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METEOROLOGICAL FACTORS ASSOCIATED WITH FROST RINGS IN ROCKY MOUNTAIN BRISTLECONE PINE AT MT. GOLIATH, COLORADO

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ABSTRACT

The meteorological factors involved in the formation of earlywood frost rings in Rocky Mountain bristlecone pine (*Pinus aristata*) have not been described in detail. This study used 51 tree-ring dated Rocky Mountain bristlecone pine trees growing at *ca*. 3500 m a.s.l. on Mt. Goliath, Colorado, to develop earlywood and latewood frost ring chronologies dating from 1930 to 2010 for investigation of the regional and large-scale weather anomalies responsible for these unusual growing season freeze events. The high-elevation meteorological station at Niwot Ridge, Colorado, was used to document the daily temperature anomalies most likely associated with these frost-damaged rings. NCEP-NCAR Reanalysis data were used to examine the synoptic meteorological conditions that tend to prevail during these unusual growing season temperature conditions. Earlywood frost rings occur during anomalous late-May and June freeze events in the Colorado Rockies associated with unseasonal mid-latitude circulation, including the penetration of a deep upper-level low pressure system and cold surface air temperatures into the west-central United States. The three latewood frost rings all occurred during September freeze events also associated with unseasonal and highly amplified mid-latitude circulation. The chronology of these early and late growing season freeze events may provide a useful independent check on daily temperature minima estimated with reanalysis techniques, and they can be extended into the pre-instrumental era thanks to the great age of Rocky Mountain bristlecone pine. Frost damage in Mt. Goliath bristlecone pine appears to be most frequent and severe in young trees found in the depressed tree line below a large cirque subject to intense cold air drainage. The development of the most detailed tree-ring records of past freeze events may therefore benefit from site selection in these cold air drainages, along with age-stratified tree sampling to ensure that the young and most frost susceptible age classes are well represented throughout the chronology.

Keywords: dendrochronology, tree rings, *Pinus aristata*, frost rings, tree line, synoptic meteorology.

INTRODUCTION

Frost damage to the annual growth rings of several tree species is known to be an indicator of unusual subfreezing temperatures during the growing season. Previous studies in the western and south-central United States have demonstrated the connection between frost-ring formation and large-scale temperature anomalies (LaMarche and Hirschboeck 1984; Stahle 1990; Salzer and Hughes 2007). These growing-season temperature anomalies appear to be linked in some cases to internal and external climate forcing factors such as the El Niño-Southern Oscillation (ENSO) and large-magnitude

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volcanic eruptions. Although the unusual growing-season circulation and temperature regimes responsible for frost-ring formation in trees may be the product of multiple causes, the synoptic meteorology of freeze events appears to be highly consistent from one frost event to another (Stahle 1990).

The climatic significance of latewood frost rings in Great Basin bristlecone pine (*Pinus longeava*) and Rocky Mountain bristlecone pine (*P. aristata* Engelm.) has been investigated by LaMarche and Hirshboeck (1984) and Brunstein (1996), respectively. However, the large-scale meteorological environment responsible for frost rings in the earlywood or springwood portion of the annual ring in bristlecone pine has not been described in detail. If consistent meteorological conditions are associated with these damaging freeze events, then these conditions can be inferred from prehistoric frost rings in millennia-old bristlecone pine trees. Dendrometeorological inferences of this nature have not been widely attempted, but can provide reasonable proxy information on short-term mesoscale weather events useful for investigating the atmospheric impacts of well-dated volcanic eruptions, ENSO extremes, or other climate forcings in prehistory. Tree-ring dated frost-ring events, which can only arise from subfreezing temperatures during the growing season at the collections site, may also provide useful independent validation data for daily temperature minima estimated with reanalysis techniques (Kalnay *et al.* 1996; Menne *et al.* 2012).

The active cambium is especially susceptible to injury when temperatures drop below freezing, producing distorted xylem tissue referred to as frost rings (Fritts 1976). The anatomical features of frost rings in conifers are diagnostic of extracellular freeze damage, and include deformed and under-lignified tracheid cells, collapsed cell walls, discolored cell contents, and disrupted rays (Glerum and Farrar 1966; Villalba and Roig 1986; Brunstein 1995). The freeze damage is triggered by the formation of ice in the intercellular spaces causing cell dehydration and external pressure on immature cambial cells and differentiating tracheids (Glerum and Farrar 1966). One day of freezing temperatures at or below –5°C during the period of active cambial growth is sufficient to cause frost injury in trees (Glock and Reed 1940). Frost rings are less frequently found in larger stems than in small branches or small-diameter trees (Gurskaya and Shiyatov 2006; Payette *et al.* 2010; Molina *et al.* 2016), likely attributable in part to the insulation of the thick bark in lower portions of the tree (Fritts 1976). But because young and vigorous trees often experience a longer growing season than mature to old-growth trees, they are also potentially more vulnerable to late and early-season freeze damage (Fritts 1969; Stahle 1990).

Two types of frost rings can be distinguished in bristlecone pine: earlywood and latewood. Earlywood frost rings occur in the first-formed xylem cells of the annual ring. Freeze events that damage the earlywood are also referred to as "spring frost" or "late-season frost" (referring to the late winter season). Earlywood frost rings often occur during so-called "false spring" events, when warm late winter conditions initiate tree growth and render the plants vulnerable to freeze damage during a late outbreak of subfreezing temperatures (NOAA 2008; Marino *et al.* 2011). Latewood frost rings occur in the last-formed xylem cells of the annual ring in response to subfreezing conditions near the end of the growing season (Glerum and Farrar 1966). These latewood freeze events are also referred to as "fall frosts" or "early-season frosts" (*i.e.* early winter season frosts).

The Rocky Mountain bristlecone pine are native to Colorado, New Mexico, and Arizona. They are related to Great Basin bristlecone pine and foxtail pine, both native to the southwestern United States (Brunstein 2006), and can be distinguished from them by the numerous white resin specks present on the needles of Rocky Mountain bristlecone pine. The objectives of this study were: (i) to use 50 tree-ring dated Rocky Mountain bristlecone pine trees growing at *ca*. 3500 m a.s.l. on Mt. Goliath, Colorado, to develop replicated chronologies of both earlywood and latewood frost rings extending from 1930 to 2010; (ii) to define the daily temperature history associated with the earlywood and latewood freeze events using the nearest long and high elevation meteorological station at Niwot Ridge; and (iii) to document the synoptic meteorological conditions that tend to prevail during these unusual growing season temperature extremes at high elevation sites in the central Rocky Mountains.

