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Seasonal variability in Northern Hemisphere atmospheric circulation during the Medieval Climate Anomaly and the Little Ice Age

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ABSTRACT

Here we report new reconstructions of winter temperature and summer moisture during the past millennium in southeastern Sweden, based on stable-isotope data from a composite tree-ring sequence, that further enhances our knowledge and understanding of seasonal climate variability in the Northern Hemisphere over the past millennium. Key features of these new climate proxy records include evidence for distinctive fluctuations in winter temperature in SE Sweden, superimposed upon the general pattern of cooling between the so-called Medieval Climate Anomaly (MCA) of the early millennium and the Little Ice Age (LIA) of the late millennium, as well as evidence for sustained summer wetness during the MCA, followed by drier and less variable conditions during the LIA. We also explore these new records within a circumpolar spatial context by employing self-organizing map analysis of meteorological reanalysis data to identify potential modern analogues of mid-tropospheric synoptic circulation types in the Northern Hemisphere extratropics that can reconcile varying seasonal climate states during the MCA and LIA in SE Sweden with less variable conditions in southwestern Canada, as portrayed by paleoclimate records developed in the same manner in an earlier study.

1. Introduction

Improved documentation of temporal and spatial variability in past global climate is needed to better anticipate the possible impacts of future climate change, especially over multidecadal and longer time-scales that are not captured in the limited span of instrumental observations. The present article contributes to this task by reporting and evaluating new reconstructions of winter temperature and summer moisture based on oxygen and carbon stable-isotope data from a composite tree-ring sequence spanning the last millennium in the Östergötland–northern Småland area of southeastern Sweden. These new reconstructions highlight the occurrence of marked changes in both winter and summer climate of SE Sweden during the past 1000 years, including a shift from variably warm winters and persistently moist summers during the Medieval Climate Anomaly (MCA, *sensu lato*; *c.* 1050–1350 CE) to variably cooler and drier conditions during the subsequent Little Ice Age (LIA, *sensu lato*; *c.* 1500–1900 CE). Such absolutely-dated, site-specific proxy records are of significant value in studies of local and regional climate and climate-related environmental change, and are incorporated increasingly into mapped compilations (e.g., Ljungqvist et al., 2012, 2016) and model-based climate field reconstructions using data assimilation (e.g., Goosse et al., 2012; Hakim et al., 2016) to provide crucial "benchmarks" of past climate states.

As part of our evaluation we also compare and contrast the new climate proxy records from SE Sweden with equivalent reconstructions from the Columbia Icefield area of southwestern Canada, developed previously using the same process-based model

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to resolve variations in key environmental factors that control stable-isotope labelling in tree-ring cellulose (Edwards et al., 2008). Scrutiny of these pairs of proxy records, which share identical seasonal time-windows at two widely-separated study sites, reveals broadly congruent patterns of change between the MCA and LIA, consistent with varying external forcing of global climate (e.g., see Mann et al., 2009); however, viewing them in tandem also highlights shifts in both seasonal parameters in SE Sweden over shorter time-scales that are not exhibited by their counterparts in SW Canada. To further probe this feature we employ self-organizing map (SOM) classification of average daily 500 hPa geopotential height reanalysis data, and associated surface climate fields, to identify and visualize mid-tropospheric synoptic circulation types that could plausibly reconcile varying winter temperature and summer moisture conditions at the two sites for selected times during the MCA and LIA. This exercise demonstrates that variability in synoptic regimes probably included characteristic shifts in the phases of the Arctic Oscillation (AO) and its regional expression the North Atlantic Oscillation (NAO), which are known to vary year-round and over multiple time-scales (Hurrell, 1995; Thompson and Wallace, 1998; Wanner et al., 2001; Hurrell et al., 2003; Folland et al., 2009), incorporated within larger-scale patterns of fluctuating circumpolar atmospheric circulation.

Table 1
Tree-ring sequences used to develop the millennial dendrochronology from SE Sweden. Sample sites are indicated in Fig. 1.

Tree	Lab. ID	Site	Lat. (°N)	Long. (°E)	Span (CE)
1	75,018	Jönköping	57.78	14.15	926–1115
2	2826	Söderköping	58.48	16.33	926–1115
3	75,099	Nävelsjö	57.4	14.88	981–1160
4	75,077	Gamleby	57.89	16.41	1146–1205
5	14,952	Söderköping	58.48	16.33	1096–1285
6	75,212	Mönsterås	57.04	16.44	1266–1345
7	14,486	Horn	57.9	15.84	1291–1380
8	14,266	Linköping	58.41	15.63	1366–1395
9	14,267	Linköping	58.41	15.63	1371–1405
10	75,406	Göberga	57.99	14.85	1391–1545
11	14,710	Norrköping	58.59	16.19	1386–1590
12	75,321	Vimmerby	57.67	15.86	1536–1690
13	14,140	Grävsten	58.36	15.93	1571–1690
14	75,609	Höglycke	57.93	15.13	1686–1740
15	14,507	Smedstorp	58.15	15.38	1716–1810
16	75018	Jönköping	57.78	14.15	1806–1895
17	94,058	Malmslätt	58.42	15.52	1871–2005
18	94,061	Malmslätt	58.42	15.52	1871–2005
19	94,009	Sandseryd	57.75	14.08	1906–2005
20	94,012	Sandseryd	57.75	14.08	1906–2005

