RECONSTRUCTING SUMMER UPPER-LEVEL FLOW IN THE NORTHERN ROCKY MOUNTAINS USING AN ALPINE LARCH (*LARIX LYALLII*) TREE-RING CHRONOLOGY

A Thesis
by
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Abstract

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Mid-latitude mesoscale weather in the climatological summer is heavily influenced by fluctuations in synoptic-scale circulation patterns. Previous research has linked Arctic amplification to alterations in summer synoptic climatology, leading to more extreme weather events in the mid-latitudes. In this study we reconstruct seasonal (JJA) upper-level (500 hPa) atmospheric flow for four geographic locations in the mid-latitudes using an alpine larch (*Larix lyallii* Parl.) tree-ring chronology derived from the Bitterroot wilderness of western Montana. Our goal is to assess the long-term (400+ year) stability of upper-level flow to place the observed trends in a historical context. We found significant relationships between alpine larch tree growth and upper-level flow patterns derived from the North American Regional Reanalysis Dataset during (1979–2015). Spatial pattern correlations indicate that tree growth increases when meridional flow and zonal flow are strong west (r = 0.504, p = 0.001, n = 37) and north (r = 0.642, p < 0.001, n = 37) of the study site, respectively. Tree growth declines when meridional flow and zonal flow are strong east (r = -0.497, p = 0.001, n = 37) and south (r = -0.584, p < 0.001, n = 37) of the study site, respectively.

Using the leave-one-out method, we calibrated and verified our linear regression models between upper-level flow and tree growth. Our 444-year climate reconstructions of 500 hPa flow show that ridging is becoming more intense in recent decades while troughs are declining in intensity.

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To my brother Elliot and my sisters Morgan and Urooj, although they are geographically separated, our long talks on the phone make me feel otherwise. Their ongoing support and encouragement, unbeknownst to them at times, has been paramount in my success as a student. I would specifically like to thank Elliot and Urooj for their willingness to edit papers, discuss future plans, and share pertinent life advice.

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Pete during my time at Appalachian State University. He has always been encouraging and constructive with my research, and therefore I could not have asked for a better advisor.

As an undergraduate student I also had the unique opportunity to be involved with Andean precipitation research with Dr. Baker Perry. This research allowed me to travel to the tropical Andes of Peru and Bolivia three times to study precipitation-glacier interactions. We traveled to over 6,400 meters, camped on glaciers, and interacted with local communities for weeks at a time. I admire Dr. Perry's dedication to his research and hope that I bring the same enthusiasm to my future work. I'd like to thank Dr. Perry for his guidance and advice in the context of research and life in general. I would also like to thank Baker and his family for providing me housing accommodations over the last year.

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Foreword

The main body of this thesis is formatted to the guidelines for manuscript submission to the *Professional Geographer*, an official journal of the American Association of Geographers.

Introduction

Mid-latitude summer synoptic climatology holds major implications for global populations because-synoptic scale circulation influences fluctuations in mesoscale meteorology. While this relationship has been established for decades, recent findings that link Arctic Amplification (AA) to alternations in summer synoptic climatology has spurred a new wave of research that aims to understand these changes in upper-level atmospheric flow (Francis and Vavrus 2012; Screen and Simmonds 2013; Wu and Smith 2016; Vavrus et al. 2017; Francis 2018; Trouet, Babst, and Meko 2018). Francis and Vavrus (2012) found that zonal flow is become weaker while meridional flow is becoming more elongated over time.

Other researchers argue the relationship between AA and extreme weather events in the mid latitudes is a result of artifacts in the methodologies rather than physical changes in upper-level flow (Barnes 2013; Barnes and Screen 2015). There is an ongoing debate in the academic literature surrounding AA and the role it plays in changes in summer synoptic climatology and extreme weather events. The two major datasets used to inform these conclusions, at maximum, have a temporal resolution of 70 years.

Associated with shifts in upper-level zonal and meridional flow are threats to public health and to the built environment through increases in extreme weather events. Weakening of zonal flow in conjunction with the elongation of meridional flow slows the progression of weather events in the mid-latitudes, leading to longer-lasting weather events, specifically heat- related events. Cvijanovic et al. (2017) and Vavrus et al. (2017) found evidence that changes in upper-level flow, in association with AA, are leading to increases in drought frequency, while Knapp and Soulé (2017) find evidence that these changes are leading to increases in wildfire activity. Whatever the resulting extreme weather may be, it has the ability to affect millions of people living in dense population centers in the mid-latitudes.

In the summer of 2015, as a second-year student at Appalachian State University, I was asked to accompany Dr. Soulé and a team of researchers to western Montana, USA to collect alpine larch samples. As an undergraduate student I had the opportunity to process the raw data into a standardized tree-ring chronology. This dataset has since been incorporated into my master's thesis research. Using KNMI Climate Explorer (Trouet and Van Oldenborgh 2013), a web-based spatial correlation tool, I found interesting spatial relationships between alpine larch tree growth in the northern Rocky Mountains and upper-level atmospheric flow using the NCEP/NCAR Reanalysis Dataset (Kalnay et al. 1996). Our preliminary analyses revealed that when meridional and zonal flow were strong to the west (east) and north (south) of the study site, respectively, there was a positive (negative) relationship to tree growth. The positive (negative) spatial patterns indicate a ridging (troughing) pattern over the study site which allows warm (cold) air to occupy the region leading to increased (decreased) tree growth. These preliminary spatial relationships indicated that alpine larch are a sensitive proxy to upper-level zonal and meridional flow and could be used to reconstruct climate.

Using the leave-one-out linear regression model, in conjunction with verification and diagnostic statistics, we reconstructed summer (JJA) upper-level flow (500 hPa) for four different locations in the United States using the North American Regional Renalysis dataset (Mesinger et al. 2006). In order to understand how upper-level atmospheric flow has changed over time, we conducted Rodionov regime shift tests and coefficient of verification statistics. Lastly, we used the reconstructed record, in association with the 120-year instrumental record to verify the relationship between ridging and troughing, and extreme weather events.

The following manuscript aims to contribute 400+ years of reconstructed upper-level flow data to the AA discussion in order to place current observations into a historical context. The goal of this research is to demonstrate how upper-level zonal and meridional wind spatially relate to radial tree growth at high elevations in the northern Rockies, use a multi-century record of standardized radial tree growth to reconstruct winds at 500 hPa over western North America, and assess how upper-level flow has fluctuated over space and time.

