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LETTER

# Reconstructing Northeastern United States temperatures using Atlantic white cedar tree rings

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## Abstract

Our knowledge of climate variability in the densely populated Northeastern United States is limited to instrumental data of the last century. Most regional paleoclimate proxies reflect a mix of climate responses, which makes reconstructing historical climate a challenge. Here we analyze tree-ring chronologies from Atlantic white cedar (*Chamaecyparis thyoides*) as a potential regional paleotemperature proxy. We evaluate our tree-ring network for spatiotemporal climate signal strength and reconstruction skill across New England. Atlantic white cedar sites in the northern section of the species' range exhibit positive significant annual growth relationships with local and regional temperatures. Chronologies constructed from northern sites yield skillful reconstructions of temperature that reproduce centennial, multidecadal, and interannual variability in the instrumental record, providing a novel paleotemperature record for New England.

## 1. Introduction

Anthropogenic changes to the climate system are global and pervasive, warming the ocean and atmosphere with consequences for and impacts on human and natural systems. Over the past century, annual surface air temperatures in the region of North America extending from the state of Maine to Washington DC (herein, the Northeast), have increased by over 1 °C, and are projected to continue to rise by at least 2.5 °C over the next several decades (Kunkel *et al* 2013, Horton 2014). A thorough understanding of Northeastern climate variability at decadal to centennial time scales is necessary in order to anticipate climate change impacts on ecological and human systems in this densely populated region. Reconstructions of past climate variability and extremes depend on identifying and utilizing high-resolution proxy paleotemperature data. These data allow us to place current trends in a long-term context, quantify the range of natural variability, develop an understanding of climatic change occurring outside the narrow range of observations, and evaluate climate models.

This study investigates the temperature sensitivity of the growth rings of Atlantic white cedar (AWC; *Chamaecyparis thyoides*) and develops a temperature reconstruction for the Northeast based on these data. Pollen and macrofossil analysis has confirmed the presence of AWC in the Northeast since at least the early Holocene (Belling 1977), and dead AWC trunks and stumps preserved in coastal sediments throughout the region (Bartlett 1909, Heusser 1949, Laderman 1989) have radiocarbon ages up to 7000 years old. Successful paleoclimate reconstructions using this species, therefore, would allow creation of annually resolved and multi-millennial Holocene temperature records for the Northeast that are otherwise unavailable.

Dendroclimatology provides a long-term view of tree growth in response to changes in regional climate. Tree-ring records have the advantage of being annually resolved and widely distributed across the mid-latitudes. However, tree growth may be influenced by a multitude of factors, especially in mesic Northeastern forests, where ring width is rarely associated with a single climate variable (Cook and Jacoby 1977, Conkey 1979, Pederson *et al* 2004). Though

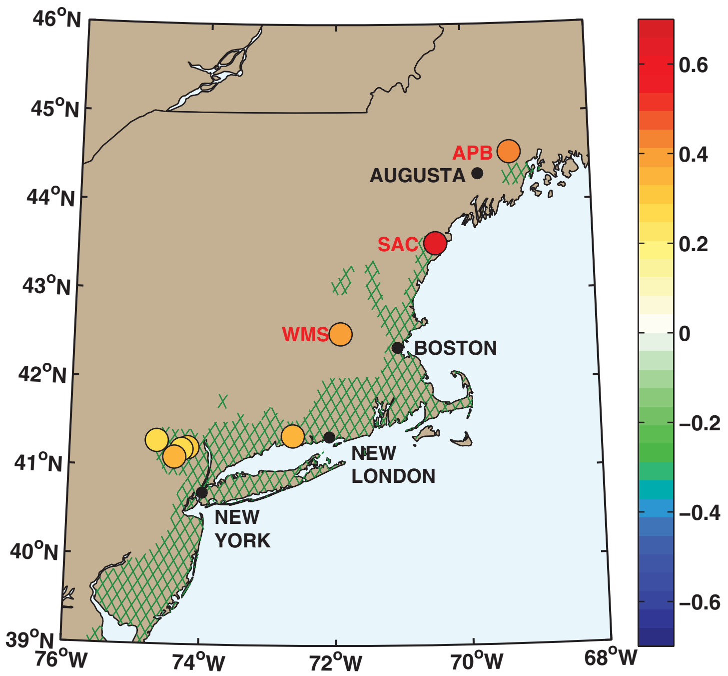


**Figure 1.** Map of tree-ring chronologies locations. The color of the circle reflects the Pearson correlation coefficient ($r$) between ring width and local average January through August temperature from the nearest grid points from the GISTEMP temperature product (Hansen *et al* 2010). Updated and recollected sites Appleton, ME (APB), Saco Heath, ME (SAC), and Westminster, MA (WMS) used for our reconstruction are labeled in red (Hopton and Pederson 2005). Green hatching indicates the species distribution as defined by the US Forest Service (Little 1978).

