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Original article

Winter in the Ouchitas—A severe winter storm signature in *Pinus echinata* in the Ouachita Mountains of Oklahoma and Arkansas, USA

Douglas J. Stevenson[a,*], Thomas B. Lynch[a], Pradip Saud[a], Robert Heineman[b], Randal Holeman[b], Dennis Wilson[b], Keith Anderson[b], Chris Cerny[c], James M. Guldin[d]

[a] Department of Natural Resources and Environmental Management, Oklahoma State University, Stillwater, OK 74078, United States
[b] Kiamichi Forestry Research Station, Oklahoma State University, Idabel, OK 74745, United States
[c] Tree-Ring Laboratory, Department of Geosciences, University of Arkansas, Fayetteville, AR 72701, United States
[d] Southern Research Station, USDA—Forest Service, Hot Springs, AR 72701, United States

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ABSTRACT

Each year severe winter storms (≈ice storms) damage trees throughout the southern USA. Arkansas and Oklahoma have a history of severe winter storms. To extend that history back beyond the reach of written records, a distinctive tree ring pattern or signature is needed. Storm-caused breakage, branch loss and bending stress provide that signature. We found a severe storm signature in shortleaf pine (*Pinus echinata*). We used three published site chronologies, a set of five new site chronologies from a growth-and-yield study conducted by Oklahoma State University and the unpublished Shortleaf Canyon chronology from a master's thesis at the University of Arkansas. Our method is based on two ring width values for the first and second growing seasons after the storm standardized to the ring widths of the seven growing seasons after the storm. Concordance between storm years predicted by tree ring patterns and actual storm years was tested using Cohen's Kappa. Concern about confounding of ice storm signals by droughts led us to test concordance between severe storms and drought in July, August and September; results were inconclusive but stand as a warning that these two phenomena cannot be distinguished with certainty in the tree ring record. Damaging severe storms occurred in about 2.8% of all years. Two out of three storms identified as "severe" produced glaze icing.

1. Introduction

Severe winter storms, including both snow and ice storms, are some of the most important causes of forest disturbance (Bragg et al., 2003). The December 2000 ice storms in Arkansas damaged or destroyed 82,100 ha of *Pinus echinata* (Burner and Ares, 2003) and heavily damaged stands in LeFlore and McCurtain Counties in Oklahoma.

To plan investments, planting and harvesting schedules, forest managers need to know how frequently these storms occur in individual stands and how damaging they might be. Climatologists and meteorologists need dates and severity data when studying past climates and weather patterns and to correct precipitation and drought severity chronologies for the occurrence of large storms. Because severe winter storms are infrequent, data collection must either await their happening or be done using tree ring proxies.

Ice storms occur most frequently in eastern North America where warm, moist air masses from the Gulf of Mexico ride up over frigid air masses from Canada, setting up inversion layers (Gay and Davis, 1993). Snow forms at the top of the warm layer, falls into warmer air below and melts. Raindrops become super-chilled when they fall into the cold layer near the ground, freezing in a phase-change reaction when striking an object, such as a power line or twig (Michaels, 1991).

Glaze icing events are quite patchy in rugged topography (Millward et al., 2010). Damaged areas are usually oriented southwest-to-northeast (Lecomte et al., 1998) and can be as narrow as 15 km and as wide as 250 km (Lemon, 1961).

Severe winter storms affect the width of tree rings (Travis et al., 1989; Lafon and Speer, 2002), presumably through loss of photosynthetic capacity and the need to use stored carbohydrate to repair

* Corresponding author.
E-mail addresses: djohns1066@yahoo.com (D.J. Stevenson), tom.lynch@okstate.edu (T.B. Lynch), pradip.saud@okstate.edu (P. Saud), bob.heineman@okstate.edu (R. Heineman), randy.holeman@okstate.edu (R. Holeman), dennis.wilson@okstate.edu (D. Wilson), keith.anderson@okstate.edu (K. Anderson), jguldin@fs.fed.us (J.M. Guldin).

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damage. Studies in Georgia and South Carolina (Travis et al., 1989) found ice damage accounted for 10-19% of ring width variance in *Pinus taeda* beyond 25–39% explained by temperature and precipitation. *P. taeda* damaged in an ice storm had reduced ring width five years after the storm (Belanger et al., 1996). Lack of a well-defined storm signal made reconstruction of storm chronologies from tree ring series difficult.

The term "ice storm" means specifically, a storm that produced glaze icing. "Severe winter storm" includes ice storms, but may also include snow, graupel, freezing rain, sleet and frequently all of them. There is no clear divide between "ice storms" and other storms and no clear divide between "large" and "small" storms.

In this study we (1) determine that there is a signal in tree rings that is associated with severe winter storms, (2) describe that signal, and (3) use it to construct sample histories of winter storms at specific sites. Our method uses ring widths standardized to the seven growing seasons following a suspected severe storm. This signal allows researchers to characterize long term variations in weather patterns at a landscape scale and permits climate, specifically severe winter storms, to be studied at finer scales and farther back in time than other records allow (Phipps, 1982).

2. Methods

In 1985 Oklahoma State University (OSU), in cooperation with the USDA Forest Service, established a growth-and-yield study of shortleaf pine (*P. echinata* Mill.) on the Ouachita National Forest in eastern Oklahoma and western Arkansas. Eighteen plots (0.08 ha) from a previous study were updated and 189 new plots installed. Tree diameters and heights were re-measured at approximately five-year intervals. In December 2000, two major ice storms (December 12–13 and December 25–27) caused severe damage to many trees and plots. These are referred to collectively as "the Christmas 2000 ice storm." An opportunity arose to study effects of severe storm damage on trees and stands with known growth histories.