Reconstructing Summer Upper-Level Flow in the Northern Rocky Mountains Using an Alpine Larch (*Larix Lyallii*) Tree-Ring Chronology

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Abstract

Mid-latitude mesoscale weather in the climatological summer is heavily influenced by fluctuations in synoptic-scale circulation patterns. Previous research has linked Arctic amplification to alterations in summer synoptic climatology, leading to more extreme weather events in the mid-latitudes. In this study we reconstruct seasonal (JJA) upper-level (500 hPa) atmospheric flow for four geographic locations in the mid-latitudes using an alpine larch (*Larix lyallii* Parl.) tree-ring chronology derived from the Bitterroot wilderness of western Montana. Our goal is to assess the long-term (400+ year) stability of upper-level flow to place the observed trends in a historical context. We found significant relationships between alpine larch tree growth and upper-level flow patterns derived from the North American Regional Reanalysis Dataset during (1979–2015). Spatial pattern correlations indicate that tree growth increases when meridional flow and zonal flow are strong west (r = 0.504, p = 0.001, n = 37) and north (r = 0.642, p < 0.001, n = 37) of the study site, respectively. Tree growth declines when meridional flow and zonal flow are strong east (r = -0.497, p = 0.001, n = 37) and south (r = -0.584, p < 0.001, n = 37) of the study site, respectively. Using the leave-one-out method, we calibrated and verified our linear regression models between upper-level flow and tree growth. Our 444-year climate reconstructions of 500 hPa flow show that ridging is becoming more intense in recent decades while troughs are declining in intensity.

Introduction

Variability in synoptic-scale circulation plays an important role in modulating mesoscale meteorology during the climatological summer in the mid-latitudes, as the strength and amplitude of meridional and zonal flow largely dictate surface weather conditions. Several studies (Porter, Cassano, and Serreze 2012; Francis and Vavrus 2012; Screen and Simmonds 2013; Wu and Smith 2016; Vavrus et al. 2017; Francis 2017) have documented changes in upper-level atmospheric flow as a result of Arctic amplification (AA), defined as the uneven heating of the high northern latitudes compared to the rest of the northern hemisphere (Francis and Vavrus 2012). Francis and Vavrus (2012) suggest that modified upper-level flow resulting from AA will lead to more extreme weather events in the mid-latitudes, specifically heat-related extremes. These atypical and extreme events carry negative implications for the built and natural environment, and have the potential to affect millions of people living in the mid-latitudes through the increased frequency of drought (Cvijanovic et al. 2017; Vavrus et al. 2017), heat waves (Meehl and Tebaldi 2004; Vavrus et al. 2017; Tang, Zhang, and Francis 2014), forest fires (Knapp and Soulé 2017), and flooding (Francis and Vavrus 2012). It is important to understand the temporal trends in upper-level flow to place the current observations in a historical context and to better prepare for changes in mid-latitude synoptic-scale summer synoptic climatology. Here we: (1) demonstrate how upper-level zonal and meridional wind spatially relate to radial tree growth at high elevations in the northern Rockies, (2) use a multi-century record of standardized radial tree growth to reconstruct winds at 500 hPa over western North America, and (3) assess how upper-level flow has fluctuated spatiotemporally.

The northern Rocky Mountains are a topographically diverse mountain range that encompass western Montana, a small portion of eastern Washington, and north-central Idaho (USDI 2017). The region contains peaks over 3,600 m, lending itself to microclimates that support species with limited geographical ranges. Here we use an alpine larch (*Larix lyallii* Parl.) tree-ring chronology, collected in 2015 in the Selway Bitterroot National Forest (BNF), to reconstruct summer (JJA) upper-level (500 hPa) atmospheric flow. Alpine larch (AL) is a deciduous conifer native to timberline zones of the northern Rocky Mountains (specific geographic range, specific elevation range) and northern Cascade Mountains (specific geographic range, specific elevation range), and responds positively to summer temperature (Arno and Habeck 1972; Graumlich and Brubaker 1986; Peterson and Peterson 1994; Kipfmueller 2008). AL are predominantly found on cold, rocky sites with northern aspects and rarely occupy southern aspects. AL actively grow when temperatures are consistently above 5.6ºC, which is approximately a 90-day growing season (Arno and Habeck 1972). Moisture is not a limiting factor in the growth of these trees as they are often found growing in cool, moist, and acidic soils (Arno and Habeck 1972).

AL are a long-lived species with early research suggesting an average lifespan of 500 years and many individuals reaching 700 years of age (Arno and Habeck 1972). Based on crossdated samples, Colenutt and Luckman (1995) concluded the mean age of trees growing at six sites in the southern Canadian Rocky Mountains was approximately 350 years old, with the oldest tree being 639 years old. In the northern Rockies of Montana, Kipfmueller (2008) found alpine larch trees dating back to AD12, and successfully crossdated samples (EPS > 0.85; Wigley, Briffa, and Jones 1984) over 1,950 years old for use in a summer temperature reconstruction. Thus, AL can provide a useful proxy measurement of climatic conditions for multiple centuries.

Screen and Simmonds (2010) documented AA and found that the Arctic has warmed twice as fast as the mid-latitudes and tropics. This has led to a decline of September Arctic sea-ice extent of 8% per decade since 1980 and has led to a 17.8% reduction of snow-cover extent in the Northern Hemisphere per decade since 1979 (Tang, Zhang, and Francis 2014). Consequently, several studies have suggested reduce sea-ice extent has altered summer synoptic circulation patterns that are causing longer lasting, more extreme weather events in the mid-latitudes including a wavier jet stream flow (Screen and Simmonds 2014; Tang, Zhang, and Francis 2014).

While numerous studies have assessed the temporal attributes of upper-level atmospheric flow, the majority are limited in temporal resolution. The current breadth of research surrounding AA and the role it plays in mid-latitude summer synoptic climatology relies heavily on the ERA-Interim Re-Analysis dataset (1979-present) and the NCEP/NCAR dataset (1948-present). Francis and Vavrus (2012) used the NCEP/NCAR reanalysis dataset to study the relationships between AA and the polar front jet stream and the associated climatic conditions in the mid-latitudes. As a result of AA they found: 1) 1000-500 hPa thickness is reduced, and 2) 500 hPa ridge peaks are becoming elongated. The implications of a reduction in 1000-500 hPa thickness is weaker zonal flow and therefore a slower progression of weather events. A more elongated ridge further amplifies the slower progression of weather events (Cohen et al. 2014). Screen and Simmonds (2014) and Tang, Zhang, and Francis (2014), who use the ERA-Interim analysis dataset in their analysis, support the claim that AA has led to the slower progression of weather patterns, leading to observed weather extremes in the mid-latitudes.

