied region. The locations were Ekhultebergens nature reserve, the southernmost site in the region, and Putbergens nature reserve, in the central parts of Mälarmården (Figure 1; Table 1). The terrain at these sites is characterized by thin soil layers with inclusion of bedrock outcrops at higher elevations and a stand dominated by a Scots pine forest. In the lower parts of the landscape, where soils are deeper and more peaty, Norway spruce (*Picea Abies*) dominates. Typical for the ground vegetation are drought-indicating species, such as dwarf shrubs (*Vaccinium vitis-idaea, Vaccinium myrtillus, Vaccinium uliginosum* and *Empetrum nigrum*) and lichens (Hägglund and Lundmark, 1977). Due to an overall lack of stumps and dead trees at the sampling sites, only living trees were used for the compilation of the chronologies. Two cores were extracted with an increment borer from the pine trees at a height of ca. 1.3 m above the base of the trunk. The samples were prepared and cross-dated according to standard dendrochronological methods (Stokes and Smiley, 1968), and the widths of the annual tree rings were measured to the nearest 0.001 mm.

Moreover, five additional chronologies, from Tyresta (Linderholm *et al.*, 2004; Linderholm and Molin, 2005), Nämdö, Stockholm (Linderholm *et al.*, 2002), Sisshammar and Kaptensudden, were obtained from the ITRDB (Figure 1; Table 1). The chronologies were selected on the basis of type of species and temporal range covered by the tree-ring data. The data from Sisshammar, Kaptensudden and partly from Nämdö were based on beams taking from historical buildings. The construction timbers used in Kaptensudden were most likely not of a local origin, but originated from the mainland or from other parts of the archipelago. The precise growth sites of the Sisshammar and Nämdö timber are unknown. Tyresta and parts

Table 1. Statistics of seven chronologies used in drought index reconstruction.

Site name	Lat. (N)	Long. (E)	Elev. (m a.s.l.)	Time span[a] (years A.D.)	No. of trees[a]	Source
(I) Ekhultebergen	58.14	16.25	110	1705–2008	17	This study
(II) Kaptensudden	59.20	18.70	30	1672–1895	21	ITRDB
(III) Nämdö	59.20	18.70	30	1582–1995	46	ITRDB
(IV) Putbergen	59.19	16.93	75	1734–2007	25	This study
(V) Sisshammar	59.20	18.34	5	1661–1910	42	ITRDB
(VI) Stockholm	59.15	18.00	72	1713–1996	20	ITRDB
(VII) Tyresta	59.18	18.29	60	1694–2000	15	ITRDB

[a] Statistics of the chronologies selected for the regional composite chronology.