Eighty-seven plots from the study were already measured for an update when the Christmas 2000 ice storm struck. The measurement protocols were re-designed to include ice damage data and the remaining plots measured, creating two groups of plots for the 2000/2001 update: those measured before the storms and those measured after them. After the 2006 update, a study of ice-caused damage was initiated. Plot measurements included pre-storm total height for all trees and height at the break for trees with broken trunks.

Tree ring data was obtained from OSU study sites at Caddo Gap, Cold Springs, Knoppers Ford, Sand Lick and Story, the Shortleaf Canyon Chronology (Cerny, 2009; Stevenson et al., 2014a,b) and the Hot Springs (Stahle et al., 1982), Lake Winona (Stahle, 1980) and McCurtain County (Stahle et al., 1982) chronologies (Fig. 1). Data was cross-dated, then intercorrelation was determined using COFECHA (Grissino-Mayer, 2001). This produced a set of nine site chronologies which we truncated to include only years with at least eight observations. Spans thus produced were: Caddo Gap: 1947–2008 (62 years); Cold Springs: 1945–2008 (64 years); Knoppers Ford: 1929–2007 (74 years); Sand Lick: 1943–2007 (65 years); Story: 1924–2007 (84 years); Shortleaf Canyon: 1868–2008 (131 years); Hot Springs: 1777–1982 (206 years); Lake Winona: 1745–1980 (236 years) and McCurtain County: 1749–1982 (234 years). We further truncated chronologies to include only years after 1884 (Fig. 2) due to the unreliable nature of earlier records.

Climatological Data (NCDC, 2011a) records are lists of daily and monthly temperatures and precipitation with occasional notes on ice accumulation, sleet and snow. There were 31 stations that

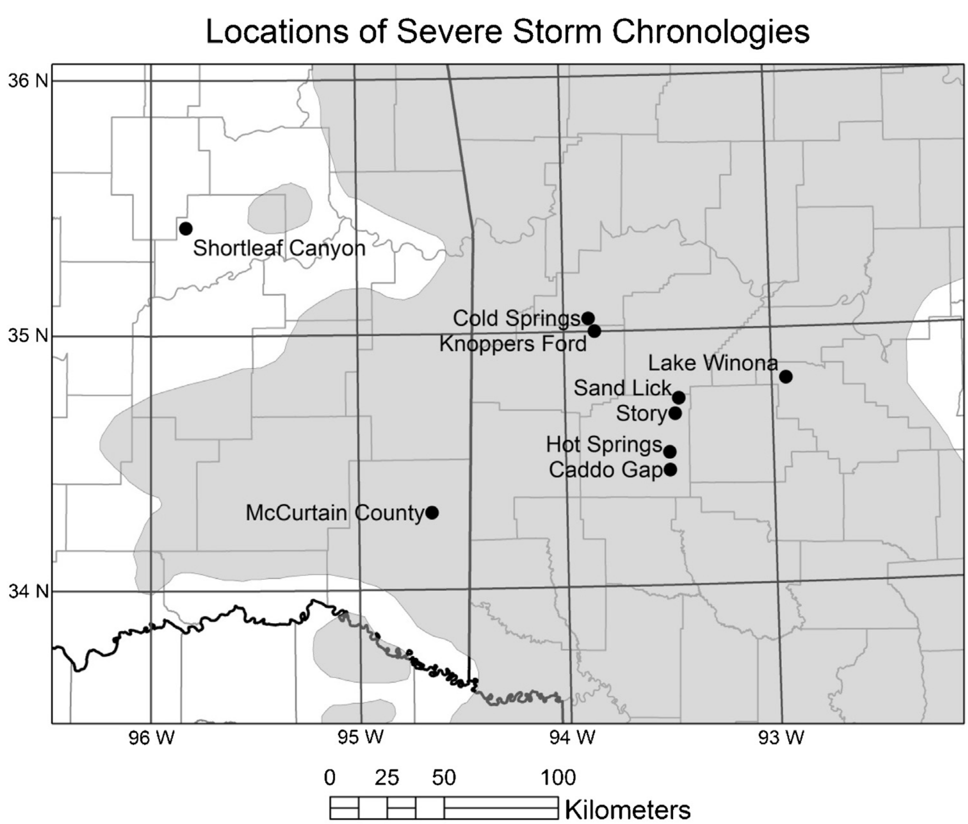

Fig. 1. Severe storm study sites. Map includes five Ouachita site chronologies, the Shortleaf Canyon chronology and three older site chronologies from the NCDC. Shaded area indicates the natural range of *P. echinata*. Shortleaf Canyon is one of five outlier stands that lie west of *P. echinata*'s principle range. Map data from ArcGIS.