successful drought reconstructions using tree-rings from the eastern United States exist (Cook *et al* 1999), the mixed climate sensitivity of eastern US species limits opportunities for skillful broad-scale paleotemperature reconstructions over the region (Mann *et al* 2009, Trouet *et al* 2013, Anchukaitis *et al* 2017) and there remain substantial uncertainties about the range of natural temperature variability due to the paucity of temperature-sensitive proxy records in the region.

AWC is a shade semi-intolerant tree found in wetlands along the United States' east coast rarely further than 200 km from the ocean (Laderman 1989, Gengarelly and Lee 2006). In the Northeast, AWC is restricted to areas too wet for other species, often with standing water for over half the growing season (Laderman 1989, Motzkin 1990, NHESP 2007). Given the abundant moisture in these forests, AWC growth might *a priori* be expected to depend less on precipitation and more on temperature (Linderholm *et al* 2002, Jean and Bouchard 1996). Preliminary research by Hopton and Pederson (2005) showed that AWC tree rings contained one of the strongest positive relationships to temperature in the Northeast. However, previous dendroclimatology research with other wetland trees has shown ring-width in those species to have a significant precipitation signal (Stahle and Cleaveland 1992, Stahle *et al* 2012). We hypothesize that precipitation is a secondary and weaker signal in AWC and that the common dominant broad-scale signal preserved in the ring width of these trees across the region is temperature (Linderholm *et al* 2002).

The potential uniqueness of this proxy lies both in the ability to extract a strong regional temperature signal as well as to extend the reconstruction through the Holocene using preserved sub-fossil wood. Here we examine a network of living Northeastern AWC tree-ring chronologies to understand the spatiotemporal characteristics of the species' climate signal, analyze tree-ring width chronologies at three sites in Maine and Massachusetts, and then use these to reconstruct regional temperatures. Our results demonstrate the utility of AWC as a temperature proxy in the Northeastern United States.

## 2. Methods

### 2.1. Studysites and sample treatment

Initial AWC collections at eight sites throughout the Northeast were made between 2002 and 2003 (Hopton and Pederson 2005). In 2015 we updated and re-sampled three of these locations: Appleton, Maine, Saco Heath, Maine, and Westminster, Massachusetts (figure 1). These sites are in the northern region of the species range, with the forest in Appleton representing the northernmost known stand of thespecies (Stockwell 1999) (figure 1) and are relatively undisturbed by anthropogenic influences (Hopton and Pederson 2005, Pederson *et al* 2004) (table 1).

At the re-collected sites, AWC dominates the canopy and is largely even-aged. The Appleton, ME, site is a bog in the headwaters of the St. George River with

**Table 1.** AWC site characteristics.

| Site code | Latitude, longitude | Elevation | Trees sampled | Time span |
|---|---|---|---|---|
| APB | 44.55 N, 69.26 W | 100 m | 40 | 1859–2014 |
| SAC | 43.53 N, 70.45 W | 46 m | 36 | 1872–2014 |
| WMS | 42.52 N, 71.93 W | 336 m | 36 | 1845–2014 |

a ground layer of *Sphagmnum* moss and fern species. Saco Heath, ME, is the only known domed bog to contain AWC, and is possibly the southernmost coalesced bog in the eastern United States (Laderman 1989). Saco Heath contains scattered aggregations of trees throughout as well as other areas of dense shrub dominated by blueberry (*Vaccinium* ssp.L.). AWC collected in Westminster, MA, are in a topographically depressed swamp environment that borders a wetland and ponds system. The Westminster swamp is considered to be a high elevation inland AWC swamp (NHESP 2007) (table 1) with interspersed tamarack (*Larix laricina*), red maple, and red spruce (*Picea rubens* Sarg.). All three sites stay wet for most, if not all, of the growing season, supplied with water from rainfall as well as flow from nearby rivers or ponds.