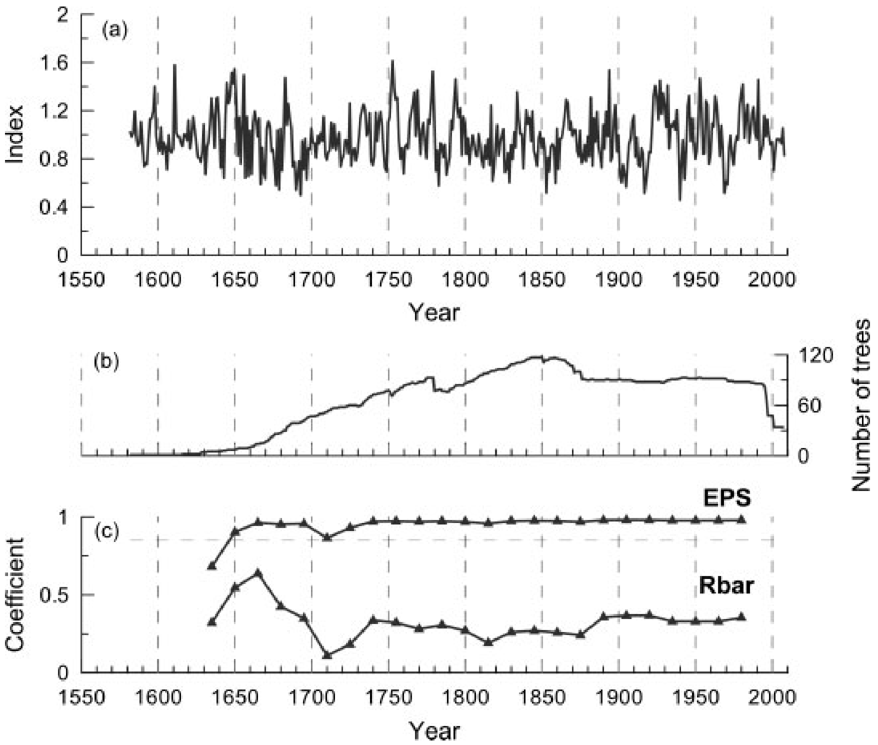

Figure 2. Plots of (a) the regional composite chronology for southeastern Sweden, (b) tree coverage and (c) running EPS and Rbar statistics calculated on a 30-year basis with a 15-year overlap.

of the Nämdö chronologies were developed from living trees growing in dry areas on the upper parts of rocky outcrops, while the Stockholm chronology was compiled from living trees growing on dry soils in connection to raised bogs.

All series were quality checked using the COFECHA software (Holmes, 1983), which verifies cross-dating among tree-ring series and indicates possible dating problems. Series showing poor synchronicity with the rest of the data were omitted, whereas the rest of the tree-ring width series from the seven sites were averaged into one single regional chronology. The ring-width measurement series were standardized using the ARSTAN software (Cook *et al.*, 2007; ver. ARS41d), in order to remove non-climatic growth trends related to tree ageing and stand dynamics (Fritts, 2001). The standardization was performed by fitting a negative exponential curve, a regression line, or a straight line to each series, depending on the individual characteristics of the curves, and then dividing the ring widths by the corresponding values of the fitted curve for each year. Variance fluctuations in the tree-ring data caused by changing sample size were removed by using the correction method proposed by Osborn *et al.* (1997). The resulting Autoregressive Standard Chronology (ARSTAN), which was produced by removing autocorrelation from individual tree-ring series through autoregressive modelling and then reincorporating the pooled autoregression model into the residual chronology (Cook, 1985), thus retaining a low frequency signal, was used in the drought reconstruction (Figure 2.). The reliability of the chronology through time was assessed using the expressed population statistic (EPS; Wigley *et al.*, 1984), which defines the number of trees required for the chronology to be representative for the whole population. EPS were calculated over a 30-year window with a 15-year overlap.

2.2. Meteorological data

A variety of indices have been developed for the purpose of defining drought and measuring the drought severity. In this study, we used the standardized precipitation index (SPI; McKee *et al.*, 1993) as an indicator for moisture conditions. The index is based entirely on precipitation data, which has been transformed into a standardized normal distribution. Thus, the SPI indicates the number of standard deviations the observed cumulative precipitation at a given time period deviates from the observational mean. The advantage of the SPI is its temporal flexibility, which allows it to be used to monitor drought on user-specified time scales (usually 1, 3, 12 or 24 months). Another advantage of using the SPI comes from its standardization, making the frequency of extreme precipitation events at any given location and at any time scale consistent.

To calculate the SPI indices, the global land surface $0.5^\circ \times 0.5^\circ$ resolution CRU TS2.1 precipitation data set (Mitchell and Jones, 2005), covering the period 1901–2002, was used (obtained from the University of East Anglia's Climatic Research Unit, http://www.cru.uea.ac.uk/cru/data/hrg.htm). Precipitation data for the region was obtained from 46 grid cells, defined by the coordinates 58.25–60.75N and 15.25–19.75E, and converted to SPI by fitting a gamma probability density function to the frequency distribution of precipitation totals summed over a 3-month time scale. The procedure was performed separately for each month and grid cell. Finally, the cumulative probability distribution was transformed into the standardized normal distribution to yield the SPI. Using SPI, the moisture status can be classified from extremely wet (SPI ≥ 2) to extremely dry conditions (SPI ≤ -2; Table 2; McKee *et al.*, 1993).

2.3. SPI reconstruction

The potential for using the tree-ring data from east-central Sweden to reconstruct climate was tested through correlation and response function analysis between individual chronologies covering the 20th century and monthly and seasonal SPI data averaged for the 58.25–60.75N and 15.25–19.75E region, as well as gridded precipitation and temperature data from the CRU TS2.1 dataset. The analysis was performed using the Dendroclim software (Biondi and Waikul, 2004).

Table 2. Classification of wet and dry conditions defined by McKee *et al.* (1993).