2. Data and methods

2.1. Development of the SE Sweden paleoclimate reconstructions

The new winter temperature and summer moisture reconstructions for SE Sweden were developed from a continuous composite tree-ring sequence spanning 950–2005 CE using archived samples of Scots pine *(Pinus sylvestris)* from architectural timbers of historical structures that had been cross-dated in the Lund University Laboratory for Wood Anatomy and Dendrochronology, linked with cores obtained from living trees (Table 1). Tree-ring sequences having robust correlations with local ring-width master chronologies were selected to maximize the likelihood of capturing coherent signals of regional climate history. Although the exact growth locations of trees harvested for building material are uncertain, the archived samples all originated from a limited geographical area near the borders between the counties of Småland and Östergötland (Fig. 1). Extended sequences (100–200 years) were generally chosen for isotopic analysis, with due caution to identify and avoid juvenile effects in the early decades of a tree's life (e.g., see McCarroll and Loader, 2004); however, several shorter sequences (minimum 30 years) were also used to strengthen links between longer sequences or to fill gaps arising because of small sample size or poor preservation of some archived material. The subfossil dendrochronology was extended to 2005 CE through cross-dating of cores obtained from four living Scots pine using a 6 mm-diameter Haglöf increment borer at two sites within the same geographical area (Sandseryd near Jönköping, northern Småland; Malmslätt near Linköping, Östergötland; see Table 1).

The tree-ring sequences were sampled for stable-isotope analysis using a scalpel under a dissecting microscope. Living-tree sequences were sampled at annual resolution to permit calibration against instrumental meteorological records (Fig. 2), while archived sequences were sampled in five-year increments to develop the long-term stable-isotope time-series (Fig. 3). Individual whole-wood samples were finely ground in a Retsch200 mixer mill and the resulting wood powder was purified to cellulose by sequentially eliminating non-cellulose components via solvent extraction, delignification, and alkaline hydrolysis, followed by freeze-drying (Sternberg, 1989). Determinations of oxygen and carbon stable-isotope ratios were performed on CO produced by high-temperature pyrolysis (for $^{18}O/^{16}O$) and CO_2 produced by combustion (for $^{13}C/^{12}C$) using continuous-flow isotope-ratio mass spectrometry (CF-IRMS) in the University of Waterloo Environmental Isotope Laboratory (e.g., see Porter et al., 2013; Edvardsson et al., 2014). The results are expressed as $\delta^{18}O$ and $\delta^{13}C$ in per mil (‰) relative to the VSMOW and VPDB standards, respectively, such that $\delta_{sample} = 1000\,(R_{sample}/R_{standard} - 1)$, where R is the $^{18}O/^{16}O$ or $^{13}C/^{12}C$ ratio in sample and standard. Replicate analyses yielded reproducibility of better than ±0.5‰ for $\delta^{18}O$ and ±0.1‰ for $\delta^{13}C$. The $\delta^{13}C$ data were corrected for declining $\delta^{13}C$ of atmospheric CO_2 since 1850 CE due to fossil-fuel combustion (the "Suess effect"), as outlined by McCarroll and Loader (2004), but further correction for potential effects of increasing atmospheric CO_2 concentration was not deemed necessary, on the basis of model calibration results (see below).

The long-term $\delta^{18}O$ and $\delta^{13}C$ records were each composited from 16 archived and four living-tree sequences, incorporating approximately 800 $\delta^{18}O$ and 400 $\delta^{13}C$ analyses in total, including replicates. Confidence in the compositing of the two long-term isotope records was bolstered by the existence of characteristic patterns of pentadal variability in both $\delta^{18}O$ and $\delta^{13}C$ in overlapping sequences. As shown by the results of Edwards et al. (2008), as well as the records developed in the present study, this method effectively captures low-frequency (multidecadal to multicentennial) signals in isotope dendrochronologies using fewer samples than more traditional approaches, although the records necessarily lack the temporal resolution of records based on isotopic analysis of individual annual rings or more elaborate pooling and compositing strategies (see discussion of Loader et al., 2013).

Modelling of the isotope records was undertaken using the coupled-isotope response-surface approach of Edwards et al. (2008). This method, building upon the results of field and laboratory studies (e.g., Edwards and Fritz, 1986; Yakir et al., 1994; Lipp et al., 1996; Edwards et al., 2000), links bilinear equations that account for the combined effects of varying temperature (ΔT) and relative humidity (ΔRH) on the overall oxygen- and carbon-isotope fractionations that occur during the synthesis of tree-ring cellulose, providing robust separation of temperature and moisture signals. The oxygen-isotope response surface is based on the premise that variations in cellulose $\delta^{18}O$ ($\Delta^{18}O$) are commonly dominated by a combination of ΔT-related variability in the $\delta^{18}O$ of water used by the tree inherited from local precipitation (Dansgaard, 1964),