We collected AWC samples following standard dendrochronological techniques (Fritts 1976, Stokes and Smiley 1968), taking two to three increment cores per tree, then drying, mounting, and sanding the increment cores. To ensure we assigned the correct year to each annual ring, the increment cores were graphically and visually crossdated (Stokes and Smiley 1968, Yamaguchi 1990). Ring widths were measured at 0.001 mm precision and crossdating was statistically confirmed using COFECHA (Holmes 1983).

### 2.2. Chronology development and standardization

To remove the geometric growth trend and isolate the climate signal in the tree-ring series, we detrended and standardized the width measurements into site chronologies at all eight sites using both a standard negative exponential or linear growth curve (NEGEX) as well as a signal free method (SF) (Melvin and Briffa 2008, Briffa and Melvin 2011). Our tree-ring series all originate from living, mature, and canopy dominant conifers, which typically and historically have been treated with a NEGEX curve to retain climate signals (Fritts 1976). More recently, signal-free standardization has been developed to attempt to avoid possible trend distortion or end effects related to the presence of common medium-frequency variability (Melvin and Briffa 2008, Briffa and Melvin 2011). To account for changes in the number of series back in time, the variance in the chronologies was stabilized based on the interseries correlation (Cook *et al* 1995) and a 67% spline (Osborn *et al* 1997, Cook and Peters 1981, 1997). We used the autoregressive (AR)-standardized version of the chronology for our climate analysis to preserve the common autoregressive structure of the tree-ring data due to variations in climate (Cook 1985). We assessed the common signals in the tree-ring chronologies using the interseries correlation and expressed population signal (EPS) statistics. Interseries correlation is the mean correlation between all the cores. EPS indicates how well the sample of trees estimates the signal of a hypothetical population and is a function of sample size and interseries correlation (Wigley 1984). The length of the chronologies were limited to years where EPS values are at least 0.85, the conventional although arbitrary threshold value (Wigley 1984). We created a Northeast regional chronology for large-scale spatial climate analysis by averaging the ring-width measurements of the three updated sites (Appleton, Saco, Westminster) to create a single series (the 'regional chronology'). To detect possible disturbance signals in our regional chronology, we analyzed the individual series that composed the region chronology using both the Nowacki and Abrams' criteria 1997, and that of Lorimer and Frelich 1989.

### 2.3. Climate data analysis

We analyzed the association between tree-ring chronologies and local climate using gridded monthly temperature anomalies data from the NASA GISTEMP combined 250 km product(Hansen *et al* 2010), gridded monthly precipitation data from version 7 of the Global Precipitation Climatology Center (GPCC Schneider *et al* 2016), gridded sea surface temperatures from the UK Met Office Hadley Centre sea surface temperature (HADISST Rayner *et al* 2003). We calculated an Atlantic Multidecadal Oscillation (AMO) index using a weighted average of the UK Met Office Hadley Centre sea surface temperature gridded product for the Atlantic from 0° N–70° N (Rayner *et al* 2003, Enfield *et al* 2001). We performed seasonal correlation analyses as described by Meko *et al* (2011) to calculate the both the Pearson correlation and partial correlation coefficients of the chronologies with monthly and seasonal temperature and precipitation. Statistical significance was evaluated using exact simulation (Percival and Constantine 2006, Meko *et al* 2011). We computed seasonal correlations for our regional chronology based on temperature and precipitation averages over an area spanning from 41° N–48° N and 74° W to 62° W. To understand the spatial extent of the temperature signal in our trees, we calculated the Pearson correlation of the regional chronology with the GISTEMP temperature field. Pointwise statistically significant correlations were determined using the approach described by Ebisuzaki (1997).

### 2.4. Temperature reconstruction

Based on our site-level climate analysis, we reconstructed regional mean January through August temperature for the region from 41° N–48° N and 74° W to 62° W using a nested composite-plus-scale (CPS) approach (Meko 1997, Esper *et al* 2002, Cook *et al* 2002, Esper 2005). This method scales the tree-ring series to the mean and standard deviation of the instrumental observations during the calibration period, and then evaluates the fit between tree-ring reconstructed temperatures and the instrumental data during the validation period. We tested the sensitivity of the reconstruction to both our choice of detrending method and to the inclusion or exclusion of data from each of the three individual updated sites. We built reconstruction models using three nests (all of the recollected sites) and two nests (only the Maine sites), as well as building a reconstruction model for both SF and NEGEX chronologies. We used a split calibration/verification (1900–1955 and 1956–2010) to train and evaluate our models (Michaelson 1987, Meko 1997). We estimated the uncertainty of our reconstruction from the root mean square error (RMSE) of validation. The variance explained by our reconstruction was quantified using the $R^2$ statistic. We also used the reduction of error (RE) and coefficient of efficiency (CE) statistics to estimate reconstruction skill, with positive RE and CE values indicating the reconstruction performed better than a naive estimate of the mean (Cook *et al* 1999, Wahl and Ammann 2007).