SPI values	Category
≥2.00	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.00 to −1.49	Moderately dry
−1.50 to −1.99	Severely dry
≤ −2.0	Extremely dry

To extend the drought history for the region back in time, a transfer model was developed using stepwise multiple linear regression in the calibration period 1901–2002. To ensure that lagged and autocorrelated growth effects in the tree-ring chronologies were included in the modelling tree-ring indices for the current year (t) and 1-year forward ($t + 1$) and backward ($t - 1$) lagged were set as potential predictors, while SPI (for year t) was set as predictand. The quality and temporal stability of the model was assessed through a split-sample method (Gordon, 1982), that divided the period of climate and tree data overlap (AD 1901–2002) into two subsets of equal length (1901–1951 and 1952–2002). Calibration and verification statistics were calculated for the first and the second half of the base period, respectively. The calibration and verification periods were then exchanged and the process repeated. The validation was performed by means of the Sign test, the reduction of error (RE) and coefficient of efficiency (CE) statistics (National Research Council, 2006).

3. Results and discussion

3.1. Chronology characteristics

The length of the seven chronologies ranged from 224 (Kaptensudden) to 414 (Nämdö) years (Table 1). Significant correlation between historical and living tree-ring series (mean inter-serial correlation = 0.557) suggested that the historical timber was probably originating from the study region, and that the data presumably contained similar environmental signal as the living tree-ring series. The historical data was therefore used to extend the chronology from living trees and to develop the drought reconstruction. The composite chronology, derived from a total number of 186 trees, covered the period AD 1582–2008 (Figure 2) and showed a mean sensitivity of 0.226. The generally accepted EPS level of ≥0.85 was reached after 1650, and stayed steadily above that threshold until 2008 (Figure 2). Drought was thus reconstructed after 1650.

3.2. Drought reconstruction

All chronologies developed from living trees were most strongly correlated with early summer precipitation in the year of growth (Table 3), providing an additional piece of evidence for the suitability of combining individual chronologies to infer past moisture variability. The composite chronology was significantly ($p < 0.01$) correlated with May and June precipitation ($r_{\mathrm{MJ}} = 0.53$), as well as with June through September SPI ($r_{\mathrm{JJAS}} = 0.45$). A spatial correlation analysis between the regional chronology and the best-fit precipitation data (May–June) indicated that the tree-ring data captured the summer precipitation signal of a broad region in east-central Sweden (Figure 5(a)). Additionally, summer temperatures appeared to be inversely related to the tree growth (not shown). The temperature relationship was however considerably weaker ($r_{\mathrm{June}} = -0.25$ for the composite

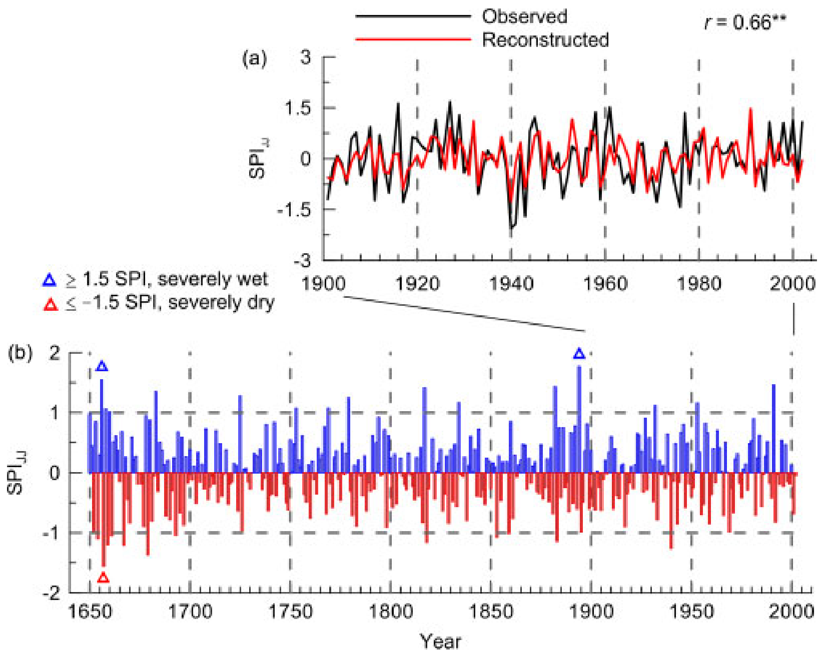

Figure 3. (a) Time-series plots of actual and reconstructed June–July SPI values. The reconstruction is based on the 1901–2002 period calibration model. **Level of probability <0.01. (b) Regional *P. sylvestris* reconstruction of June–July SPI spanning the time period 1650–2002 (EPS >0.85).