Although AA has been linked to increases in more frequent severe weather events in the mid-latitudes, this area of research continues to be highly contested. For example, Barnes and Screen (2015) provides evidence that a weakening and elongation of meridional flow is an artifact of the methodologies rather than true changes in mid–latitude summer synoptic climatology. These findings are corroborated by Barnes (2013). Using the NCEP/NCAR dataset (1948-2012) and the ERA-Interim Re-Analysis dataset (1980-2012), Barnes (2013) found no significant increase in the amount of blocking events within the instrumental record in relationship to AA. Synoptic blocking is associated with extreme weather events in the mid-latitudes. If the frequency of blocking events were increasing because of AA, there would be a greater likelihood of extreme weather events in the mid-latitudes.

Tree-ring data has been used successfully to reconstruct jet stream flow in the Northern Hemisphere. Trouet, Babst, and Meko (2018) reconstruct latitudinal positioning of the North Atlantic Jet to AD 1725 in Europe using two tree-ring records; one from the British Isles and other from the northeast Mediterranean. They found significant anomalous changes in the latitudinal positioning of the North Atlantic Jet that lead to heatwaves, droughts, and increased wildfire activity in Europe. Wise and Dannenberg (2014) reconstructed cool-season pressure patterns over North America using a network of tree-ring chronologies and found pronounced periods of persistent cool-season pressure patterns resulting in historic drought and pluvial periods. Others (e.g., Nichols, Kelly, and Andrews 1978; Casty et al. 2005; Wise and Dannenburg 2017) have reconstructed aspects of synoptic climatology in relation to fluctuations in upper-level flow in the mid-latitudes, but we find that a temporally robust record of upper-level flow for the North American mid-latitudes is still lacking. With the current breadth of literature not reaching a consensus regarding the relationship between AA and summer synoptic climatology, our study provides a historical perspective of upper-level (500 hPa) atmospheric flow in North America, specifically western United States and southeastern Canada.

Methods

a. Study Area

We collected alpine larch samples from four study site locations (Carlton Ridge, McCalla Lake, Sapphire Ridge, and Trapper Peak) in the BNF in western Montana (Figure 1). Elevation at the study sites ranged from 2,400 to 2,800 meters. Arno and Habeck (1972) note that 2,300 meters represents the lower threshold for AL growth in the SBW, indicating that some of our sampling locations were at the lower limits of AL habitat. In the BNF temperatures range from -6.4ºC in January to 16.3°C in July (National Climatic Data Center 2016). Average precipitation for the region is 9.7 cm annually (National Climatic Data Center 2016).

b. *Field Sampling*

At each of the four study sites, we extracted a minimum of two core samples per tree using a 5.15 mm diameter increment borer from a minimum of 30 trees chosen via selective sampling. We sampled at breast height and perpendicular to the downward slope to avoid ring pinching. We avoided sampling trees with visible damage (e.g., bore damage, lightning scars, fire scars) and trees growing within a closed canopy (i.e., overlapping limbs).

c. *Laboratory and Statistical Procedures*

Cores were glued onto wooden mounts and sanded using progressively finer grit (100-400 um) to reveal cellular structure. We examined all cores using a microscope and assigned an individual calendar year for each annual ring on each sample, a process known as crossdating (Stokes 1996). Using WINDENDO (Regent Instruments, Inc. 2011), we measured the width of each ring to 0.001 mm precision. Crossdating accuracy was confirmed using the program COFECHA (Holmes 1983; Grissino-Mayer 2001) and date adjustments (i.e., addressing missing rings) were made to cores that were flagged to correct errors. We standardized all cores from our four study locations (CRL, n = 57; MCL, n = 21; SRL n = 30, and TPL, n = 41; total = 149 cores) using the program WINARSTAN (Cook 1985). Based on previous findings by Montpellier et al. (2018), we developed a standardized chronology (COMBO) using negative exponential detrending methods to achieve the greatest climate signaling. COMBO had an interseries correlation of 0.619, mean sensitivity of 0.311, and an expressed population signal (EPS) of >0.85 (Wigley, Briffa, and Jones 1984) during AD 1590–2015.

Using KNMI Climate Explorer (Trouet and Van Oldenborgh 2013; https://climexp.knmi.nl), a web-based spatial correlation tool, we identified significant spatial patterns between summer (JJA) zonal and meridional flow indices at 500 hPa from the NCEP/NCAR Reanalysis 1 dataset (Kalnay et al. 1996) and standardized radial tree growth (COMBO) in the BNF (Figure 2). The significance, direction, and location of these relationships suggested that the alpine larch tree-ring record might provide a sensitive proxy record of upper-level flow.

Next, we used 500 hPa zonal and meridional wind values (ms^{-1}) from the North American Regional Reanalysis (NARR) dataset (Mesinger et al. 2006). The NARR are high-resolution gridded data (32km) dating back to 1979. We used WINARSTAN and negative exponential curves to individually standardize the 149 core samples in the COMBO chronology and then assessed the relationship between each core and NARR zonal and meridional flow during June, July, August and mean summer flow (JJA) using Pearson correlation. As the strongest relationships were between tree growth and JJA upper-level flow, we used JJA for a more focused analysis using a subset of core samples (n = 37) that provided strong relationships with both zonal and meridional wind values. This chronology (hereafter BEST) had an interseries correlation of 0.689, mean sensitivity of 0.314, and an expressed population signal (EPS) of >0.85 (Wigley, Briffa, and Jones 1984) during AD 1571-2015.

We used Pearson correlation to examine the relationships between 500 hPa zonal flow and 500 hPa meridional flow and tree growth (BEST) at 378 grid point locations between 25° and 65°N and 90° and 140°W. As we identified using COMBO, core areas of negative and positive relationships exist with zonal and meridional flow. From within these core areas, we selected four grid points that had the strongest relationship with tree growth and used the flow indices from these grid points as our dependent variables for climatic reconstructions of upper-level flow. Because the NARR data set is limited in temporal resolution (n = 37 years), we verified the regression models using the leave-one-out (L1O) method. We calculated the reduction in error statistic (RE), the coefficient of efficiency (CE) statistic, the root mean square error (RMSE), as well as the Pearson correlation values between instrumental upper-level flow and modeled upper-level flow (Fritts 1976; Cook 1994).

To assess the temporal stability of upper-level atmospheric flow, we used a Rodionov regime shift (Rodionov 2004; Rodionov and Overland 2005) with a ten-year cut off length to detect significant ($p<0.05$; >2 standard deviations) shifts in the reconstructed upper-level atmospheric flow. According to Rodionov (2004), a shorter cut-off length is more restrictive and requires greater fluctuations in the dataset to produce a statistically significant 'shift'.