Figure 1. The depressed tree line on Mt. Goliath, Colorado, is partially illustrated in the foreground of this image. The glacially sculpted cirque is located upslope to the left, and cold air drains in the foreground. Note the sparse growth of stunted trees in the cold air drainage way (foreground), the closed canopy conifer forest in the middle distance, and the true alpine tree line near the summit of Mt. Goliath (top left).

SITE DESCRIPTION

The study site is located on Mt. Goliath in the central Rocky Mountains (39°N 105°W at 3758 m a.s.l.) near the northern limit of the bristlecone pine range in Colorado. The site is east of the Mt. Evans highway on well-drained soil derived from granitic parent material. The collection site was chosen on S and SE exposures near the alpine tree line, on the lower slopes of a glacially sculpted cirque, and along the lower edge of a hanging valley. Cold air would tend to flow from the cirque and over the lip of the hanging valley. This apparent topographically enhanced airflow pattern is reflected in the position of the depressed tree line and in the open woodlands of stunted bristlecone pine some 200 to 300 m below the lip of the hanging valley (Figure 1). Core sampling of bristlecone pine was concentrated on trees within and adjacent to this cold air drainage path because we suspected that the most detailed record of frost damage would be recovered from these stunted tree line individuals. Previous studies have detected the strongest tree growth response to temperature in close proximity to the absolute tree line, regardless of tree-line elevation (Salzer *et al.* 2009; Kipfmueller and Salzer 2010). Geiger *et al.* (2003) noted that frost damage to trees can be modulated by forest density, structure, and location. In a similar manner, we hypothesize that the bristlecone stands that are the most sensitive to growing-season freeze events will be found at tree line or in cold air drainageways like our sample site at Mt. Goliath. Our sampling of living bristlecone pine in and outside of cold air drainageways was not sufficiently extensive to formally test this hypothesis, but the numerous frost-damaged rings discovered in our available samples indicate that attention to microsite detail may prove to be important in the development of detailed centuries-long frost-ring chronologies of bristlecone pine.

METHODS

Cores were extracted non-destructively from over 51 living bristlecone trees using 5.15-mm-diameter increment borers. Two collections were used to compile the chronologies, the first collection was obtained during the Third Annual North American Dendroecological Fieldweek, held in 1992 (Bunkers *et al.* 1992), and was updated with a second collection from a field expedition in September 2010. To ensure that the derived frost-ring chronology accurately represents all freeze events sufficiently severe to damage trees, both field collections were concentrated on "young" vigorous trees in the 50 to 100-year age class.

Standard dendrochronological techniques were used to prepare and date the core specimens. All cores were dried, mounted, polished, and then crossdated using the methods described in Stokes and Smiley (1996). After the exact annual dates were determined for all growth rings, the years with anatomical evidence for frost injury were recorded for all specimens. Frost rings occur in both the earlywood (springwood) and latewood (summerwood) portions of bristlecone pine growth rings at Mt. Goliath. Frost-damaged rings are readily apparent on polished radial surfaces at magnifications from 10 to 70×, and include deformed discolored cells and disrupted rays (Figure 2). Frost rings in trees often synchronize among many trees in a stand and across many forest stands in a given climate province (LaMarche and Hirschboeck 1984; Stahle 1990; Brunstein 1996). The meteorological signal of subfreezing temperatures is independent of the growing-season-long climate signal important for ring width, so when frost rings are present they provide a second chronological marker for