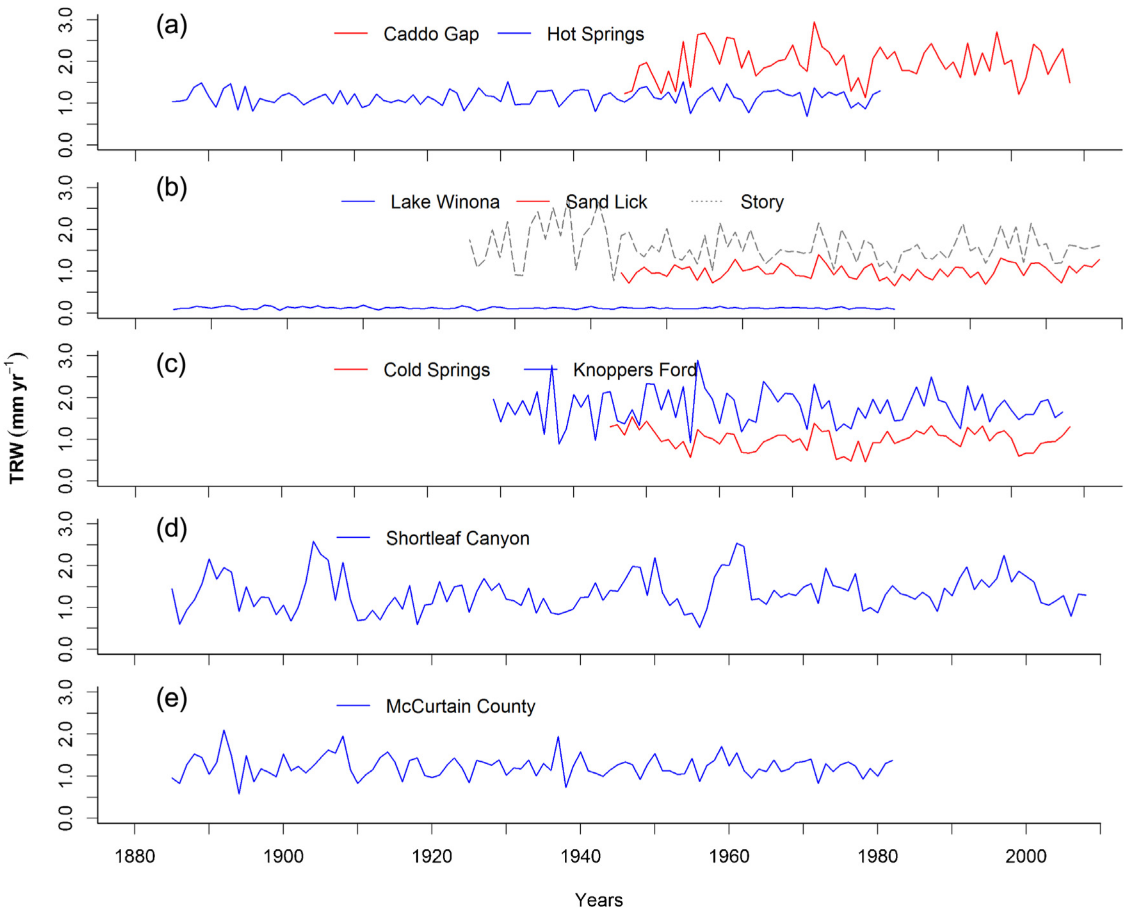

Fig. 2. Detrended tree ring width by climate division. Rows (a) and (b): Arkansas Division 5; Row (c): Arkansas Division 7; Row (d): Oklahoma Division 6; Row (e): Oklahoma Division 9. Lake Winona has narrow rings because it is on an extremely dry site.

recorded these measurements on or within 50 km of the Ouachita National Forest, most of which did not operate at any given time. Good records go back to 1 January 1906 (Alciatore, 1906).

The National Climate Data Center (NCDC) publication *Storm Data and Unusual Weather Phenomena* (*Storm Data*) (NCDC, 2011b) consists of descriptions of storms going back to January 1959. To fill in missing information prior to 1959, we developed profiles from *Climatological Data* by listing daily high and low temperatures and precipitation at a weather station close to each study site. Cold Springs and Knoppers Ford data came from Booneville, Arkansas (temperatures) and Cold Springs, Arkansas (precipitation). Lake Winona data came from Dardanelle, Arkansas and McCurtain County from Smithville (temperature and precipitation) and Hee Mountain, Oklahoma (precipitation only). For Shortleaf Canyon we used data from Eufaula, Oklahoma. Caddo Gap, Hot Springs, Story and Sand Lick data came from Mount Ida, Arkansas (1923–1938 and November 1943–2007) and Story, Arkansas (1939–March 1943).

Descriptions in *Storm Data* (NCDC, 2011b) that included the terms "ice storm," "glaze," "freezing rain," "sleet," "winter storm," "snowstorm" or "heavy snow" were used as indicators of a storm. Glaze icing occurred when there was only 0.635 cm of precipitation; thus, a weather event was considered "severe" if at least 0.635 cm of precipitation occurred while temperatures were between −3° and 1° C. and damage to trees, buildings, powerlines or glaze icing on roads was reported in multiple climate divisions (NOAA, 2015). Climate divisions are multi-county areas of relatively-similar weather. In the event of a missing report, reports from adjacent divisions were used to get an idea of what should have been in the missing one.

There are newspaper accounts of severe storms in 1886 and 1894 (Colson, 1886) and drawings of a severe storm in 1881 (Black Hawk, 1890). Before the advent of electric lines, paved highways and airports, ice storms caused little newsworthy damage and were rarely mentioned in newspapers (Nielsen-Gammon and Johnson, 2004). From weather records, profiles and newspaper articles a list of all known storms to strike eastern Oklahoma and/or western Arkansas was compiled back to 1881 (Table 1).

As a rough check on the uniformity of weather, monthly average temperature and precipitation at Mena, Arkansas were used to estimate those at Booneville, Arkansas (67 km away), using a linear regression model. For average monthly temperature, $r^2 = 0.991$; for average monthly precipitation, $r^2 = 0.547$. Standard deviation was 0.80 °C for temperature and 4.52 cm for precipitation. There is remarkable uniformity between these stations. In a straight-line model, differences due to elevation are averaged into the constant.

2.1. *Drought and severe storm concordance*

Drought might be associated with winter storms (Zhang and Xue, 1994), confounding both storm and drought signals. To determine if this was so, we used Cohen's Kappa (Cohen, 1960; Landis and Koch, 1977; Lowry, 2013a,b), a measure of agreement between two sets of categorical observations, both of which may contain error, to assess the level of concordance. One category was the list of storms developed from *Storm Data* and *Climatological Data*

(Table 1), while the other was a list of summer droughts determined by averaging the Dai Palmer Drought Severity Index values for July, August and September (JAS PDSI) (NOAA, 2012) with values below −1.40 indicating drought. Values of Kappa between 0 and 1 indicate positive agreement, while values near zero indicate little agreement. A negative value of Kappa indicates discordance.