chronology) than the correlation with the moisture variables. These findings were generally consistent with previous dendroclimatic studies of *P. sylvestris* in the hemiboreal zones of central Sweden and in the southern parts of Finnish boreal forest belt (Lindholm *et al.*, 1997, 2000; Linderholm *et al.*, 2003, 2004; Helama and Lindholm, 2003; Linderholm and Molin, 2005), which demonstrated that *P. sylvestris* growth in these latitudes is more dependent on summer precipitation than temperature. Based on the results from the correlation analysis a transfer model for estimating mean June–July SPI was developed. Calibration over the full 1901–2002 period gave the following, highly significant ($F = 25.02$, $p < 0.001$), regression equation:

$$\mathrm{SPI}_{\mathrm{June-July}} = -1.05 + 3.08\mathrm{TRI}_t - 1.13\mathrm{TRI}_{t-1} - 0.88\mathrm{TRI}_{t+1}$$

The final model extended the regional drought history back to 1650 (Figure 3) and explained 41.6% of the variance (R^2, adjusted for degrees of freedom) in the observed SPI data (Table 4). The split-sample verification and calibration statistics showed slightly poorer reconstruction skills for the latter half of the 20th century compared to the earlier half, but proved that the model was reproducing the mean and the variance in the SPI data with a significant fidelity. Both the verification RE and CE statistics were positive (Table 4), indicating a satisfactory reconstruction model.

Wet (SPI $\geq$ 1) and dry (SPI $\leq$ -1) thresholds in the reconstructed SPI time series were determined through the classification defined by McKee *et al.* (1993; Table 2). However, since the reconstruction only accounted for approximately half of the observed SPI variance, it is likely that it does not capture the true frequency of dry and wet periods and likely underestimates the extremes. The full reconstruction (Figure 3) contained 17 wet and 13 dry years that had been ranked as moderate or severe to its nature. Out of these 4 wet and 8 dry years were clustered in the latter half of the 17th century (Table 5). Although applying a correction method for mitigating the variance increase caused by temporal changes in the density of series being averaged together for the final chronology, it is evident that some of the variance changes are still present in the early portions of the reconstruction, thus explaining the large number of abnormally wet/dry years. In contrast, the 18th century was absent of any extreme (SPI ≤ -2.0) or even moderate (SPI ≤ -1.0) summers in term of dryness (Table 5). The worst single year drought was estimated year 1657 (SPI $=$ -1.55), whereas the wettest single year summers were found in 1656 and 1894 (SPI $=$ 1.54 and 1.77, respectively).

Multi-year moisture variability was investigated by quantifying regimes of below and above average moisture conditions (SPI $=$ 0) in terms of duration, magnitude and intensity. Each episode was then ranked according to its severity (see Biondi *et al.*, 2002). The reconstructed SPI consisted of 36 wet and 46 dry multi-annual events, most of which lasted no longer than 2 years. The longest pluvial event took place in 1750 and lasted for 7 consecutive years, whereas the two most prolonged dry events occurred in 1674 and 1709 and lasted for 4 years. Table 6 lists the 10 highest scored wet and dry episodes, respectively. The 1895–1896 dry and 1655–1656 pluvial regimes achieved the greatest event scores within the full reconstruction. Notable is the marked variability characterizing the 20th century. Out of the 10 top scored

Table 3. Pearson correlation coefficients between ring-width indices and hydrometeorological data, extending from previous October through current September, for the time period A.D. 1901–2002. The data are total monthly precipitation (CRU TS2.1 dataset) for the grid cell centered over 58.25–60.75N and 15.25–19.75E and a 3-month standardized precipitation index calculated from the precipitation data. Note that the analysis has only been performed on the chronologies spanning over the 20th century. All of the coefficients are significant at a 0.05 level.