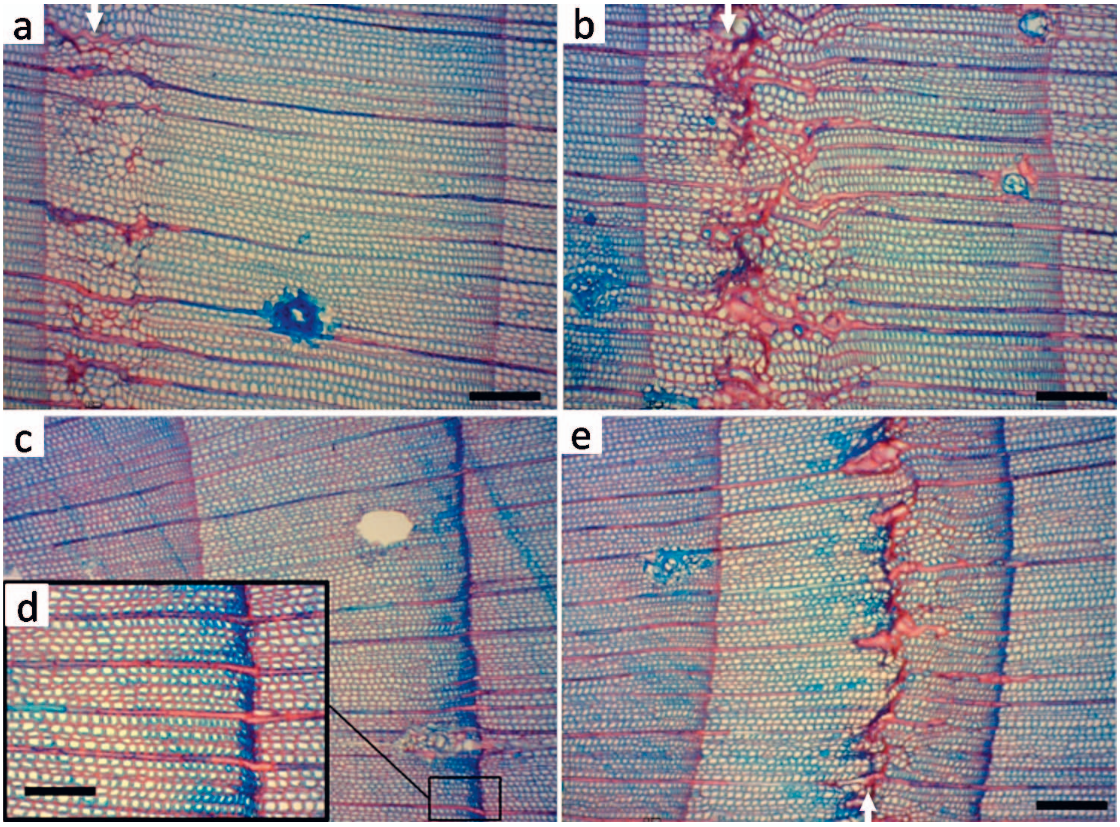

Figure 2. Four examples of frost-injured tree rings in earlywood and latewood of bristlecone pine at Mt. Goliath are illustrated (growth advances from left to right in all images, all examples were rated as "significant" frost damage). Earlywood frost injury in 1981 (a) and 1985 (b) included a zone of collapsed amorphous tracheid cells, discolored cell contents, and disrupted rays. Note that the freeze event in 1981 occurred on June 15, but on June 26 in 1985 (Table 2), and the position of the frost damage in both examples is roughly consistent with this timing. Two types of latewood frost rings are illustrated in (c), (d), and (e). In 1965 the freeze occurred on September 20 and the damage was restricted to the final-formed latewood cells (c–d). In 1961 the freeze occurred on September 3 and the frost damage is located in the middle of the ring near the onset of latewood formation (e). These examples indicate that the position of the frost damage within the annual ring provides an approximate indication of the calendar date of the freeze event (*i.e.* early *vs*. late June for EW, early *vs*. late September for LW). Black bars indicate 0.2 mm for (a–c) and (e); 0.1 mm for (d).

the exact dating of tree-ring series (Stahle 1990; Brunstein 1996).

The frequency of frost injury in any given year was tested for significance using the binomial distribution (Equation 1) to attach confidence intervals (CI) to the observed frequency of frost injured rings out of the total available sample of dated rings for each year (using $p < 0.05$):

$$CI = 1 \pm \left(\sqrt{\frac{pf \times (1 - pf)}{n}} \right) \times 2 \qquad (1)$$

where pf is the proportion of dated trees with frost injury in any given year, and n is the total number of trees dated to that year (Stahle 1990). The background frequency of frost rings was calculated as the simple ratio of all frost rings to the total number of dated rings. To be significant, the CI must exceed the random background frequency of frost-ring occurrence.

Climatic data were obtained from the Niwot Ridge meteorological station D-1, which is located only 45 km N of Mt. Goliath at an elevation similar to the study site. Station D-1 is a ridge-top alpine tundra site at 3739 m a.s.l. (12,264 ft) in the

Niwot Ridge Long-Term Ecological Research site and is the highest continuously-operating weather station in North America (Niwot Ridge LTER 2019). The Mt. Goliath bristlecone pine stand is in the 3400–3600 m elevation range, and is located in a cirque valley cold-air drainageway below the local ridgeline. Daily minimum and maximum temperature data are available for station D-1 from 1952 to 2008 and were plotted and examined to identify the exact day during the early growing season when the freeze events responsible for frost-ring formation probably occurred. Although the daily temperature data at Niwot Ridge are highly variable, the exact date of the unusual freeze event during years with significant frost-ring damage was usually not ambiguous.

The daily minimum temperature data were separated into two groups of frost-ring years and non-frost years (remaining years with no frost event). Time series of daily temperature were centered on the likely date of all significant earlywood frost-ring events and the composite mean daily temperature was computed for 40 days before and 35 days after the freeze event to estimate the magnitude of the daily temperature anomalies typically associated with earlywood frost rings. Similar daily temperature composites were prepared for the latewood frost rings. Standard errors were computed to highlight the large temperature differences between the composite means of frost and non-frost years for predetermined periods before and after each hard freeze. The differences in means of frost and non-frost years were also tested for three intervals before and after the freeze dates (separately for earlywood and latewood events): (1) a 10-day interval, starting one day before to eight days after the day of the composite freeze event, (2) a three-week interval prior to the composite freeze event, and (3) a three-month period prior to the composite freeze event. These tests help identify the temperature anomalies associated with the freeze events as well as the temperature history prior to the onset of freezing.

Earlywood frost rings are often associated with unusual late-winter warmth that tends to advance spring growth and render the trees vulnerable to late-season outbreaks of cold air (so-called "false spring"; Stahle 1990; Schwartz *et al*. 2006). For latewood frost rings, cool mid-summer temperatures can delay the onset and termination of radial growth in high-elevation bristlecone pine, making the still active cambium vulnerable to frost injury during early cold season outbreaks of subfreezing air (LaMarche and Hirschboeck 1984). Surface and upper air meteorological data were obtained from the NCEP-NCAR 40-Year Reanalysis (Kalnay *et al.* 1996). Synoptic maps were then plotted using NOAA's compositing tool available at: http://www.esrl.noaa.gov/psd/data/composites/day/.

RESULTS AND DISCUSSION

Frost Injury in Bristlecone Pine at Mt. Goliath, Colorado

The derived frost-ring chronology is based on 82 exactly-dated cores from 51 trees at the Mt. Goliath site and extends from C.E. 1930 to 2010. If a frost ring occurred on more than one core from a single tree it was only counted once per tree. Millennium-old bristlecone pine are present at Mt. Goliath, but this study focused on young frost-sensitive trees in order to derive a detailed frost-ring chronology suitable for comparison with meteorological data. Dating accuracy was confirmed by comparison with the 1000-year-long Mt. Goliath bristlecone pine chronology independently developed by Graybill and Idso (1993).

Years with frost-damaged rings varied in terms of the number of trees injured and the severity of cell damage (Figures 2 and 3). The background frequency of frost-injured rings (*i.e.* the ratio of all frost rings to the total number of dated rings) was 8.84% and indicates that the study site and sample trees are both susceptible to growing-season freeze events. For comparison, the background frequency of frost-damaged rings at 34 post oak sites in and near the southern Great Plains averaged 1.55% and never exceeded 3.35% (living trees only; Stahle (1990)). Earlywood frost rings alone at Mt. Goliath occur at a frequency of 6.67% out of all dated rings, compared with 2.17% for latewood frost rings.