Values of Kappa (K) were categorized using the method of Landis and Koch (1977). Category names are: Poor: $K < 0.00$; Slight: $0.00 < K \leq 0.20$; Fair: $0.20 < K \leq 0.40$; Moderate: $0.40 < K \leq 0.60$; Substantial: $0.60 < K \leq 0.80$; Almost Perfect: $0.80 < K < 1.00$ and Perfect: $K = 1.00$. When capitalized, the words are referring to these categories. The Perfect category refers to perfect concordance between two sets of data that may contain errors. It means that one set exactly duplicates the other, errors and all. For Cohen's Kappa, $Z = K/s$. Z is the Z-score from a Standard Normal curve. s is the Standard Error for the dataset.

2.2. Storm signal

A possible indicator of severe storms is a sudden decrease in tree ring width (Travis et al., 1989; Lafon and Speer, 2002). Lafon and Speer (2002) noted a two-year reduction in total ring width (TRW) following ice storms and speculated it might be diagnostic. To indicate an ice storm they required a 40% reduction in TRW from the average of the previous five years in at least 10% of trees and an increase in TRW of at least 50% in at least 10% of trees. This is a bipartite signal.

Our severe winter storm signal consisted of a two-year decline in TRW followed by an increase to almost-normal in the third year and resumption of normal growth in the fourth year; although, if the tree was severely damaged, that might be a new normal. Canopy damage results in the loss of photosynthetic capacity, producing reduced radial growth while the tree regrows its crown (Belanger et al., 1996). Radial growth is sensitive to injury-induced stress because stem growth has low priority for resource allocation within the tree (Pedersen, 1998). The width of the storm ring is compared to the width of rings that come after it. The diagnostic is a growth rate in the first and second growing seasons that is between 70% and 90% of the growth rate in the third and fourth growing seasons in 10–30% of trees. Severe winter storms occur in the late fall and winter; the following growing season is in the first growing season/year following the storm. We did not observe a bipartite signal as did Lafon and Speer, but we noted a two-year reduction in TRW for known storm years 1868, 1874, 1886, 1910, 1925, 1963, 1992, 1993 and 2001. Years also initiating a two-year reduction in ring width included 1753, 1772, 1788, 1799, 1810, 1837 and 1850. A three-year reduced ring width signal in 1824–1826 is unexplained, but also occurs in other chronologies in the area.

Severe storm detection

We speculated that there might be a relationship among ring widths after a severe storm that would become apparent if the data were standardized. For each ring we calculated the mean of its width plus the width of the six subsequent rings to yield 7Mn. From each of the seven observations we subtracted 7Mn, squared the result and summed results over the seven observations. We divided this sum by seven and took the square root to yield 7SDev. Two variables, Stan1 and Stan2 (Fig. 3), were then calculated, Stan1 by subtracting 7Mn from the first observation and dividing by 7SDev and similarly, Stan2 by subtracting 7Mn from the second observation and dividing by 7SDev. Stan1 is the standardized ring width for Year 1 and Stan2 is the standardized ring width for Year 2. We generated values of Stan1 and Stan2 for each year of the chronology.

Storm calendars were constructed by listing TRW (Fig. 2), PDSI (Fig. 4), Stan1 and Stan2 (Fig. 3), the last two of which were computed using output from ARSTAN 'STNDRD' version (Cook and Holmes, 1986) of each chronology using the "subtraction" option. These were compared with the actual and estimated storm records from Table 1. We constructed severe storm calendars for all nine chronologies (Figs. 2 and 3).

By examining known storms we settled on ad hoc values of Stan1 ≤ −0.900 and Stan2 ≤ −0.250 as indicative of severe winter storms. We required that both conditions be met for a storm to be "severe." When Stan2 was small enough, but Stan1 was not, we designated the storm as "small." We then compiled a list of possible storm years from each chronology and compared it with a list of storms from the historical record (Table 1).

Table 1
Sample record of storms that affected study plots from 1980 to 2009. Actual record goes back to 1881. Table has been truncated in the interests of brevity. The year is the first growing season after the storm. Sources of information are: CD = Profile developed from *Climatological Data* and SD = *Storm Data and Unusual Weather Phenomena*. States: AR = Arkansas, MO = Missouri and OK = Oklahoma.

Year	Remarks
2009	*Ice Storm* January 26–28. Freezing rain and sleet over most of AR. Heaviest icing along MO border tapering off farther south. Severe tree damage in Ft. Smith (SD)
2006	*Winter Storm* February 17–18. One inch sleet in portions of McIntosh County, OK (SD)
2005	*Ice Storm* February 26. Up to 2 cm freezing rain in isolated areas. 5000–6000 people without power (SD)
2002	*Winter Storm* (AR), *Heavy Snow* (OK) February 5–6. 15 cm snow in Poteau; 5 cm in McAlester. Snow and sleet in western AR. Power outages due to tree breakage (SD)
2001	*Ice Storm* December 12–13 and Dec 25, 2000. Heavy damage to trees and powerlines throughout AR and eastern OK (SD)
1997	*Winter Storm* January 8–9. Snow, sleet and freezing rain in western AR. Accumulation on trees and grassy areas (SD)
1995	*Ice Storm* (AR), *Freezing Rain* (OK) January 5–7. Freezing rain and drizzle. A few trees and power lines downed. 5000 people without power (AR). Freezing rain (OK). (SD)
1993	*Snow and Ice* (OK) *Ice Storm* (AR). January 17–19. Sleet and freezing rain in OK; freezing rain, about 8000 people without power (AR) (SD)
1992	*Heavy Snow* (AR), *Snow Storm* (OK) January 17–18. Up to 7 in. of snow broke tree limbs and power lines (AR). Six to eight inches of snow in McCurtain and LeFlore (OK) (SD)
1990	*Freezing rain, sleet snow* (OK), *Flash Flood* (AR) Febtuary 14–15. Freezing rain and sleet in OK. Heavy rains and flooding in AR. (SD)
1988	*Snow Storm* (AR), *Heavy Snow* (OK). January 5–7. "Largest snow storm of the century" and "coating of sleet and freezing rain" in AR. Over 10 inches of snow with four-foot drifts in OK (SD)
1987	*Heavy Snow/Ice Storm* (OK) January 16–17. Freezing rain and sleet; coating of ice up to 1 inch thick on trees and power lines; 100,000 people without power. No report for AR (SD)
1985	*Low Temperature* (AR), *Winter Storm* (OK) February 2–4. Up to 8 inches of snow in northeast OK
1984	*Ice Storm* (AR), *Winter Storm* (OK) December 20–21, 1983. Mainly freezing rain and drizzle; trees and power lines down; timber damage extensive (AR). Average monthly temperature coldest on record; freezing rain, freezing drizzle and snow, depths less than three inches (OK) (SD)
1982	*Unusual Cold* (AR), *Freezing Temps* (OK) January 10–12. Arctic outbreak; record low temperatures (AR). Temperature near 10 below (OK) (SD)
1981	*Wind, Ice Storm* (OK), No report for AR. February 10. Freezing rain; high winds (SD)
1980	Storms on February 1 and 17. No reports in SD. Extreme cold (<−12 °C) and storms inferred from station logs (CD)