Precipitation												
Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
EKHU								0.370	0.270			
NAMD							−0.240	0.341	0.380			
PUTB								0.262	0.394			0.224
STHL								0.303	0.372			
TYRE								0.296	0.353			
Composite								0.372	0.423			
SPI												
Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
EKHU	0.304							0.237	0.477	0.366	0.213	0.197
NAMD	0.282								0.381	0.444	0.342	
PUTB									0.394	0.369	0.181	
STHL									0.391	0.425	0.260	0.216
TYRE									0.370	0.431	0.222	
Composite									0.474	0.487	0.280	0.198

dry and wet events, the 20th century included 6 dry and 4 wet regimes. In contrast, the 18th was absent in any dry regimes and the 19th century in any wet regimes ranked in the top 10 categories.

To highlight the decadal variability, reconstructed SPI was smoothed using locally weighted regression (loess filter with a 20-year window; Cleveland and Devlin, 1988). The most marked pluvial phase in the preinstrumental period occurred in the mid 1720s encompassing over 50 years, while the most extended long duration drought was reconstructed between 1660s and 1720s (Figure 4). Other notable pre-instrumental periods with drought conditions sustained for several years were evident in the mid-1800s to early 30s and in the 1840s–50s.

Table 4. Calibration and verification statistics for the tree-ring reconstruction of June–July SPI.

Calibration	1901–1951	1952–2002	1901–2002
Verification	1952–2002	1901–1951	
Calibration			
r	0.746**	0.590**	0.659**
R^2	0.56	0.35	0.43
R^2_{adj}	0.53	0.31	0.42
Verification			
r	0.558**	0.692**	
R^2	0.31	0.48	
RE	0.175	0.426	
CE	0.171	0.425	
Sign test (+/−)	36/15	38/13	

** Level of probability <0.01.

Table 5. Moderate and severe wet and dry single years in the reconstructed SPI, based on the classification defined by McKee *et al.* (1993).

Wet years		Dry years	
Moderate	Severe	Moderate	Severe
1658	1656	1652	1657
1660	1894	1654	
1683		1659	
1725		1661	
1753		1667	
1769		1679	
1779		1693	
1817		1818	
1834		1853	
1882		1859	
1932		1883	
1953		1940	
1991			
1981			
1991			

In order to establish the spatial context of the reconstructed drought, the SPI data was compared to precipitation reconstructions from southeastern Finland (Helama *et al.*, 2009) and the eastern part of central Sweden (Jönsson and Nilsson, 2009), the closest two independent tree-ring summer moisture reconstructions available (Figures 1 and 4). Although warm season precipitation in the region is often of a convective nature and therefore related to smaller scale weather systems (Jaagus, 2009),

Table 6. Top 10 scorings of multi-annual events of below and above average moisture conditions for the 1650–2002 time period. Duration is defined here as the number of consecutive years of below/above average moisture conditions, and magnitude is the sum of all the reconstruction values for a given duration. Intensity is the ratio between magnitude and duration.

Years	Duration	Magnitude	Intensity	Score[a]
Dry events				
1895–1896	2	−1.48	−0.74	205
1969–1971	3	−1.92	−0.64	199
1669–1670	2	−1.29	−0.64	191
1955–1956	2	−1.23	−0.61	186
1959–1960	2	−1.22	−0.61	183
1939–1941	3	−1.45	−0.48	178
1901–1902	2	−1.18	−0.59	176
1818–1820	3	−1.43	−0.48	173
1917–1919	3	−1.42	−0.47	171
1690–1691	2	−1.09	−0.54	168
Wet events				
1655–1656	2	1.84	0.92	214
1778–1779	2	1.56	0.78	203
1957–1958	2	1.49	0.74	196
1945–1946	2	1.47	0.74	194
1979–1981	3	1.91	0.64	192
1793–1794	2	1.42	0.71	187
1650–1651	2	1.42	0.71	185
1952–1954	3	1.53	0.51	180
1662–1664	3	1.49	0.50	178
1750–1761	7	3.03	0.43	175

[a] The event score was obtained by summing the ranking of magnitude and intensity of each event, giving the highest scorings for the most severe events (Biondi *et al.*, 2002). Wet and dry regimes were scored separately.