We assessed the variability of the reconstructed data by calculating the coefficient of variation (CV) for each decade in the reconstructed period. To do this we calculated standard deviation and mean for each decade in the reconstructed period, working backwards from 2015 (i.e., 2015-2006; 2005-1996, etc…). We then plotted each decadal CV value to compare them temporally. In the NARR dataset, meridional flow from south to north is recorded as a negative value, north to south is positive. As values for the WEST gridpoint were both positive and negative and the values for the EAST gridpoint were all negative, we added a 10 ms^{-1} constant to the 500 hPa windflow values to ensure that all values were above zero prior to calculating CV for these gridpoints.

Results and Discussion

Spatial pattern correlations indicate that tree growth increases when meridional flow and zonal flow are strong west and north of the study site, respectively. The positive correlation patterns are indicative of a ridging pattern that promotes warmer temperatures in the BNF and results in enhanced growth for alpine larch. When meridional and zonal flow are strong east and south of the study site, respectively, negative correlations are present. This trough pattern allows colder air from Canada to occupy the region and results in reduced radial growth for alpine larch (Figure 3).

The four locations that we used for the upper-level atmospheric flow climate reconstructions had strong relationships to tree growth in the BNF (NORTH: $r = 0.642$, $p < 0.001$, $n = 37$; SOUTH: $r = -0.584$, $p < 0.001$, $n = 37$; EAST: $r = -0.497$, $p = 0.001$, $n = 37$; WEST: $r = 0.504$, $p = 0.001$, $n = 37$; Figure 3). Positive RE and CE values, in association with the RMSE values being within one standard deviation of the sample mean, confirm the validity of the four climate reconstructions (Table 1; Fritts, 1976). Pearson correlation values indicate the instrumental record is closely associated with the values produced by the L1O and full linear regression models (Table 1).

The four, 444-year (1571–2015) upper-level atmospheric flow climate reconstructions, in association with the Rodionov regime shifts, indicate that upper-level flow in western North America has fluctuated over time, yet we conclude that conditions observed within the instrumental record are not unprecedented during the reconstructed record (Figure 4; Figure 5). These findings are similar to al. Trouet, Babst, and Meko (2018), who found that the current latitudinal positioning of the North Atlantic Jet falls within the range of preceding years.

The Rodionov regime shifts indicate that current upper-level flow to the north and west of the study site is intensifying, and has been since the late 1990s, signifying an increase in ridging (Figure 4; Figure 5). With an increase in the frequency of ridging since the late 1990s, we observe a decrease in upper-level flow to the south and east of the study site, demonstrating a decrease in troughing. The Rodionov regime shifts between the four climate reconstructions share similar attributes throughout the reconstructed record (Figure 5). We recognize that the four reconstructions are statistically constrained because they were developed from the same tree-ring chronology. Except for WEST not experiencing a regime shift in 1945, and NORTH not experiencing a regime shift in 1640, all other regime shifts occur on the same calendar year, although the magnitude of the shifts vary.

Zonal flow north and south of the study site exhibit an inverse relationship; as upper-level flow increases (decreases) in strength north of the study location, upper-level flow to the south is weakened (strengthened). The same pattern exists when meridional flow to the east and west of the study site are compared; as upper-level flow increases (decreases) in strength east of the study location, upper-level flow to the west is weakened (strengthened).

Decadal CV analysis of the four climate reconstructions reveal a decrease in the variance of upper-level flow since the late 1980s (Figure 6). Although we reached an EPS of 0.85 in 1570, high variance in the early period of the climate reconstructions is likely associated with the smaller sample size of core samples and should be interpreted cautiously. Decreases in variance, in conjunction with the previous findings that indicate increased ridging around the BNF, suggest that summertime upper-level ridging is becoming a more dominant and consistent pattern in western North America compared to troughing events.

Numerous studies have linked the presence of ridging to extreme weather events in the mid-latitudes (Meehl and Tebaldi 2004; Francis and Vavrus 2012; Tang, Zhang, and Francis 2014; Trouet, Babst, and Meko 2018). Although the scope of our study does not evaluate the latitudinal positioning of upper-level flow, our findings are concurrent with that of Meehl and Tebaldi (2004) who indicate that 500 hPa ridging is becoming more frequent, and resulting in longer lasting, more extreme heat waves. Knapp and Soulé (2017) link reductions in Arctic sea-ice extent (ASIE) to increased ridging in summertime in the western United States and that have caused warmer drier conditions promoting increases in wildfire activity and this trend should continue if ASIE remains continues to decline.

We postulate that with decreased variability in upper-level flow in conjunction with increased intensity of ridging, the mid-latitudes of western North America will experience more extreme heat-related weather events. We corroborated these findings by evaluating the relationship between our climate reconstructions and climatic variables from Montana Climate Division 1, within which all four-study sites are located. Over the 120-year instrumental record, the relationships between upper-level flow and surface climatic conditions are significant and have a logical direction (Table 2). For example, positive values from NORTH and WEST are indicative of enhanced summertime ridging, leading to warmer temperatures, reduced precipitation, and drought conditions that, in turn, are conducive for enhanced wildfire activity.

The reconstructed upper-level flow patterns also are logical in the context of individual years and longer time periods with significant climate anomalies. For example, the summer of 1993 was the coldest summer on record in Montana Climate Division 1 (National Climatic Data Center 2016). From summer 1992 to 1993 there was a dramatic switch from ridging to troughing in upper-level flow (Figure 7a). This troughing pattern during 1993 lead to anomalously low mean, maximum, and minimum temperatures and above normal precipitation and PDSI values. The troughing pattern that contributed rain and cool conditions to the region resulted in zero acres burned in 1993 (i.e., no fires were recorded in Montana or Idaho during the summer of 1993).

In the summer of 1961, Montana experienced anomalous ridging that generated record-breaking warm temperatures and below normal precipitation totals for the region (National Climatic Data Center 2016). The anomalous ridging of 1961 was concurrent with high summer mean, maximum and minimum temperatures and low precipitation leading to drought conditions (Figure 7a-g).

The 1930s were an abnormally dry period for western Montana. Mean August PDSI values for Montana Climate Division 1 in the 1930s were -2.74, and all years from 1928–1940 recorded drought conditions (Figure 7d). Concurrent with the extended drought, our reconstructions of JJA 500 hPa suggest this period was dominated by ridging, as both NORTH and WEST recorded above average upper-level flow values for each year of the 1930s and SOUTH and EAST were below average, suggesting an extended period of summertime ridging was concurrent with the 1930s drought.