## 3. Results

### 3.1. Climate signals

There is a clear trend of increasing temperature correlation with higher latitudes in our extended AWC network (figure 1). However, this trend is not monotonic; the AWC series from Saco Heath has the highest correlation with winter-through-summer temperature but is at a lower latitude than the northernmost Appleton site. The cluster of sites near 41° N all have correlations with temperature less than $r = 0.35$. Our seasonal correlation analyses (figure 2) confirm that local temperature has the strongest correlation with the northern three sites and our temperature-sensitive AWC series show a broad winter-through-summer sensitivity with a peak seasonal correlation with mean temperatures in January through August (Hopton and Pederson 2005). Whilering widths of trees growing in cold environments generally reflect growing season spring and summer temperatures, tree-ring width can also be influenced by temperatures in the prior winter months (Jacoby *et al* 1996, Pederson *et al* 2004).

The Appleton site has significant correlations with January–September temperatures, with the strongest correlations in the early spring. Appleton shows no significant precipitation partial correlation (figure 2(*a*)). Saco Heath has the highest correlation values with temperature, with seasonal correlations reaching $r = 0.66$ (figure 2(*b*)). The site also has statistically significant secondary and partial correlations with precipitation, especially in summer. Westminster swamp shows positive and significant winter through summer temperature correlations, and a seasonally narrow but significant summer precipitation signal (figure 2(*c*)).

### 3.2. Regional chronology

Our complete regional chronology consists of 232 cores from 116 trees at three sites, with a series mean intercorrelation value of $r = 0.49$ over a common period of 170 years, from 1845–2014, and EPS values over 0.95 back to 1860 (Wigley 1984). No significant endogenic disturbance was detected in the chronology. We found that both SF and NEGEX chronologies had high Pearson correlations to regional temperature, but the SF detrending procedure increased the amplitude of the early and late ring-widths beyond reasonable growth patterns for the species (Cook *et al* 1995). Consequently, we used the NEGEX detrended chronologies for the remainder of our analysis and reconstruction, which preserved low frequency signals without exaggerating the growth trend over recent decades.

Similar to the individual sites of which it is composed, the strongest seasonal temperature signal for the regional chronology spans from winter through the end of the growing season (figure 3). The regional chronology also shows broad and significant correlation with temperature spatially, with significant correlations over eastern New England and with particularly high correlations of $r > 0.50$ over the adjacent North Atlantic to 65° W (figure 4, figure 6). Correlations over land cease to be significant south of Long Island, NY, but continue north of Maine into Canada. Western New England still has field correlation values over $r = 0.4$, but these fail to be statistically significant when accounting for autocorrelation (Ebisuzaki 1997).

### 3.3. Reconstruction

A skillful reconstruction of January through August mean temperature is possible using the two Maine tree-ring sites back to 1872, when the Saco Heath chronology currently ends (figure 5). Our model has positive RE and CE scores of 0.33 and 0.08, respectively, and an $r^2$ value of 0.34 from 1872–2014. Results of our cross validation for a three site (including Westminster) reconstruction had positive RE and CE values with an early validation period and late calibration period, but slightly negative CE values with a reversed calibration and verification period. These low frequency metrics can be sensitive to the calibration/verification period—particularly CE (Wahl and Smerdon 2012, Wahl and Ammann 2007)—and we found that relatively small shifts in thecalibration/validation period affected these statistics. Our sensitivity tests using SF instead of NEGEX chronologiesall yielded negative cross-validation RE and CE scores, indicating