Data continues back to 1885, but is not shown due to a shortage of space.

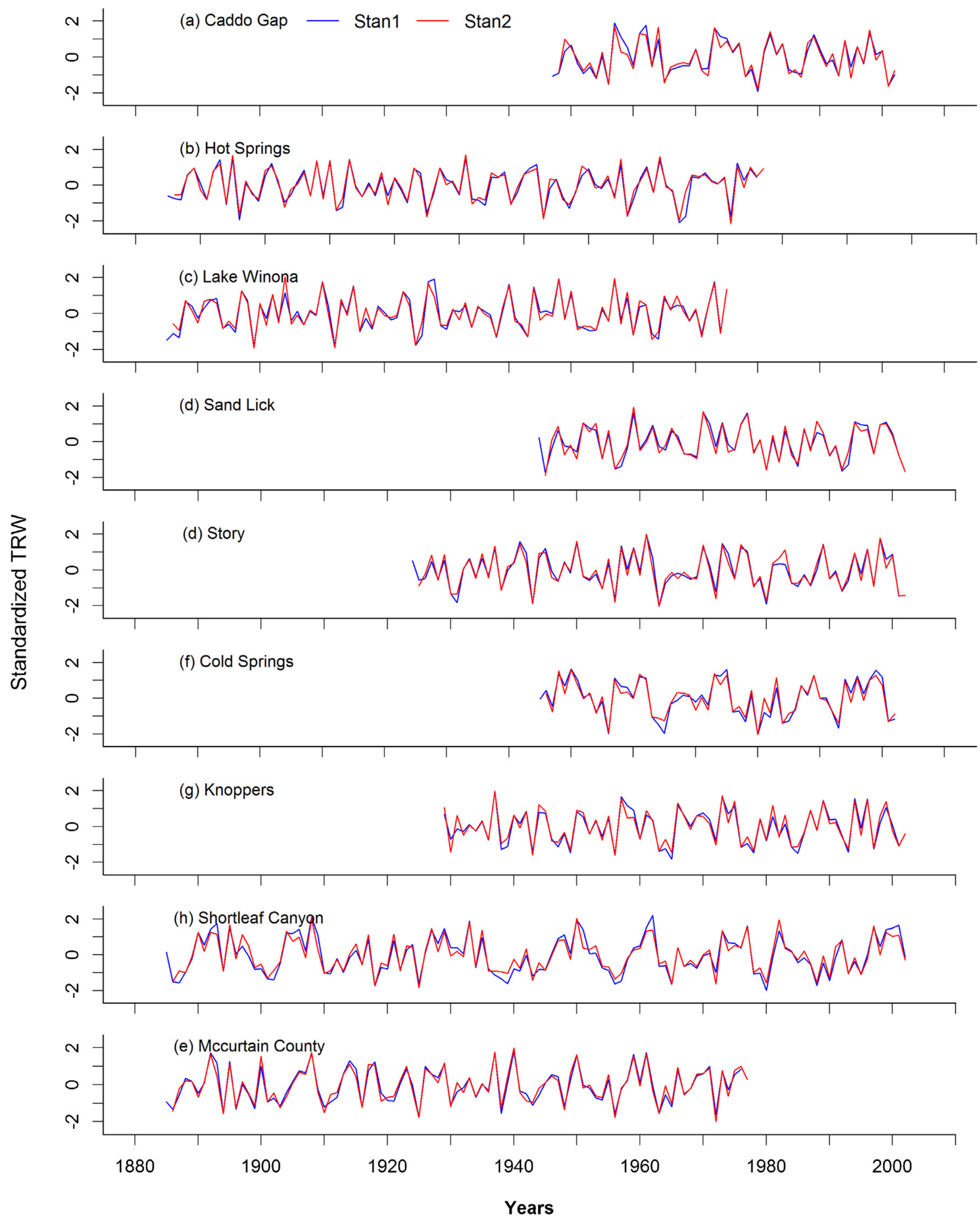

Fig. 3. When Stan1 is less than −0.900 and Stan2 is less than −0.250 a severe winter storm is indicated. The standardization process removes all trends longer than seven years.

3. Results

3.1. Droughts vs. severe storms

Concordance tests for winter storms vs. JAS PDSI (Fig. 4) were not conclusive. Some showed concordance, but most did not (Table 2). Concordance between winter storms and summer droughts is just strong enough to confound results. This suggests that some "winter storm" signals may actually be the result of droughts and vice versa.