The summer of 1910 in the western United States was marked by below-average precipitation (Figure 7a-g) in association with an early snowmelt (Chapman 1910; Egan 2009). Chapman (1910) notes that conditions that were typical in late September (e.g., forests and grass lands were dry) were present in early August. These conditions, in association with strong winds, lead to what is commonly referred to as “The Big Burn”, two-day period in August 1910 when approximately 1.2 million hectares burned in northeast Washington, northern Idaho, and western Montana, resulting in one of the largest forest fires in United States history (United States Forest Service https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/s telprdb5444731.pdf; Egan 2009). The instrumental record (Figure 7b-g) confirms Chapman’s observations of low precipitation and high drought index. Concurrent with below-average precipitation, drought conditions (August PDSI values of -2.7) and increased surface winds, enhanced ridging contributed to the Big Burn of 1910 in the western United States. Our upper-level climate reconstruction suggests a ridging pattern in the summer of 1910 was present (Figure 7a-g). While the ridging observed in 1910 was not of the same magnitude as that observed in 1961, extreme weather events in 1910 resulted in more damage to the built environment and high loss of human life (Egan 2009).

Our reconstructions are logical in context of the latter stages of the Little Ice Age. Mann (2002) found that North America experienced its coldest temperatures of the little ice age during the 19th century. Approximately two thirds of the years in the 19th century record are below-average flow in NORTH and WEST and above average flow in SOUTH and EAST in our upper-level reconstructions (Figure 4), suggesting enhanced troughing conditions that would co-occur with colder summer conditions in western North America.

Conclusion

Observed shifts in upper-level flow are occurring in the summer due to reductions in the cryosphere, which leads to extreme weather events such as heat waves and droughts (Meehl and Tebaldi 2004; Tang, Zhang, and Francis 2014; Cvijanovic et al. 2017; Vavrus and Wang 2017). In this study we investigated a spatial relationship between alpine larch tree growth in the BNF and upper-level (500 hPa) zonal and meridional flow. We found zonal flow north (south) and meridional flow west (east) of our tree-ring study sites positively (negatively) impacts radial tree growth, as these conditions are conducive to upper-level ridging (troughing) which leads to above (below) average temperatures. Given the strength of these relationships, we were able to successfully reconstruct upper-level flow for four geographic areas in western North America beginning in AD 1571. We found that ridging has increased since the 1990s. While these increases are not unprecedented over the 444-year period of our climate reconstruction, we found the variance in upper-level flow is decreasing, suggesting that shifts between ridging and troughing patterns are becoming less common over western North America during the summer months. We compared the reconstructed record to historical years in western Montana and found that years of extreme ridging correspond to years of increased temperatures, drought, and wildfire activity, and decreased precipitation. Vavrus et al. (2017) predict that increased ridging over North America will persist into AD 2100, with the greatest increases between 40° and 45° N, which is near the latitude of our study sites. If ridging continues to increase, in conjunction with reduced variance of ridging and troughing, we postulate that heat-related extreme weather events will continue to become more common, with concomitant consequences for humans through stressors placed on agricultural practices, increased occurrence of wildfires, and threats to water resources.

References

Arno, S. F., and J.R. Habeck. 1972. Ecology of alpine larch (*Larix lyallii* Parl.) in the Pacific Northwest. *Ecological Monographs* 42:17-450.

Barnes, E. A. 2013. Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes. *Geophysical Research Letters 40*(17):4734-4739.

Barnes, E. A., and J.A. Screen. 2015. The impact of Arctic warming on the mid-latitude jet-stream: Can it? Has it? Will it? *Wiley Interdisciplinary Reviews: Climate Change 6*(3): 277-286.

Casty, C., D. Handorf, C. C. Raible, J. F. González-Rouco, A. Weisheimer, E. Xoplaki, J. Luterbacher, K. Dethloff, and H. Wanner. 2005. Recurrent climate winter regimes in reconstructed and modelled 500 hPa geopotential height fields over the North Atlantic/European sector 1659–1990. *Climate Dynamics 24*(7-8):809-822.

Chapman, H. H. 1910. "Fires on the Flathead Forest in Montana." American Forestry, vol. 16 (November 1910): 657-658.

Cohen, J., J. A. Screen, J. C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, and J. Jones. 2014. Recent Arctic amplification and extreme mid-latitude weather. *Nature geoscience 7*(9):627.

Colenutt, M. E. and B. H. Luckman. 1995. The dendrochronological characteristics of alpine larch. *Canadian Journal of Forest Research 25*(5):777-789.

Cook, E. R. 1985: *A time series analysis approach to tree-ring standardization.* Master's thesis, University of Arizona.

Cvijanovic, I., B. D. Santer, C. Bonfils, D. D. Lucas, J. C. Chiang, and S. Zimmerman. 2017. Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall. *Nature communications 8*(1):1947.

Egan, T. 2009. *The big burn: Teddy Roosevelt and the fire that saved America*. Houghton Mifflin Harcourt.

Francis, J. A., and S. J. Vavrus. 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters 39*(6).

Francis, J. A. 2018. Why Are Arctic Linkages to Extreme Weather Still up in the Air?. *Bulletin of the American Meteorological Society 98*(12):2551-2557.

Fritts, H. 1976. Tree rings and climate London. *Ace demle Press*.

Graumlich, L. J., and L. B. Brubaker. 1986. Reconstruction of allual temperatures (1590-1979) for Longmire Washington, derived from tree rings. *Quaternary Research* 25:223-234.

Grissino-Mayer, H. D. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-ring research*.

Holmes, R. L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-ring bulletin*.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, and Y. Zhu. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American meteorological Society 77*(3):437-471.

Kipfmueller, K. F., 2008. Reconstructed summer temperature in the northern Rocky Mountain wilderness, USA. *Quaternary Science* 70:173-187.

Knapp, P. A., and P. T. Soulé. 2017. Spatio-Temporal Linkages between Declining Arctic Sea-Ice Extent and Increasing Wildfire Activity in the Western United States. *Forests 8*(9): 313.

Mann, M. E., 2002. Little ice age. *Encyclopedia of global environmental change 1*:504-509.

Meehl, G. A., and C. Tebaldi. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science 305*(5686):994-997.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E. H. Berbery, and M. B. Ek. 2006. North American regional reanalysis. *Bulletin of the American Meteorological Society 87*(3):343-360.

Montpellier, E. E., P. T. Soulé, P. A. Knapp, and J. S. Shelly. 2018. Divergent growth rates of alpine larch trees (*Larix lyallii* Parl) in response to microenvironmental variability. *Arctic, anarctic and Alpine Research 50(1)*

National Climatic Data Center. 2016. U.S. National/State/Divisional Data. http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp.