The high frequency of earlywood and latewood frost rings appears to be related to the specific position of the sample trees at the lip of a hanging valley just below a large cirque depression that funnels cold air drainage off of Mt. Goliath and into the stunted bristlecone woodlands. The effect

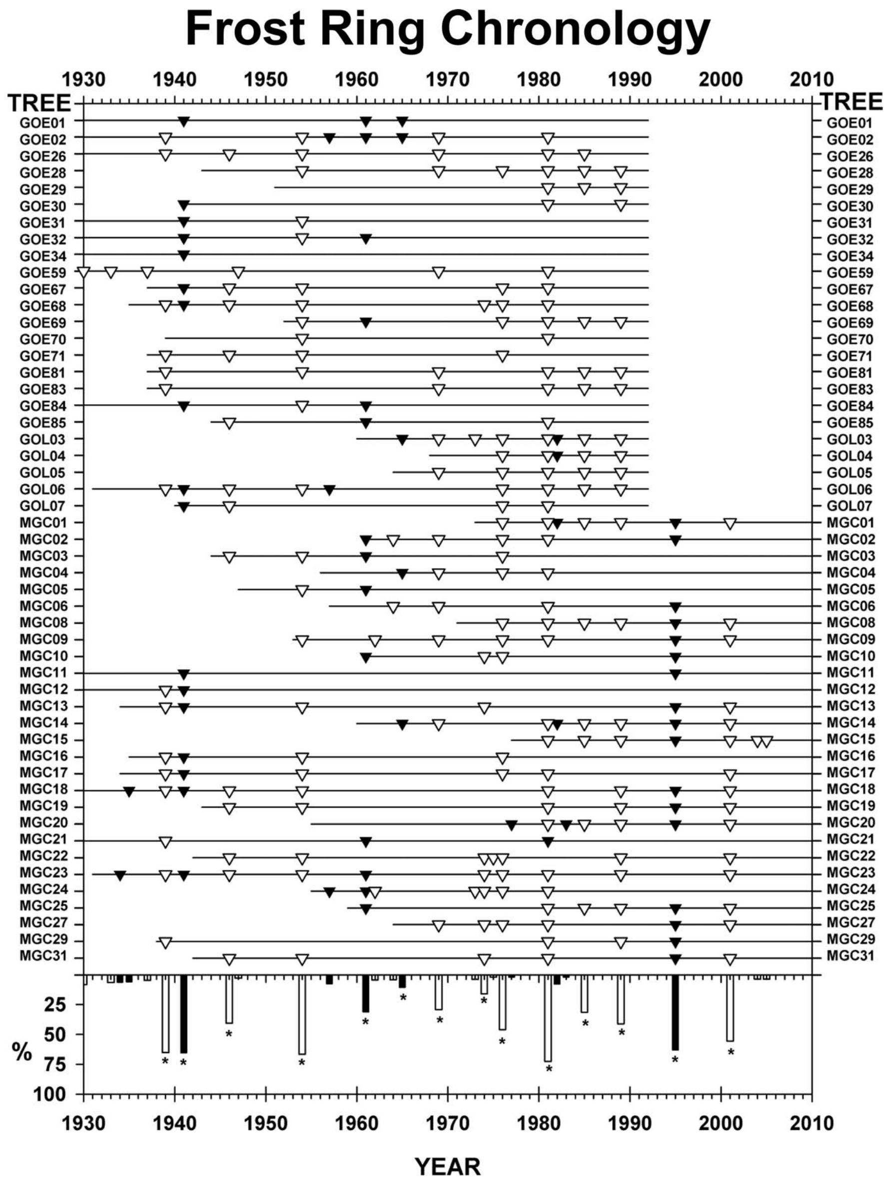

Figure 3. The frost-ring chronologies based on bristlecone pine samples from 51 trees at the Mt. Goliath study site are illustrated from 1930 to 2010. Years with evidence for frost injury are identified for each tree chronology by an inverted triangle and are differentiated into earlywood frost (open) and latewood frosts (black triangle). The first collection from 1992 is plotted at the top of the chart (tree codes GOE and GOL), followed by the second collection in 2010 (codes MGC). The relative frequency of frost-damaged rings each year is plotted at the bottom (in percent, y-axis reversed). Asterisks indicate a significant frequency of frost-damaged earlywood and latewood rings (open and black bars, respectively; also see Table 1).

of cold air drainage is apparent in the stressed, widely spaced, and wind-flagged bristlecone pines (Figure 1). This open tree-line forest of small trees extends 200 to 300 m downhill into the closed canopy conifer woodlands adjacent to or well below the cold air drainage way. The frequency of frost-damaged rings in bristlecone pine within and outside of the cold air drainage path was not quantified, but many specimens from both positions were examined and the trees within the

Table 1. The 14 years with a statistically significant number of earlywood and latewood frost rings are listed in the top row ($p < 0.05$). The other 21 years with possible frost-damaged rings are listed in the bottom row (*i.e.* proportion of damaged rings is not significant).

	Earlywood Frost Injury	Latewood Frost Injury
Significant frost damage	1939, 1946, 1954, 1969, 1974, 1976 1981, 1985, 1989, 2001	1941, 1961, 1965, 1995
Possible frost damage	1930, 1933, 1937, 1940, 1942, 1947, 1962, 1964, 1973, 1975, 2004, 2005	1934, 1935, 1938, 1957, 1977, 1980, 1982, 1982, 1983

drainageway appear to record more frost damage events than trees nearby.

A significant frequency of frost injury was recorded during 14 years from 1930–2010 (Table 1; Figure 3). Ten of the 14 dated and replicated frost rings were restricted to the springwood portion of the growth ring and reflect late-season freeze events during the beginning of the growing season (*i.e.* 1939, 1946, 1954, 1969, 1974, 1976, 1981, 1985, 1989, and 2001). Four frost-ring events were restricted to the latewood and reflect early-season freezes during August or September (*i.e.* 1941, 1961, 1965, and 1995). The latewood frost rings of 1941 and 1965 were previously identified by LaMarche and Hirschboeck (1984) and Brunstein (1996). The fraction of cores exhibiting earlywood frost injury ranged from 16% to 73%, and from 11% to 65% for the cores with significant latewood damage.

Brunstein (1996) also reported the 1965 latewood frost ring in Rocky Mountain bristlecone pines growing on Almagre Mountain (3340–3700 m a.s.l.) in the southern Front Range, Colorado. The 1965 frost damage was found in the latewood of five trees in a total of 47 trees sampled with the 1965 annual ring (11% of relative frequency). The relative low frequency of the 1965 frost-ring in Mt. Goliath could be related to local meteorological conditions or might indicate that most trees had already ceased cambial activity at Mt. Goliath (*ca.* 70 miles (113 km) NW from Almagre Mountain).

Possible frost-damaged rings were identified in 21 additional years from 1930 to 2010 (Table 1; Figure 3). These non-significant frost-ring years might reflect a late-season freeze that occurred while most trees were still dormant, misidentified anatomical damage from another source, or perhaps insufficient sampling of the population of frost-sensitive trees at Mt. Goliath. This large number of possible frost-ring events may reflect both the sensitivity of the sample site to growing-season freeze events and the potential for the reconstruction of a more detailed frost history if the sample of dated and frost-damaged trees can be increased.