In testing concordance between winter storms and JAS PDSI, values of K ranged from 0.141 (Knoppers Ford) to 0.309 (Lake Winona) (Table 2). Sand Lick produced a negative value for Kappa. Four out of nine chronologies showed significant concordance ($\alpha = 0.050$).

3.2. Storm signal

The decline from pre-storm ring width varied between 6% and 71% with an average of 33% in the two years following the storm.

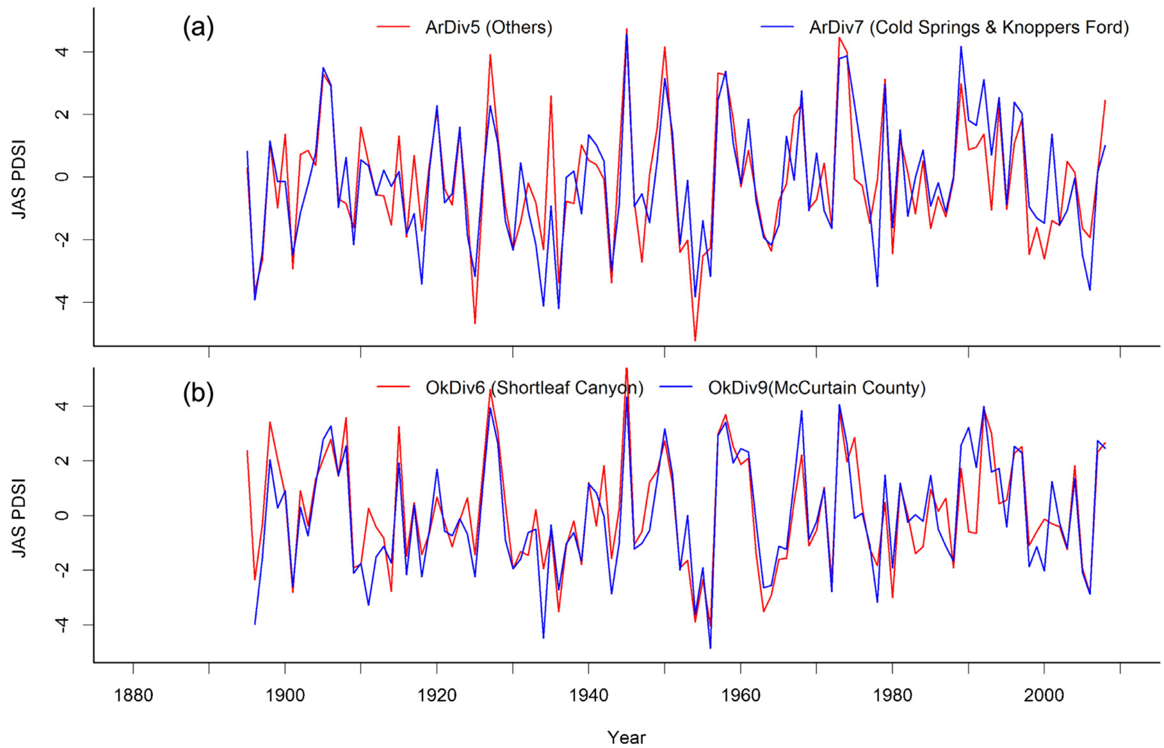

Fig. 4. Dai Palmer Drought Severity Index for four climate divisions in Oklahoma and Arkansas averaged for the months of July, August and September (JAS PDSI).

Table 2
Cohen's Kappa (K): concordance between severe winter storms and averaged PDSI values for July–September. s = standard error; Con = concordance using Landis and Koch (1977) strength of agreement term (Slight: $K < 0.20$; Fair: $0.21 < K < 0.40$; Moderate: $0.41 < K < 0.60$). A = correctly predicted winter storm years; B = false positives; C = false negatives; D = correctly predicted normal years. $Z = K/s$.

Site	PDSI	est. K	s	p-value	Conc.	A	B	C	D
Caddo Gap	−2.40	0.213	0.202	0.291	Fair	1	5	1	57
Cold Springs	−2.00	0.506	0.212	0.017	Moderate	3	4	1	55
Hot Springs	−3.00	0.450	0.214	0.035	Moderate	3	4	2	55
Knoppers Ford	−0.50	0.126	0.141	0.370	Slight	3	24	0	37
Lake Winona	−3.90	0.216	0.309	0.516	Fair	1	2	4	80
McCurtain	−2.60	0.506	0.212	0.017	Moderate	3	4	1	56
Sand Lick	−1.40	[a]	[a]	[a]	a	0	19	3	43
Shortleaf	−2.80	0.431	0.208	0.039	Moderate	3	5	2	105
Story	−1.80	0.107	0.221	0.628	Poor	1	13	0	50

[a] Sand Lick values could not be calculated.

In trees with less than 55% crown loss, ring width returned to pre-storm conditions in the third year. Trees with crown loss between 55% and 65% had not recovered pre-storm ring widths by the 2012 update. Trees with greater than 65% crown loss showed declining radial growth rates in 2012. We checked the values of Stan1 and Stan2 for the list of known severe storms (Table 1) and found that Stan1 was less than −0.900 and Stan2 was less than −0.250 for all known severe storms.

Results for each storm calendar were summarized (Table 3). There were no Poor and no Perfect concordances and only one Moderate. In eight out of nine chronologies, concordance was either Substantial or Almost Perfect. There were not many severe storms so that a negative signal had a low probability of hitting a storm year; thus, there were few false negatives. Correct and incorrect predictions for the occurrence of severe winter storms are shown in Fig. 5.