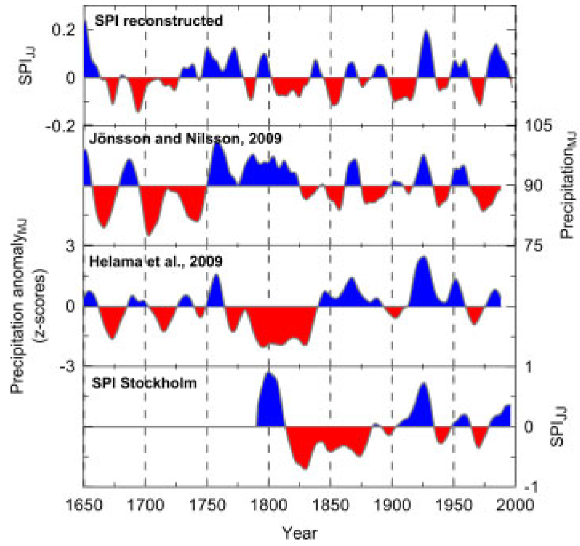

Figure 4. Time-series of reconstructed June–July standardized precipitation index from southeastern Sweden, May–June precipitation from east-central Sweden (Jönsson and Nilsson, 2009), and May–June precipitation anomalies from southeastern Finland (Helama *et al.*, 2009). The bottom plot shows observed June–July SPI from Stockholm meteorological station. All the datasets were smoothed with a 20-year low-pass (first order) loess filter.

all three locations showed similarities in the recorded May–June precipitation pattern. The precipitation climate in Stockholm was slightly more homogeneous to east-central Sweden compared to southeastern Finland ($r = 0.581$ and $r = 0.320$, $n = 109$, $p < 0.01$ with east-central Sweden and southeastern Finland, respectively). Comparison of the tree-ring reconstructions revealed reasonably good correspondences on inter-annual time scales (based on first-differences $r = 0.515$, $n = 350$, $p < 0.01$ with Jönsson and Nilsson, 2009; $r = 0.366$, $n = 343$, $p < 0.01$ with Helama *et al.*, 2009). Even though different standardization methods were used to generate the tree-ring chronologies (see Cook, 1985; Briffa and Melvin, 2011 for a detailed discussion on standardization approaches and their implications) and slightly different model predictors were included to produce each reconstruction model, resemblances between the reconstructions were also found on decadal or lower frequency domains (Figure 4). Tendencies toward a phasing of the 1660s drought with generally dry conditions in the east-central Sweden and southeastern Finland reconstructions are evident. Jönsson and Nilsson (2009) recognized the spell as the Late Maunder Minimum, the coldest phase of the Little Ice Age, overlapping with a period of low solar activity and enhanced volcanism. Characteristic for the weather conditions in northwestern Europe during this period was cold and dry springs and summers (Luterbacher *et al.*, 2001). Support for the 1800s–early 30s drought can be found in the Helama *et al.* (2009) reconstruction. This period of drought was also noted in a documentary source picturing weather conditions in east central Sweden between 1815 and 1833 (Linderholm and Molin, 2005), reporting severe drought during several years within the period.

Reconstructed SPI was further compared to June–July SPI derived from long precipitation observations from Stockholm meteorological station (1786–2001, Figure 4). A comparison to the early portions of the record, independent from the CRU TS2.1 dataset, yielded a significant relationship at an inter-annual time scale (based on first-differences $r = 0.543$, $n = 114$, $p < 0.01$). Since the observations were severely overestimating the true precipitation in the early part of the record (Eriksson, 1981), longer term trends were not retained for analysis and were not discussed herein.