The absence of frost injury in some sample trees during years with a significant frequency of frost damage is believed to reflect both microsite differences (that affect the intensity and duration of subfreezing temperatures) and physiological differences among individual trees, which may affect the early initiation or termination of radial growth during the growing season. Younger trees growing near or in cold-air drainageways appear to record the largest number of earlywood frost rings, as has been noted in other frost-vulnerable forests worldwide (*e.g.* Geiger *et al.* 2003). The sample of dated trees is not large enough to test these suspected ecological associations of frost-ring formation, but southern exposures would certainly favor the early initiation of tree growth during warm springs, and trees located on terrain subject to cold-air drainage likely experience the most intense subfreezing temperatures during late-season cold waves.

Daily Temperature Analysis

The daily temperature data for station D-1 from 1952 to 2008 were examined for the growing season (April–October) to identify the exact timing of the severe subfreezing weather responsible for frost damage to the Mt. Goliath bristlecone pine. The minimum temperature data for Niwot Ridge are plotted in Figure 4a from April 1 to July 31 for the eight earlywood frost events (1954, 1969, 1974, 1976, 1981, 1985, 1989, and 2001), and Figure 4b from July 1 to October 31 for the three latewood frost events (1961, 1965, and 1995). In all cases, minimum temperatures fell below –5°C during the probable growing season freezes associated with these 11 frost-ring events. Previous empirical and experimental research has demonstrated that

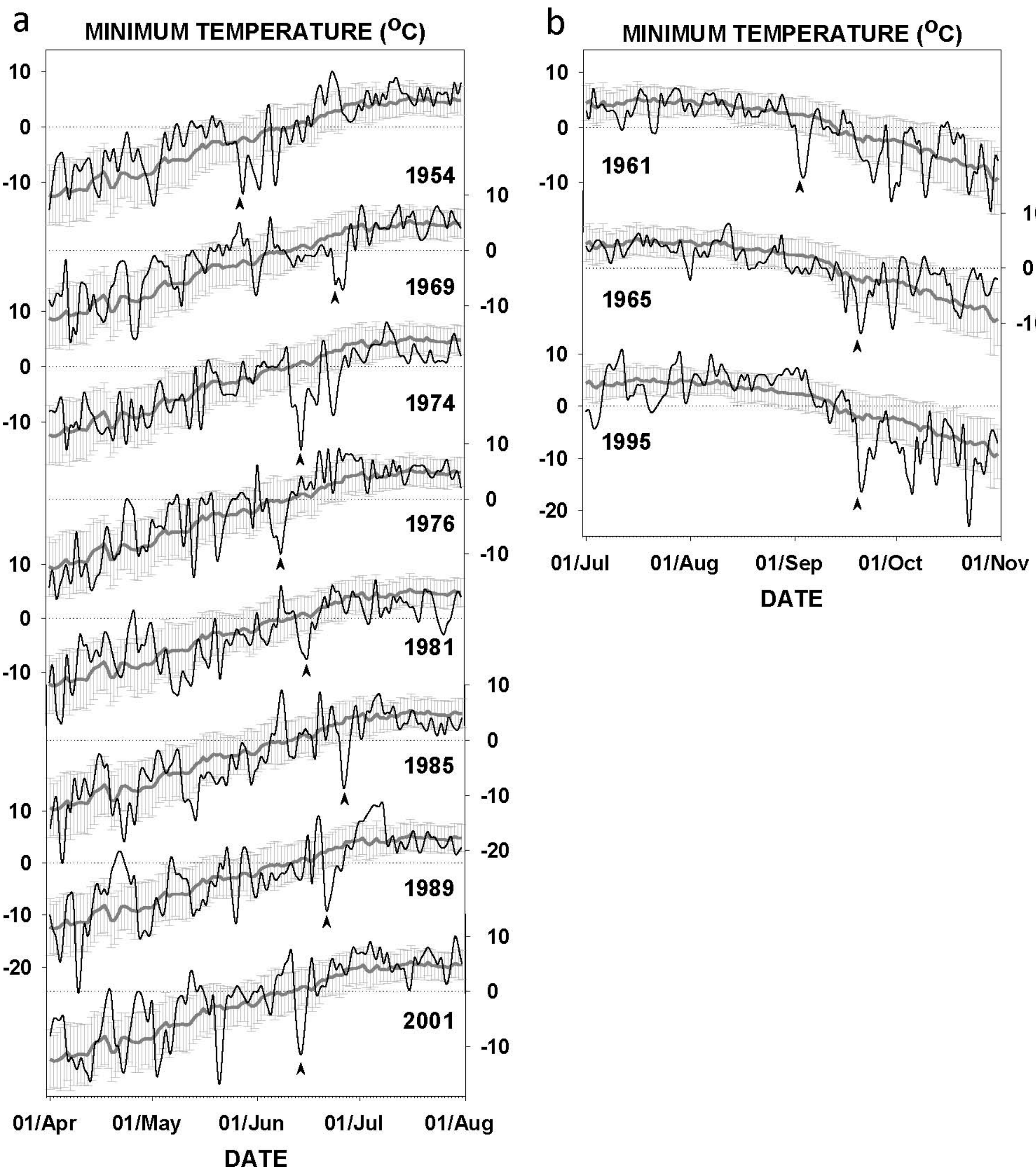

Figure 4. The daily minimum temperature data for Niwot Ridge station D-1 from April 1 to July 31 for the eight years with earlywood frost events (a) and from July 1 to October 31 for the three years with a significant frequency of latewood frost damage (b). The gray line is the average daily minimum temperature computed for the 46 remaining non-frost years from 1952 and 2008. The gray bars indicate one standard deviation from mean minimum for the non-frost years.

temperatures below –5°C during the period of active growth are sufficient to induce traumatic freeze damage in trees, including the unique anatomical features that are characteristic of frost-injured growth rings (Glock and Reed 1940; Glerum and Farrar 1966; Stahle 1990; Figure 2).

Most earlywood frost events contemporaneous with the Niwot Ridge D1 temperature record

Table 2. The probable calendar dates of freeze events for earlywood and latewood at Mt. Goliath, based on an analysis of the Niwot Ridge temperature record at station D1 (available from 1952 to present). The freeze date for 1941 (*) was estimated using regional temperature and circulation data.