Reconstructions show that on average, severe winter storms occur at about 19-year intervals at McCurtain County (12 times between 1749 and 1976), 19-year intervals at Lake Winona (12 times between 1745 and 1974), 26 years at Story (3 times between 1924 and 2001), 18 years at Knoppers Ford (4 times between 1929 and 2001), 19 years at Shortleaf Canyon (7 times between 1868 and 2002), 29 years at Cold Springs (2 times between 1945 and 2002) and 15 years at Sand Lick (4 times between 1943 and 2001). At Caddo Gap there was a 21-year interval between the two "large"

Table 3
Cohen's Kappa (K) for severe winter storms in the Ouachita Mountains: concordance between predicted and actual severe winter storms using standardized ring width values. s = standard error; Z = Standard normal Z-value ($Z = K/s$); p-value corresponding to Z-value; Conc. = concordance using Landis and Koch (1977) strength of agreement terms (Moderate: $0.41 < K \le 0.60$; Substantial: $0.61 < K \le 0.80$; Almost Perfect: $0.80 < K < 1.00$). A = correctly predicted storm years; B = false negatives; C = false positives; D = correctly predicted normal years.

Site	est K	s	p-value	Conc.	A	B	C	D
Caddo Gap	0.791	0.207	<0.001	Substantial	2	0	1	54
Cold Springs	0.650	0.243	0.004	Substantial	2	0	2	53
Hot Springs	0.852	0.148	<0.001	Almost perfect	3	0	1	88
Knoppers Ford	0.748	0.142	<0.001	Substantial	5	1	2	70
Lake Winona	0.852	0.148	<0.001	Almost perfect	3	0	1	86
McCurtain County	0.581	0.205	0.002	Substantial	2	0	2	80
Sand Lick	0.482	0.360	0.090	Moderate	1	1	1	55
Shortleaf Canyon	0.866	0.094	<0.001	Almost perfect	7	2	0	110
Story	0.849	0.149	<0.001	Almost perfect	3	1	0	63

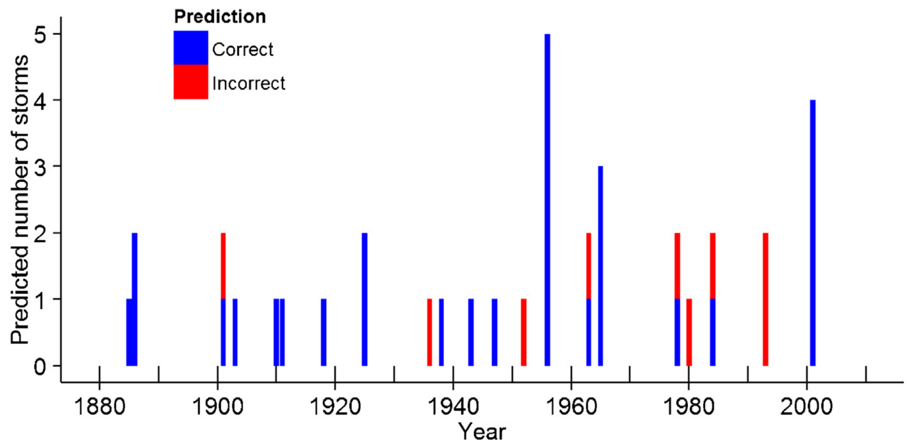

Fig. 5. Correct Storm Predictions vs. Incorrect Storm Predictions. The figure covers the historical period (1885–2001) for the Ouachita National Forest. "Correct" and "Incorrect" results in the same year are the result of a severe storm in one climate division, but not in another. The storm of 1886 was the worst one on record; the incorrect predictions for 1993 were the result of a heavy snow storm. Height of the bar is indicative of the number of chronologies, not severity of storms.

storms, but only those two large storms in 56 years (1947–2002). At Hot Springs, the interval between large storms averaged 33 years (6 times between 1777 and 1976). On average, damaging winter storms occurred about once in 24 years, the range being 12–33 years.

One severe storm (1992) produced no evidence of breakage; two others (1963 and 2001) did. Before 1963 one can't really tell because the broken tops and branches have long since rotted away. The chance of a severe winter storm in any given year in the Ouachita Mountains is about 1 in 24 (4.1%) with a two-thirds chance of trunk damage, or about a 2.8% chance of stem breakage by a winter storm in a given year.

4. Discussion

4.1. Interpreting the data

Drought could have been a factor in producing the narrow rings and severe storm signature. In 1980 JAS PDSI at Caddo Gap was −2.44, the sixth driest summer out of 62 years. There were five years with dryer summers that did not have the severe storm signal. In the case of 2001, JAS PDSI was −1.39, the eleventh driest summer. Nine of the 11 driest summers out of 62 were rejected. In these two cases, drought seems an unlikely cause of the observed signal.

Four out of nine sites showed significant ($p < 0.100$) concordance between severe winter storms and summer drought. This does not indicate a link with sufficient confidence to conclude that there is one, but it does point out the risk of assuming that one does not exist. Droughts and severe winter storms are confounded at least part of the time. This poses a risk of removing the storm signal when removing the drought signal and vice versa. Some "winter storm" signals are actually the result of droughts.

There was no storm in 1986 at Caddo Gap. In 1986, JAS PDSI was −0.62 and in 1987 it was −1.27. JAS PDSI indicates a dry year, not really a drought, in 1987. $Stan1_{(1986)}$ and $Stan2_{(1986)}$ are both low enough to indicate a severe storm. The low value of $Stan2_{(1986)}$ was probably the result of dryer-than-normal conditions in 1987. In this case, a false positive was produced. About one positive result in six was false.

Reconstructions of the various storm chronologies were visually compared with each other. Results were as expected with different chronologies showing large storms in most of the same years and small storms in most of the same years. When there was a discrepancy, it was usually one site showing a small storm while another showed a large one. Also as expected, the greatest differences were between the Shortleaf Canyon and Lake Winona sites which are also the farthest apart geographically (Fig. 1).

We observed that older stands tended to suffer less damage than younger stands so storms that hit them registered as smaller. A similar effect was noted by Bragg et al. (2003). Tree breakage will have to be corrected for age, density and species before it can be used as an indicator of storm intensity.