Nichols, H., P. M. Kelly, and J. T. Andrews. 1978. Holocene palaeo-wind evidence from palynology in Baffin Island. *Nature 273*(5658):140.

Peterson, D. W., and D. L. Peterson. 1994. Effects of climate on radial growth of subalpine conifers in the Northern Cascade Mountains. *Canadian Journal of Forest Research,* 24: 1921-1932.

Porter, D. F., J. J. Cassano, and M. C. Serreze. 2012. Local and large-scale atmospheric responses to reduced Arctic sea ice and ocean warming in the WRF model. Geophysical Research Letters 117:D11115.

Regent Instruments Canada, Inc. 2011. WINDENDRO for Tree-ring Analysis.

Rodionov, S. N., 2004. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters 31*(9).

Rodionov, S. N., and J. E. Overland. 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. *ICES Journal of Marine Science* 62(3):328—332.

Screen, J. A. and I. Simmonds. 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature 464*(7293):1334.

Screen, J. A. and I. Simmonds. 2013. Exploring links between Arctic amplification and mid-latitude weather. *Geophysical Research Letters 40*(5):959-964.

Screen, J. A. and I. Simmonds. 2014. Amplified mid-latitude planetary waves favour particular regional weather extremes. *Nature Climate Change 4*(8):704-709.

Stokes, M. A. 1996. *An introduction to tree-ring dating*. University of Arizona Press.

Tang, Q., X. Zhang, and J. A. Francis. 2014. Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. *Nature Climate Change 4*(1):45-50.

Trouet, V., and G. J. Van Oldenborgh. 2013. KNMI Climate Explorer: a web-based research tool for high-resolution paleoclimatology. *Tree-Ring Research 69*(1):3-13.

Trouet, V., F. Babst, and M. Meko. 2018. Recent enhanced high-summer North Atlantic Jet variability emerges from three-century context. *Nature communications 9*(1)180.

United States Department of the Interior (USDI). 2017. *Rocky Mountain Delineation.* https://www.nature.nps.gov/geology/education/concepts/concepts_rockies.cfm--rocky mountain delineation

United States Forest Service. The Great Fire of 1910. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5444731.pdf

Vavrus, S. J., F. Wang, J. E. Martin, J. A. Francis, Y. Peings, and J. Cattiaux. 2017. Changes in North American atmospheric circulation and extreme weather: Influence of Arctic amplification and Northern Hemisphere snow cover. *Journal of Climate 30*(11)4317-4333.

Wigley, T. M. L., K. R. Briffa, and P. D. Jones. 1984. On the average of correlated time series, with applications in dendroclimatology and hydrometeorology. *American MeteorologicalSociety* 23:201-213.

Wise, E. K. and M. P. Dannenberg. 2014. Persistence of pressure patterns over North America and the North Pacific since AD 1500. *Nature communications 5*:4912.

Wise, E. K. and M. P. Dannenberg. 2017. Reconstructed storm tracks reveal three centuries of changing moisture delivery to North America. *Science advances 3*(6)1602263.

Wu, Y. and K. L. Smith. 2016. Response of Northern Hemisphere midlatitude circulation to Arctic amplification in a simple atmospheric general circulation model. *Journal of Climate 29*(6):2041-2058.

Table 1 Verification statistics for the leave one out and full regression models used to reconstruct upper-level (500 hPa) atmospheric flow.

Statistic	NORTH	EAST	SOUTH	WEST
RE (L1O)	0.668	0.849	0.744	0.825
RE (Full)	0.587	0.753	0.624	0.746
RMSE (L1O)	1.600	1.114	1.405	1.631
RMSE (Full)	1.536	1.211	1.226	1.876
Coefficient of Efficiency	0.411	0.247	0.341	0.254
Standard Deviation (Actual)	1.614	1.395	1.510	2.171
r-value (Full/L1O)	0.995**	0.986**	0.994**	0.995**
r-value (Actual/Full)	0.641**	0.497**	0.584**	0.504**
r-value (Actual/L1O)	0.578**	0.395*	0.510**	0.425**

Table 2 Relationship (Pearson) between reconstructed upper-level (500 hPa) flow and climate variables derived from Montana Climate Division 1 (Temperature PDSI, and Precipitation; 1895-2015) and the United States Geological Survey (Wildfire; 1985-2015). One asterisk is significant at the 0.05 level while two asterisks indicate significance at the 0.01 level.

	NORTH/WEST	**SOUTH/EAST**
Mean Temperature (JJA)	.495**	-.495**
Maximum Temperature (JJA)	.529**	-.529**
Minimum Temperature (June)	.326**	-.326**
Precipitation (JJA)	-.411**	.411**
PDSI (August)	-.488**	.488**
Hectares Burned (August)	.425*	-.425*