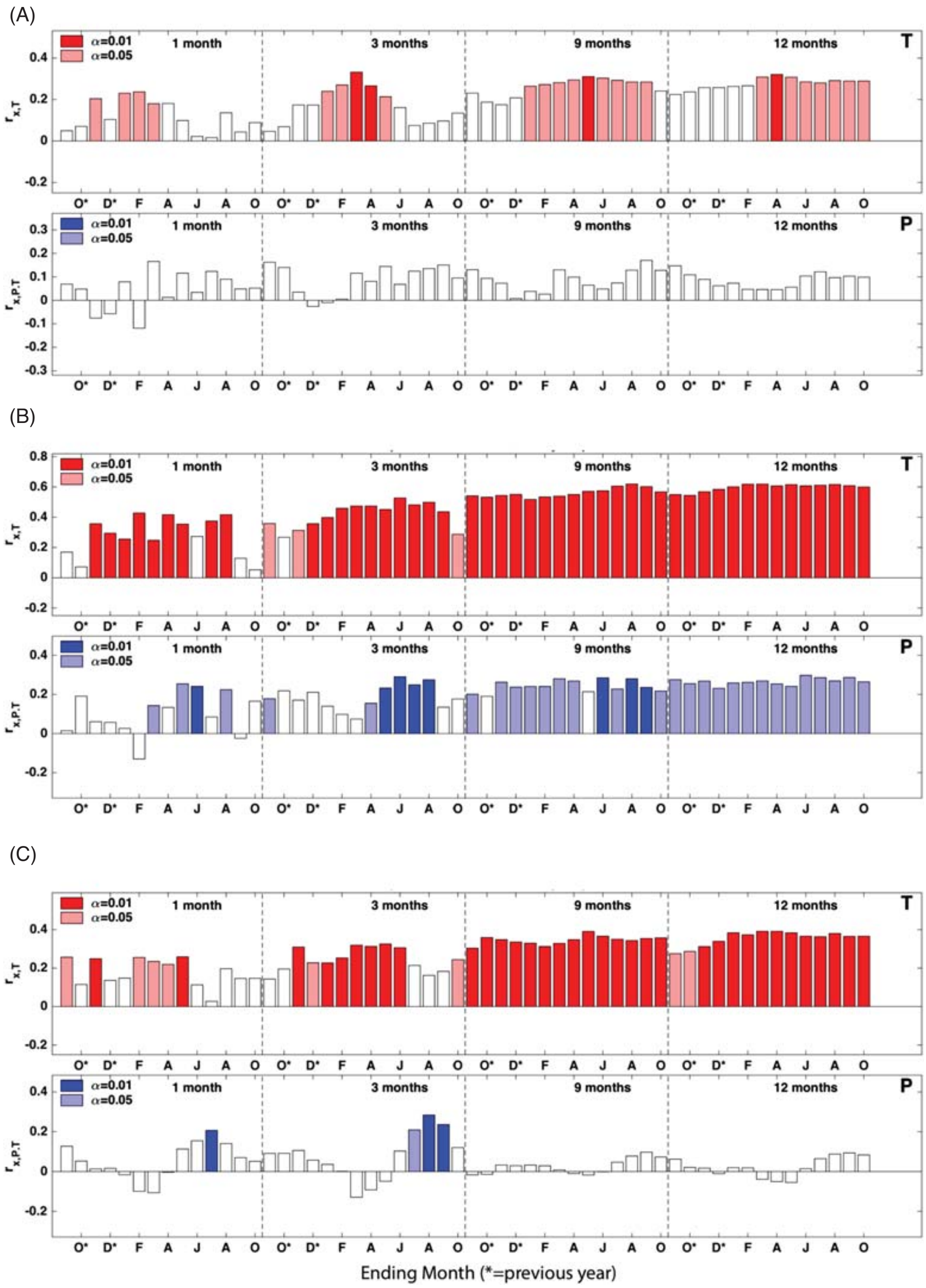


**Figure 2.** Seasonal correlations and partial correlations (Meko *et al* 2011) of the (*a*) Appleton, ME (*b*) Saco Heath, ME and (*c*) Westminster, MA chronologies with regional temperature and precipitation. The top line shows the correlation between the chronology and monthly temperatures. The bottom line shows the partial correlations between the chronologies with monthly precipitation. Both variables are shown for 1, 3, 9 and 12 month long seasons. For seasonal analysis, the month indicates the last month of a seasonal mean of the given length.

that low frequency behavior and detrending choices in this chronology strongly influenced reconstruction skill.

Our skillful reconstruction of Northeast temperature tracks instrumental temperature within $\pm 1$ RMSE for most of the calibration and validation period. The tree-ring reconstruction captures both the long-term century-scale trend as well as multidecadal variability. Our chronologies have somewhat smaller rings in the earliest 1920s, latest 1960s, and late 1990s, compared to observed temperatures. The reconstruction shows a decade and a half of relatively stable mean temperatures from the late 1870s to the 1900s, prior to our calibration and validation periods, but indicate cold winter-through-summer temperatures in 1866 and 1868. However, in this portion of our reconstruction the skill is reduced because the Saco Heath chronology does not cover this period.