4.2. False signals

We were able to identify the source of some false storm signals. In the dormant season of 1936/1937 there was a site disturbance (logging?) at Knoppers Ford. The trees that survived to contribute cores in 2008 responded by setting pitch in rings prior to 1937 and undergoing release, producing wide rings in 1937 and 1938. The Dust Bowl drought in 1933–1936 followed by wide release rings in 1937 and 1938 mimicked the storm signal, producing a false positive in 1936.

In 2005 and 2006, drought in the southwest part of the study area produced two consecutive years with narrow rings, followed by two years with wider rings. Between 1886 and 2006, the period for which reliable historical data is available for Shortleaf Canyon, the severe storm configuration occurred four times, one of which was the 2005/2006 false positive.

False positives often coincided with years that had minor storms. There was a problem deciding which storms might be bad enough at a given site to qualify as "severe." A storm that caused heavy damage out in the woods might not have been very bad at the weather station, 15 km away and 200 m lower. Perhaps the easiest way to separate "small" storms, "large" storms and false signals is to compare adjacent chronologies. A "large" storm should cover a large area, affecting many chronologies in a region. A "storm" that shows up only on one chronology is more-likely to be a false signal.

4.3. Historical records vs. tree rings

There are serious problems with the historical records. *Storm Data* only goes back to 1959 and there are numerous gaps. *Climatological Data* goes back to January 1906 locally, with one low-quality record (Dallas, Arkansas) going back to September 1896. The PDSI (Fig. 4) goes back to January 1895. Before that there are only a few newspapers and other scattered records. Though 31 weather stations operated intermittently on or near the Ouachita National Forest, only eight – Booneville, DeQueen, Hot Springs, Mena, Mount Ida, Smithville, Subiaco and Waldron – have operated more-or-less

continuously for the decades needed to calibrate tree ring series. Smithville was shut down in 2006.

In seven out of nine chronologies, the narrowest rings in each are associated with severe winter storms combined with drought (Caddo Gap 1980; Cold Springs 1976; Knoppers Ford 1938; Sand Lick 1980; Shortleaf Canyon 1956; Story 1980). At Lake Winona, the narrowest ring was 1838. The year met the severe storm criteria, but was grouped with the 1837–1840 cluster of three consecutive narrow rings, a phenomenon which has not yet been explained. In each of these, removal of the drought or ice storm signal would remove the other. At McCurtain County, the narrowest ring was 1879. At Hot Springs, the narrowest ring was 1758, which met the severe storm criteria and was the first of a set of three narrow rings as with Lake Winona. Neither the 1837–1840 narrow rings nor the 1879 single narrow ring occur during droughts (Muhs and Holliday, 1995; Herweijer et al., 2005).

Distance between research sites and weather stations could be an issue. They are: Shortleaf Canyon to Eufaula: 26 km; Cold Springs to Booneville: 11 km; Cold Springs to Cold Springs: 2 km; Sand Lick to Mount Ida: 26 km; Sand Lick to Story: 8 km; Story to Mount Ida: 20 km and Story to Story: 5 km. All are considerably less than the 76 km between Mena and Booneville mentioned above. The Cold Springs site is within sight of the Cold Springs weather station.

4.4. Ice storm damage and related influences

Winter storm damage might be distinguishable from ring-width variations caused by rainfall, temperature and insect defoliation (Stahle et al., 1985; Swetnam and Betancourt, 1990; Graumlich, 1993). Most trunk breakage occurs above commercial height and so has little immediate effect on timber volume. If enough canopy is left, broken trees continue to grow and produce timber above the storm-caused break. However, storm damage creates entry-routes for fungi; decay progression over the ensuing decades can hollow out a tree, rendering it cull. More work is needed on the progression of decay-causing fungi and their effects on net volume. With ice storm models (Travis et al., 1989; Stevenson et al., 2010) the loss of radial growth caused by severe storms can be quantified. This should be done by incorporating ice storm models into growth-and-yield simulators, such as that developed by Lynch et al. (1999).

Lafon and Speer (2002) applied their method to *Quercus prinus* L. and *Q. velutina* Lam. We have observed a double narrow ring pattern in *Pinus taeda* L. from southeast Oklahoma, resulting from the same December 2000 storm (Stevenson et al., 2015, 2016). These methods need to be tested in other species before the technique can be applied to tree species generally. Also, both our method and the Lafon and Speer method need to be tested on more chronologies. Larger sample sizes will allow refinement of the thresholds used to determine whether growth changes are sufficient to indicate a severe storm.

Wind storms may trigger release but not suppression (Lafon and Speer, 2002; Frelich and Ostuno, 2012) and except in extreme cases like hurricanes and tornados, affect a relatively small number of trees (Reilly, 1991); wind does not usually produce widespread canopy damage (Lafon and Speer, 2002). It should be possible to develop better methods of separating these signals. Droughts tend to be longer-lasting than wind storm signals; perhaps this difference could be used to distinguish them.

In some hardwood species, a two-part signal may indicate ice-caused breakage. This may be distinguishable from damage caused by rainfall, wind, droughts and insect defoliation (Stahle et al., 1985; Swetnam and Betancourt, 1990; Graumlich, 1993). By combining signals from multiple species, like pines and oaks, it should be possible to distinguish between wind storms, ice storms and severe and small snow and ice storms.

5. Conclusions

Severe winter storms break trunks and limbs and cause severe bending, injuring trees and leaving a characteristic two-year decline in ring width. This can be detected using rings laid down in response to injury. Drought may be coincident with severe winter storms and can confound the severe winter storm signal. Drought and site disturbance occasionally cause a false positive signal. Severe winter storms occur in about 4.1% of all years. About two out of three severe storms produce glaze icing, giving a 2.8% chance of damage by severe storms at a given site in a given year.

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