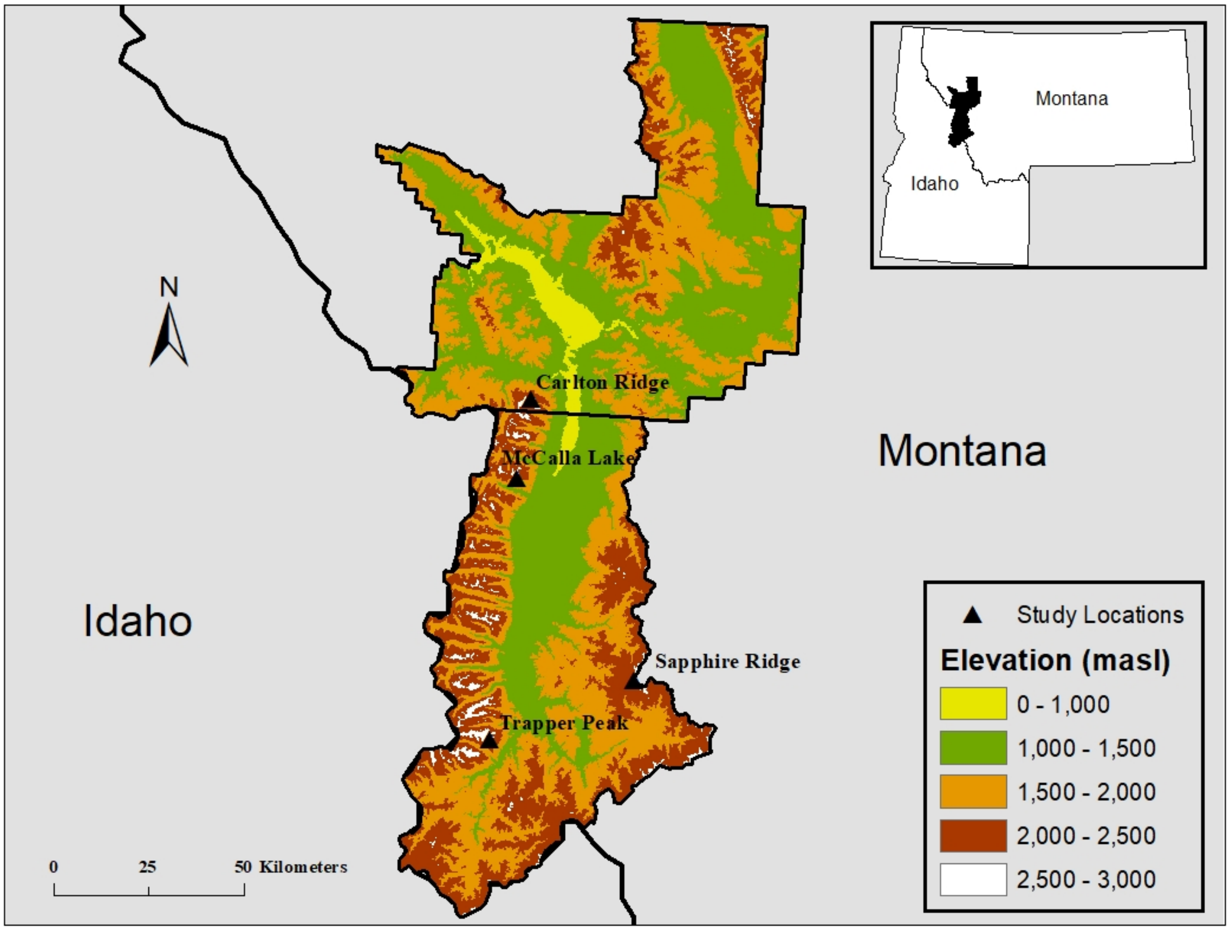

Figure 1 Study sites in the Bitterroot National Forest of western Montana, USA. The boundaries of Missoula (north) and Ravalli (south) counties are shown.

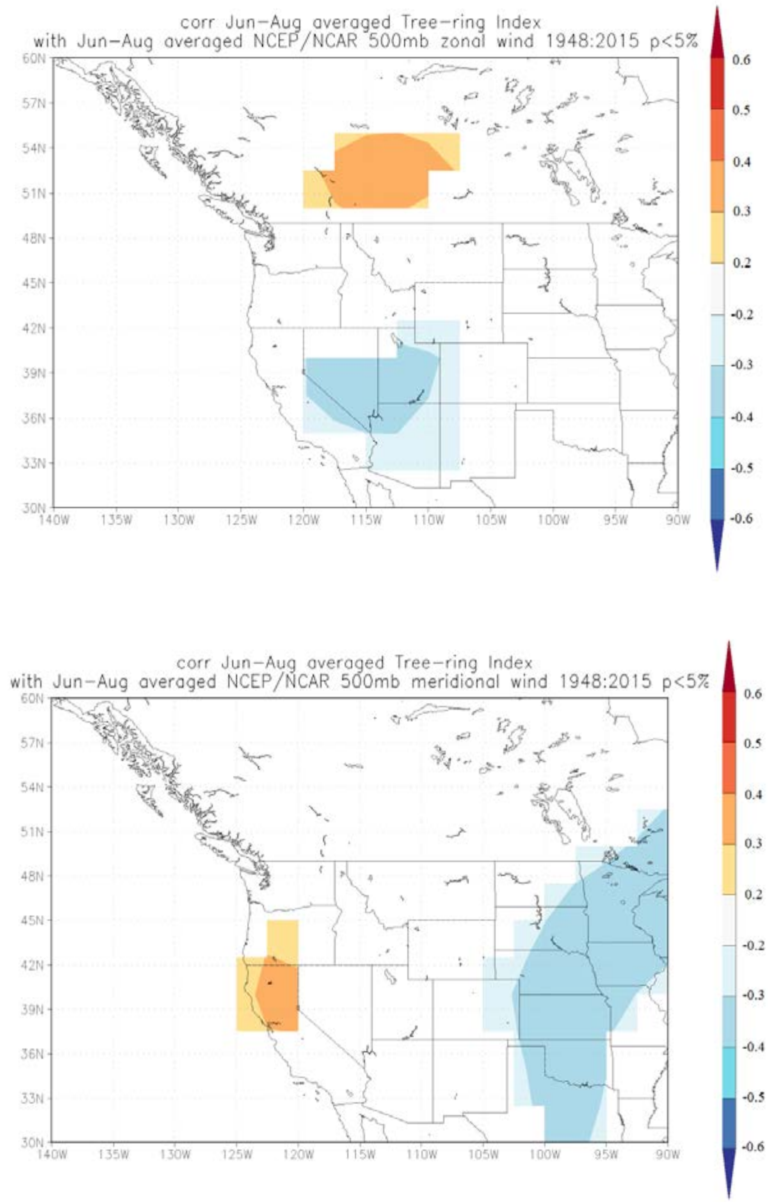

Figure 2 Significant ($p < 0.05$) spatial pattern correlations between the COMBO tree-ring chronology and a. zonal wind (500 hPa) and b. meridional wind (500 hPa) from the NCEP/NCAR Reanalysis 1 dataset (1948-2015).