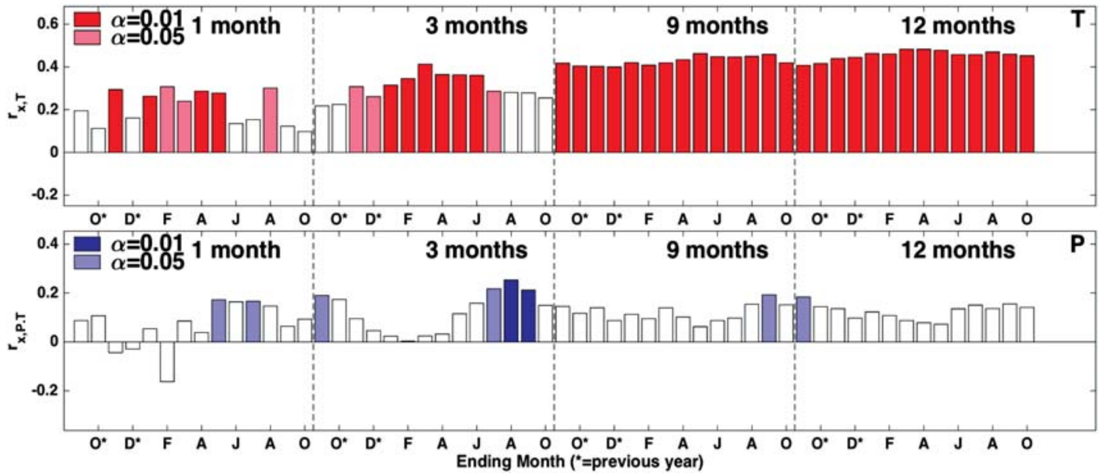


**Figure 3.** Correlations and partial correlations (Meko *et al* 2011) of the regional chronology with NE temperature and precipitation. The top row shows the Pearson correlation between the chronology and monthly or seasonal temperatures. On the bottom row the partial correlations between the chronologies with monthly or seasonal precipitation. Both variables are shown with1, 3, 9 and 12 month seasons. For seasonal analysis, the month indicates the last month of a seasonal mean of the given length.

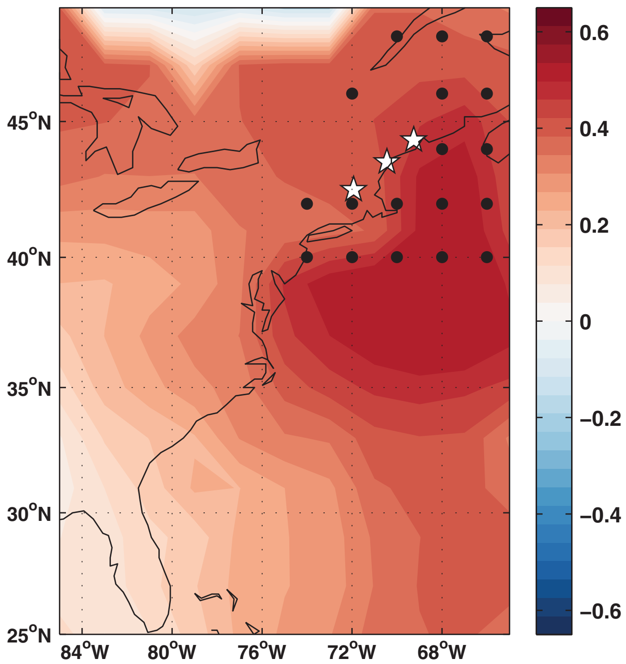


**Figure 4.** Field correlation between January through August mean temperature from GISTEMP (Hansen *et al* 2010) and our regional AWC chronology. Locations of the individual sites included in the chronology are indicated by the stars. Colors show the correlation and significant ($p < 0.05$) grid cells are stippled. Significance levels are calculated account for the strong degree of autocorrelation using the method described by Ebisuzaki (1997).