Previous work have showed that tree-rings from arid environments from many regions of the world can successfully be used to reconstruct past precipitation and drought variability on local to regional scales (Davi *et al.*, 2006; Touchan *et al.*, 2007, 2008). Due to the proximity to the North Atlantic Ocean and its high-latitude location, Sweden lacks arid and semi-arid environments, making temperature the primary climatic forcing in controlling the pine growth in large parts of the country (Grudd *et al.*, 2002; Gunnarson and Linderholm, 2002), or a combined influence of both temperature and precipitation, where the individual importance of one or other of the variables may vary with time (Linderholm *et al.*, 2004). This fact complicates tree-ring based moisture reconstructions in the region, which can be manifested through a low predictive value of the reconstruction models. This study demonstrates, however, a potential for developing moisture sensitive chronologies for southern Fennoscandia. In contrast to some of the earlier reconstructions from the region (Helama and Lindholm, 2003; Linderholm and Molin, 2005) our model performs fairly well and is of comparable quality to several drought reconstructions from arid sites in southern Europe and Asia (Touchan *et al.*, 2005; Davi *et al.*, 2008). An attempt to reconstruct June through August SPI over east central Sweden was made by Linderholm and Molin (2005), who utilized meteorological data from a single 0.5° × 0.5° grid cell and based the reconstruction solely on tree-ring data from Tyresta National Park. Their reconstruction showed a modest result, capturing 24% of the variance in the instrumental SPI data. The increased performance of our model shows that a more robust reconstruction can be obtained if a network of moisture sensitive chronologies is used, and if the model is calibrated against meteorological data that are averaged for the whole region instead of using a single grid point or a single weather station data. This notion has long been recognized (Fritts, 2001), but still it is encouraging that Swedish tree-ring data can provide useful information of past regional droughts.

3.3. Mid-tropospheric circulation pattern

Changes in the spatial distribution, frequency and amount of precipitation are tightly linked to variations in atmospheric circulation patterns. Since European weather develops downstream of the North Atlantic storm track, it is largely steered by the Azores Subtropical High and the Icelandic Low. The association between dry and wet years in southeastern Sweden and regimes of atmospheric circulation was assessed by screening observed June–July SPI data from the study region (58.25–60.75N, 15.25–19.75E) over the 1948–2002 period for moderate to extreme moisture years (SPI $\geq$ 1.0, ≤ -1.0), for which composite plots of gridded May–June 500 hPa geopotential height anomalies (from the 1968–1996 mean) were constructed. The atmospheric fields were extracted from the NOAA/OAR/ESRL PSD, Boulder, CO, USA (http://www.esrl.noaa.gov/psd/). The resulting five driest (SPI ≤ -1.0; years 1951, 1959, 1966, 1971, 1976) and eight wettest (SPI $\geq$ 1.0; years 1958, 1961, 1977, 1991, 1995, 1998, 2000, 2002) years were also present as below and above average, respectively, moisture conditions in the reconstructed SPI series. Drier than average summer conditions in southeastern Sweden were associated with the northeastern flank of the Azores High extending over the British Isles and the North Sea (Figure 6(a)), resulting in a blocking of the eastward movement of the Icelandic low pressure systems over Scandinavia and redirecting them southward towards central Europe. Correlation analysis between

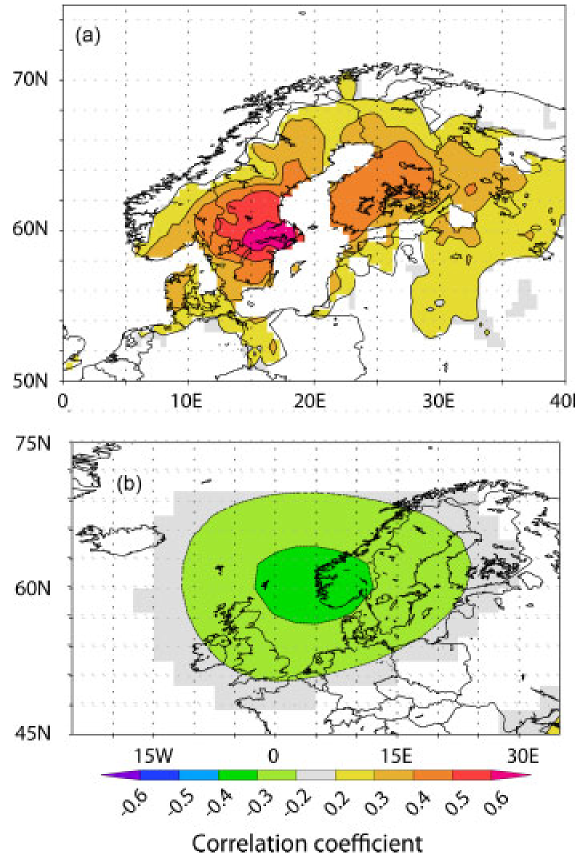

Figure 5. Spatial correlation fields between reconstructed SPI and (a) gridded May–June precipitation (CRU TS2.1, Mitchell and Jones, 2005) covering the period 1901 to 2002, and (b) May–June reconstructed 500 hPa pressure grids over the 1659–1999 period (Luterbacher *et al.*, 2002). The plots are created using KNMI Climate Explorer (Royal Netherlands Meteorological Institute, http://climexp.knmi.nl). Coloured areas are significant at $p < 0.10$.