Earlywood Frost Injury		Latewood Frost Injury
28 May 1954	15 June 1981	9 September 1941*
26 June 1969	26 June 1985	3 September 1961
6 June 1974	22 June 1989	20 September 1965
14 June 1976	13 June 2001	21 September 1995

occurred in June, except for the 28 May event in 1954 (Table 2). There were three consecutive low temperature episodes in the early growing season of 1954: 28 May (–12°C), 2 June (–11°C), and 6 June (–9°C; Figure 4a). May 28 was likely the day of the frost damage event in 1954 because (1) the presence of a warm spell during the days prior to freezing temperatures, and (2) it was the coldest day registered during a weeklong cold wave. The timing of the other freeze events is less ambiguous (Figure 4a). Latewood frost events (Figure 4b) occur late in the growing season during the month of September (Table 2).

A few other growing-season freeze events were observed at Niwot Ridge but were not associated with frost rings in the sample cores from Mt. Goliath. This lack of frost-ring formation may partly reflect the large variability of daily temperature at Niwot Ridge and/or differences in microclimatology between the ridge top Niwot Ridge temperature station and the Mt. Goliath collection site in a cirque depression. Many of the Niwot Ridge freeze events that did not result in frost-ring damage occurred in early June and late September when the Mt. Goliath trees may have been dormant. Dry conditions might also explain some of these differences because drought can delay or shorten the period of tree growth, thus preventing frost injury (Fritts 1969). The average season of active cambial division at Mt. Goliath is not known, but likely varies by two to three weeks each year because of prevailing temperature and moisture conditions.

To examine the magnitude of the temperature anomalies involved in the formation of latewood and early-season frosts in Mt. Goliath bristlecone pine, the date of the hard freeze (F = 0) was used to sort the daily temperature data before and after the events (Figure 5). The time series plots of mean daily temperatures for all frost and non-frost years with their respective two standard errors were then used to determine if these 11 frost events represent clear departures from the normal seasonal temperatures. In general, significant cold temperatures persisted for only a few days before and after the event (F) for the earlywood frost years, but the cold anomalies related to earlywood and latewood frost events were both extreme and highly significant (Figure 5; Table 3).

The prevailing meteorological conditions prior to the formation of earlywood and latewood frost rings were quite different at Mt. Goliath. Temperatures were not significantly warmer for the period prior to the hard earlywood freeze events. The lack of prolonged antecedent warmth indicates that the earlywood frosts at Mt. Goliath do not represent classic false spring events, but rather highly unusual outbreaks of subfreezing temperatures early in the growing season (*i.e.* "early growing season freeze events"). However, minimum and maximum temperatures were both below-normal on average during the summer prior to the three latewood frost events ($p < 0.01$; Table 3). Note also that earlywood frost events were not a prelude to colder mid-growing season conditions (F + 7 to F + 30, Figure 5a), but the latewood freeze events did initiate at least a month of colder-than-normal temperatures (F + 1 to F + 30, Figure 5b), though the sample only includes three events.

Synoptic Meteorology of Frost Rings in Mt. Goliath Bristlecone Pine

The composite map of 500 mb geopotential heights during the most extreme days of the eight spring freeze events contemporaneous with daily weather observations at Niwot Ridge indicates a wave train of anomalous low and high pressure cells in the mid-tropospheric flow over much of the Northern Hemisphere (Figure 6a). The most extreme feature is the deep trough located over the western United States, which in conjunction with the ridge over the eastern North Pacific, resulted in the advection of an intense pool of cold surface air into the central Rocky Mountains. Surface air temperatures were more than 8°C below average during these eight spring frost events (Figure 6b). The

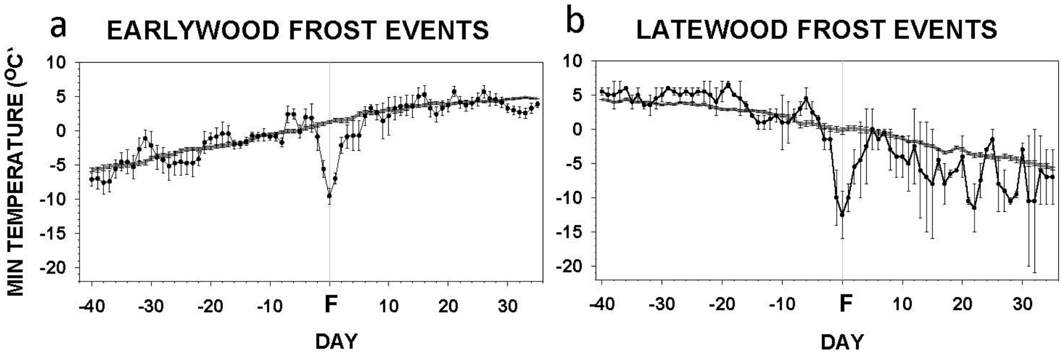

Figure 5. The composite daily average minimum temperature anomalies of eight earlywood (a) and three latewood (b) frost episodes are plotted for 40 days before and 35 days after the hard freeze event [day (F) = 0], along with the average daily temperatures computed from remaining non-frost years between 1952 and 2008. The confidence intervals represent the two standard errors associated with each daily average.

mid-tropospheric geopotential height and surface air temperature anomalies observed on the freeze dates are most likely responsible for all eight earlywood frost rings, which are entirely consistent with the composite maps illustrated in Figure 6a,b. In fact, the deep 500 mb trough and anomalously cold surface air temperatures were present over the central Rocky Mountains in all eight individual events (not shown). The exact Julian date of these consistent local to synoptic-level meteorological conditions associated with earlywood frost rings cannot be determined in the pre-instrumental era, but they are large enough to be useful for comparison with daily meteorological reconstructions using reanalysis techniques during the early growing season (*i.e.* late May–June).

An amplified meridional pattern also developed in the mid-troposphere during the three late-summer frost-ring events (see also Hirschboeck *et al.* 1996), but these September wave trains were located at higher latitude and the most extreme heights were recorded in the strong ridge over the Gulf of Alaska (Figure 7a). This anomalous ridge protruded into western Canada along with a positively tilted trough extending from northern Canada into the central Rockies, causing cold surface air advection into Colorado where temperatures more than 7°C below the 1981–2010 mean were recorded (Figure 7b). Brunstein (1996) noted that the latewood frost events in 1941, 1961, and 1965 occurred not only because of advected cold air, but also because these systems contained enough moisture to produce significant snowfall. Strong radiational cooling in the wake of record early snowfall in 1965 allowed temperatures to fall to as low as –15°C over portions of Colorado (Brunstein 1996). Snow cover may also have amplified the 1995 latewood frost ring event because the weather station at Stapleton Field in Denver (1600 m elevation) recorded 188 mm of snowfall

Table 3. T-tests comparing mean daily maximum and minimum temperatures (°C) of frost and non-frost years for various time intervals before and after the freeze event (F).