## 4. Discussion and conclusions

The annual growth rings of AWC are significantly correlated with mean January–August temperatures across New England, incorporating a sensitivity to winter temperatures prior to the growing season (figure 2). Cold winter temperatures and heavy snow packs have been shown to limit annual growth in temperate species by sustaining low soil temperatures and delaying the onset of radial growth (Brubaker 1980, Gedalof and Smith 2001, Peterson and Peterson 2002, Pederson *et al* 2004). The strongest temperature signals are observed at the higher latitude and interior sites (figure 1, table 1) and allow for a skillful cross-validated temperature reconstruction. However, there is not a simple spatial pattern to the local temperature correlation related to latitude, nor distance from the coast.

We hypothesized that AWC growth should have a primary temperature signal and a reduced sensitivity to precipitation variability, since the species' environment appears to provide consistent access to water

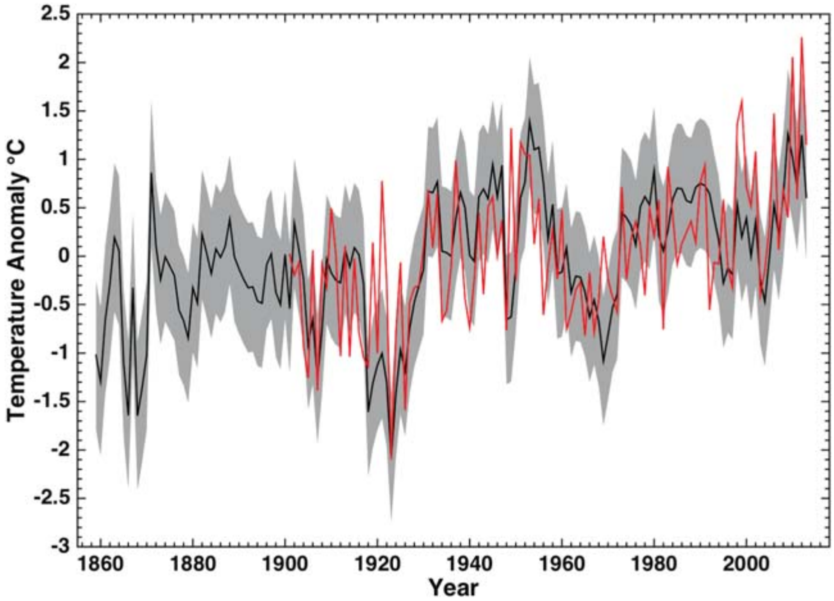


**Figure 5.** Nested CPS reconstruction of mean January–August temperature anomalies with two chronologies, Appleton and Saco Heath. Anomalies calculated as deviations from 1951–1980 means. Target instrumental data is shown in red, reconstruction record from tree-ring widths in black. The shaded uncertainty represents ±1 root mean square error (RMSE) of validation.

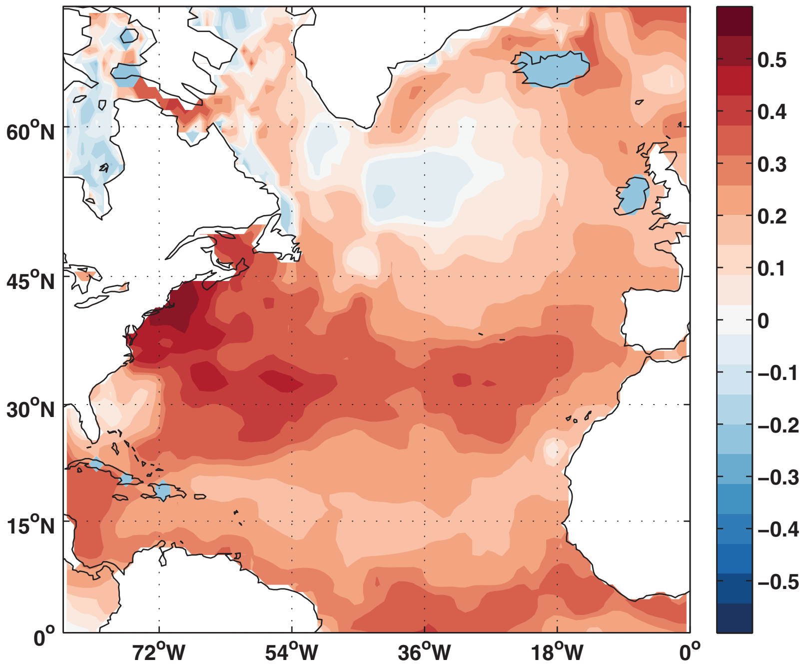


**Figure 6.** Mean January–August sea surface temperature simple correlations with the regional chronology. Sea surface temperature data from UK Met Office Hadley Centre (HadISST1 Rayner *et al* 2003).