reconstructed SPI and gridded monthly 500 hPa geopotential height fields from Lutenbacher *et al.*, (2002) over the 1659–1999 time interval showed a similar result (Figure 5(b)). Dry-year pressure composite indicated that increased precipitation is associated with cyclonic structure extending over western part of central Scandinavia (Figure 6(b)), probably originating from an eastward passage of Icelandic cyclones that form along the 55–65°N latitude belt. The accompanied increases of the zonal westerly air flow results in advection of warm and moist air masses from the North Atlantic into Scandinavia.

4. Conclusions

Tree-ring data is one of the most powerful high-resolution proxies of climate variability of the recent past. However, while most tree ring-based studies from northern high latitudes have focused on temperature reconstructions, few attempts have been made to examine past precipitation and drought variability. We presented the first regional high-resolution of summer drought for southeastern Sweden, spanning the past 350 years. The reconstruction captured 41.6% of the variance in the instrumental SPI

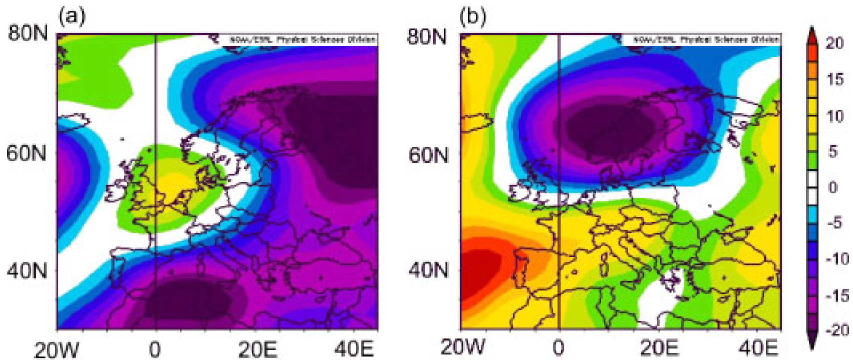

Figure 6. 500 hPa geopotential height composite anomalies for May–June during (a) the driest (SPI ≤ -1.0; years 1951, 1959, 1966, 1971, 1976) and (b) wettest (SPI ≥ 1.0; years 1958, 1961, 1977, 1991, 1995, 1998, 2000, 2002) summers in the recorded SPI data from southeastern Sweden over the 1948–2006 time period. The heights are expressed as anomalies from the 1968–1996 mean. The plots are created using NCEP Reanalysis Derived data provided by the NOAA/OAR/ESRL PSD, Boulder, CO, USA (http://www.esrl.noaa.gov/psd/).

record, showing that tree-ring data from southern Sweden contain valuable hydro-climatic information, which may be used to assess past summer moisture conditions. Verification against the closest independently developed moisture reconstructions confirms our results. On the whole, our results point to the general wetness of the 18th century and the dryness of the 19th century. The tree-ring record suggests that the most outstanding pluvial phase in the pre-instrumental period took place in the mid-1720s and lasted over 50 years. Pre-instrumental multi-decadal periods of below average moisture conditions were reconstructed in the 1660s–1720s, 1800s–early 30s, and in the 1840s–50s.

Large-scale atmospheric circulation analysis recognized low-pressure systems extending over western part of central and southern Scandinavia as the dominant circulation mode responsible for most of the summertime moisture in southeastern Sweden. When high-pressure systems are centered over British Isles and the North Sea the eastward passage of mid-latitude cyclones is blocked. Under such circumstances drier than average conditions are recorded in the area of interest.

The most prominent changes in Fennoscandia in a future warmer climate will likely be related to precipitation (Alcamo *et al*., 2007), and to be able to assess possible implications of such a change, firm knowledge about its past natural variability is needed. The response of tree growth to moisture conditions presented in this study is an encouraging indication of the potential for future use of dendrochronology in drought reconstructions for southern Fennoscandia. Additional data, including other tree species and tree-ring parameters, the use of historical timber, and a denser network of tree-ring sites will likely provide a more complete understanding of past drought variability in the region.

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