	Period	Degrees of Freedom	Frost Years (°C)	Non-frost Years (°C)	T test	P
Earlywood frost	F-28 to F-7, max	8004	5.6	5.7	– 0.221	0.825
	F-28 to F-7, min		– 2.2	– 2.1	– 0.248	0.805
	F-1 to F+8, max	3678	7.2	10.1	– 4.98	<0.001
	F-1 to F+8, min		– 2	1.6	– 7.27	<0.001
Latewood frost	15 Jun–15 Sep, max	4463	10.3	11.6	– 5.356	<0.001
	15 Jun–15 Sep, min		2.8	3.4	– 2.887	0.004
	F-1 to F+8, max	1378	1.4	7.2	– 6.430	<0.001
	F-1 to F+8, min		– 5.0	– 0.8	– 5.282	<0.001

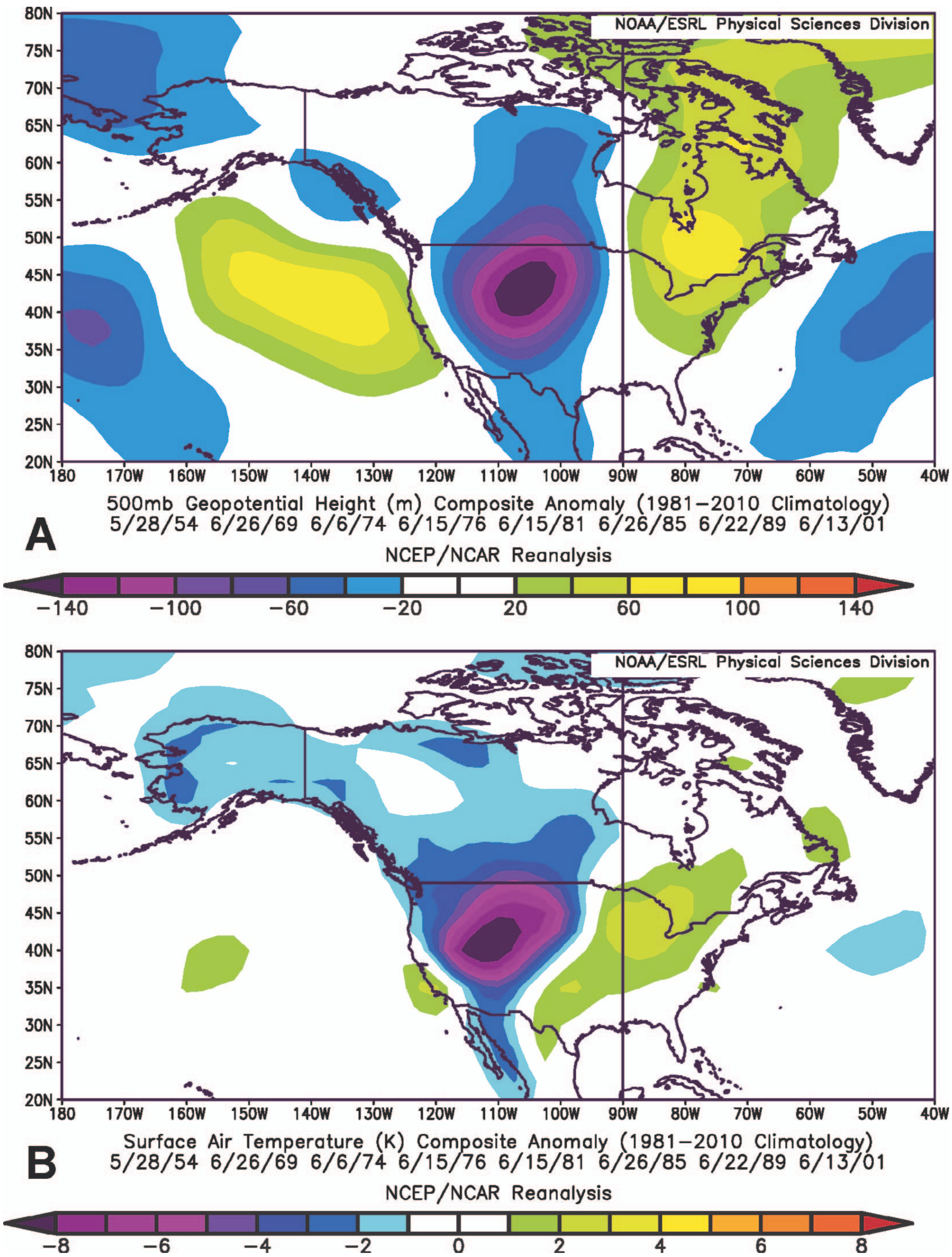

Figure 6. Composite 500mb geopotential height (a) and surface temperature anomaly fields (b) observed during the eight earlywood frost-ring dates identified in Table 2 (*i.e.* 1954, 1969, 1974, 1976, 1981, 1985, 1989, and 2001; climate normal period = 1981–2010). Note (a) the meridional circulation pattern over the mid-latitude Northern Hemisphere, the deep upper-level low-pressure cell over the central Rocky Mountains, and (b) the anomalously cold surface temperatures typical of earlywood frost ring events. The NCEP-NCAR reanalysis data (Kalnay *et al.* 1996) were accessed and plotted at: http://www.esrl.noaa.gov/psd/data/composites/day/.