(Laderman 1989). However, different hydrological conditions between sites may distinguish their climate response. Appleton and Westminster swamp have a minor and largely insignificant secondary precipitation signal (figure 2(*a*), (*c*)), while there are significant partial correlations to precipitation at Saco Heath (figure 2(*b*)), which also has the strongest temperature signal. Hopton and Pederson (2005) proposed that a precipitation signal at Saco Heath could arise due to its unique domed-bog environment. Domed-bogs are formed by the accumulation of peat over time, eventually perching the ecosystem above the regional water table. These environments thereafter rely on precipitation for water, and have been shown to be sensitive to changes in the water table, possibly explaining the secondary precipitation influence at Saco Heath (Laderman 1989, Hopton and Pederson 2005, Linderholm *et al* 2002, Boggie 1972, Bouriaud *et al* 2014, Jean and Bouchard 1996). AWC sites located in New York, New Jersey, and Connecticut all have lower correlations with local temperatures (figure 1), irrespective of hydrological setting. The observed sensitivity to individual site factors across New England indicates that the climate response of AWC varies in response to local conditions, which can guide further sampling and the choice of climate reconstruction targets.

Our analysis shows broad and statistically significant spatial correlations between our regional chronology and surface temperature across New England and the adjacent Atlantic Ocean (figure 4). This, and the multidecadal variability in our temperature reconstruction, prompted us to compare the regional chronology with an index of the AMO. Our temperature has a positive but weak correlation with the AMO index ($r = 0.26$), primarily due to differences between the AMO, regional chronology, and regional temperature variability between 1960 and 2000 (Kushnir 1994, Kerr 2000, Enfield *et al* 2001). The correlation is similarly weak between the instrumental data itself and the AMO index ($r = 0.14$). Therefore, despite some similarities, the low correlation between the AMO index and our reconstruction (or with the instrumental temperature target itself) demonstrates that New England temperatures have epochs of decadal variability distinct from the basin-wide mean North Atlantic sea surface temperature (SST) signal. This is related to the spatial structure of the SST relationship (figure 6), which not surprisingly has the strongest associations with tree-ring reconstructed temperatures along coastal New England and in the western Atlantic, but weak correlations elsewhere. In contrast, the correlations between the AMO index itself and the SST field from which it is derived is strongest in the eastern tropical and extra-tropical North Atlantic (Kushnir 1994, Alexander *et al* 2014). Our analysis shows that AWC chronologies can be used in regional temperature reconstructions and capture multidecadal temperature variability, but also highlights the challenge of linking large-scale features of North Atlantic ocean–atmosphere variability (including AMO) to terrestrial paleotemperature proxies in the eastern United States (Cook *et al* 2002).

AWC ring widths can be used to skillfully reconstruct January through August mean temperature signal over New England (figure 5). There are, however, periods with disagreements between the tree-ring estimated and recorded temperature. The largest of these occurs in the late 1910s and early 1920s. Raney *et al* (2016) note that conifers in wetland environments can be sensitive to fluctuations in groundwater hydrology; however, we do not find any influence of local hydrology in our tree-ring records. Despite the history of commercial AWC exploitation in New England, we found no evidence of widespread or large scale drainage changes or logging at any of the sites, and we detected no disturbance related growth patterns in the ring-widths themselves. Local influences related to ecosystem processes or natural stand dynamics appear to be the mostly likely source of non-temperature variability at our northern sites. We found that the use of SF instead of traditional NEGEX chronologies results in an overestimation of recent temperature trends and a lack of reconstruction skill. The cause of this detrending behavior is not known, but could be related to our generally even-aged stands (Melvin and Briffa 2014). Additional investigation is needed to identify the source of this bias.

Skillful reconstructions based on tree-ring width are needed to help understand the climate history of the region.Our findings here support the continued development of a long-term AWC record from New England. Historically, AWC was highly valued as a timber product and the harvesting of AWC ecosystems for lumber and the draining for agriculture led to a loss of AWC swamps in the Northeast (Emerson 1981, Laderman 1989). However, sub-fossil wood found across the region buried and preserved in bogs and swamps can provide proxy data covering the last several millennia or more (Bartlett 1909, Heusser 1949, Laderman 1989). Further collection and analysis of northern AWC trees and a concerted effort to extend these chronologies using subfossil material will substantially enhance the region's Holocene paleotemperature record.

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