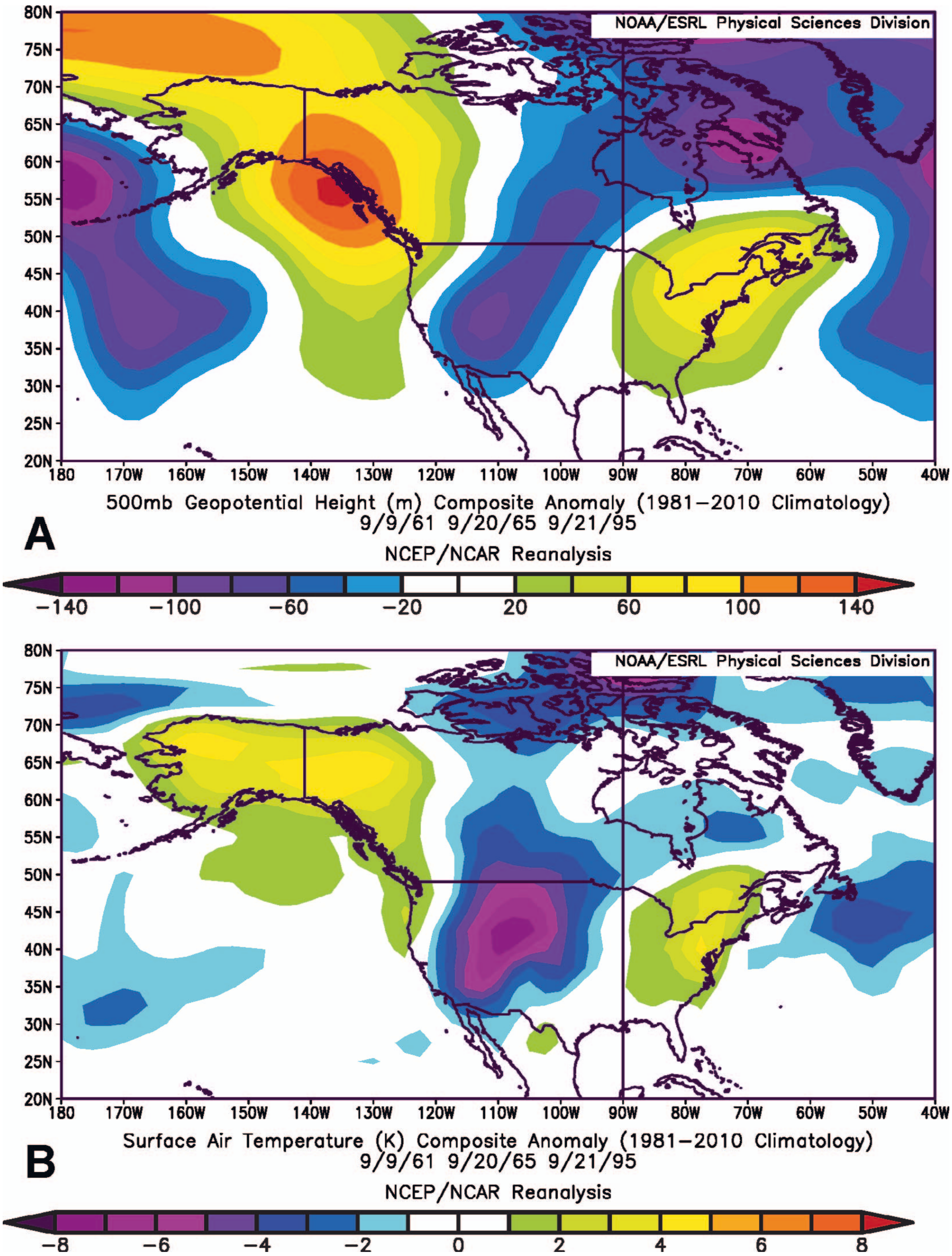

Figure 7. Same as Figure 6 for three latewood frost ring events (1961, 1965, and 1995; Table 2). Anomalous meridional flow in the mid-troposphere over the Northern Hemisphere was associated with both the early and late season frost rings (Figures 6a and 7a), and unseasonably cold surface air temperatures over the Rocky Mountains (Figures 6b and 7b).

from 20–21 September 1995, during the postulated freeze event at the Mt. Goliath tree-ring collection site.

CONCLUSIONS

The high frequency of frost-damaged tree rings in the cold air drainageway at Mt. Goliath, Colorado, indicates that this tree-line cirque valley may be one of the most frost-susceptible forest locations yet reported. Site selection is a key principle of dendroclimatology, and it may be equally important to the development of frost-ring chronologies of past freeze events on dendrometeorological time scales. It should be possible to select bristlecone pine or other high elevation conifers at tree line adjacent to cirque valleys and other cold air drainageways for the development of more detailed and more robust frost-ring chronologies of growing season freeze events. The absolute elevation of tree line has changed in response to Holocene temperature changes over western North America (Salzer *et al.* 2009), and there does appear to be an age effect on frost-ring registration. Young and vigorous bristlecone seem to be more susceptible than senescent individuals. But if age-stratified core sampling of bristlecone pine can be conducted at the most frost sensitive locations, as those tree-line positions have changed elevation over time, then it may be possible to develop robust millennium-long frost-ring chronologies. Salzer *et al.* (2009, 2014) designed this tree-line tracking strategy to sample the most temperature-sensitive trees and to compile what may be the most accurate annually resolved temperature estimate yet reported for the western United States. Future comparisons of the continuous summer mean temperature estimates based on absolute tree-line ring-width records with well-replicated event chronologies of frost rings could provide interesting insight into the possible relationships between low-frequency temperature changes and severe freeze events during the growing season.

The frequency of frost-damaged trees in a given year appears to be roughly proportional to the severity (*e.g.* 2001) and/or timing (*e.g.* 1981) of the growing season freeze event. Frost rings are more common in earlywood than in latewood for our collections from Mt. Goliath, and the earlywood events are not strongly related to the late-winter warming typical of false spring. There was a 500 mb ridge over the western United States with warm air advection about one week prior to most spring freeze events (Barbosa 2010, not shown), but it was weak. Consequently, the earlywood frosts may primarily represent unusual outbreaks of severe subfreezing temperatures early in the growing season (spring). In contrast, episodes of below-average summer temperatures were observed during the three latewood frost-ring events at Mt. Goliath and may have delayed the onset and termination of radial growth in high-elevation bristlecone pine, rendering the trees vulnerable to frost damage during late-summer or early-fall outbreaks of cold air, in a kind of "false summer" that might be inversely analogous to false spring. Of course a substantially larger sample size of latewood frost ring events would be required to test these hypotheses.

Earlywood and latewood frost rings in bristlecone pine at Mt. Goliath are formed during highly amplified mid- to high-latitude atmospheric circulation regimes that result in the large-scale advection of cold air masses into the west-central United States. These surface and mid-tropospheric meteorological anomalies were observed during every earlywood and latewood frost ring event registered during the instrumental era. When more long and robust frost-ring chronologies are developed from the most frost-susceptible forest locations, the suite of anomalous atmospheric conditions may also be inferred for frost-ring events in the pre-instrumental era. Such chronologies should be able to add discrete daily-timescale meteorological extremes to the high-quality summer mean temperature inferences already available from continuous chronologies of annual ring width.

DATA AVAILABILITY

The frost-ring data and the daily temperature measurements used in this analysis from Station D-1 at Niwot Ridge are all available from the authors and the International Paleo-Freeze Data Bank at the NOAA Paleoclimatology Program: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data.

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