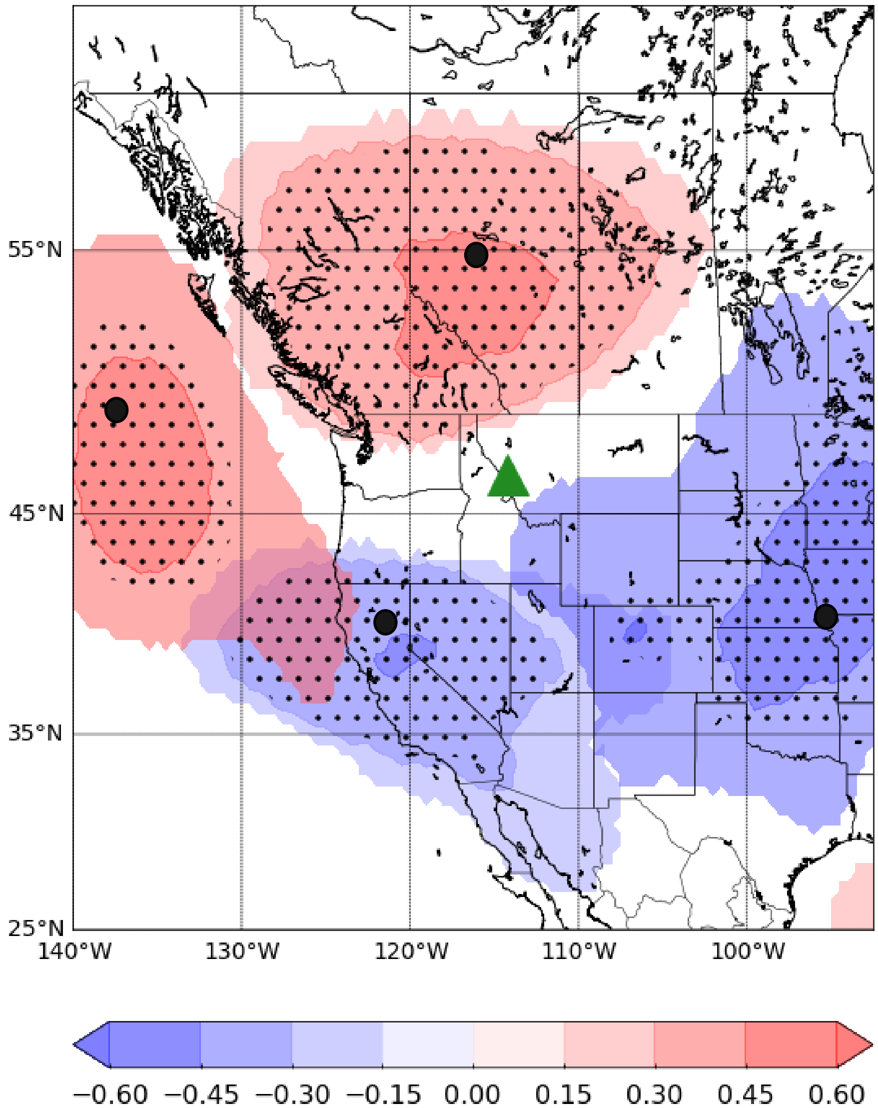

Figure 3 Spatial relationship (Pearson) between the BEST tree-ring chronology and upper-level (500 hPa) zonal and meridional flow from the North American Regional Reanalysis dataset (1979-2015). Colors indicate r values and black gridpoints indicate significance (p= 0.01). Large black dots indicate the four locations of our climate reconstruction.

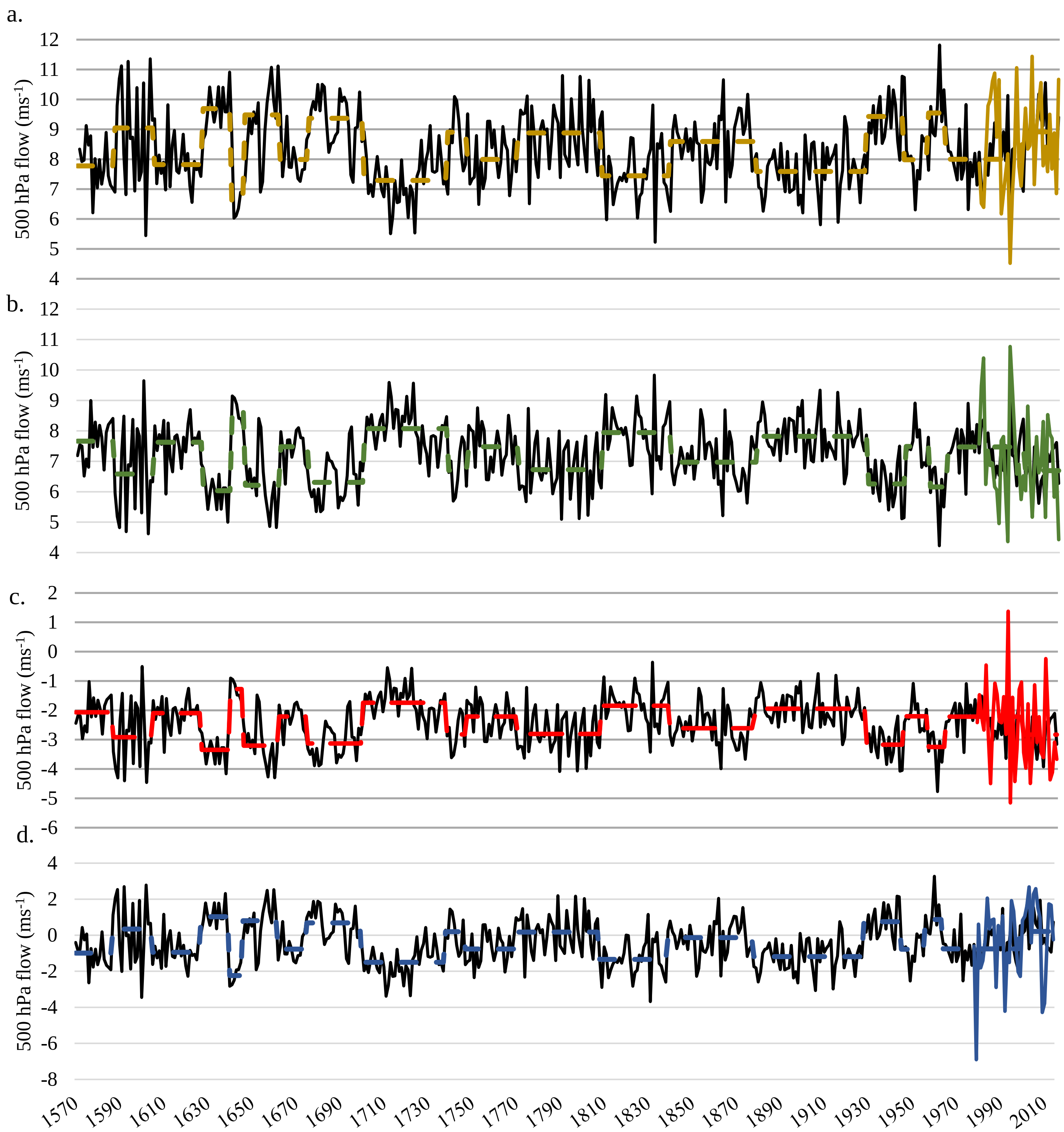

Figure 4 Climate reconstructions (solid black lines) of upper-level (500 hPa) atmospheric flow from 1571 to 2015 using the BEST tree-ring chronology for the four cardinal (a. north, b, south, c. east, and d. west) gridpoints having the strongest relationship between standardized radial tree growth and 500 hPa flow in the instrumental record (1979-2015). Solid color lines depict the actual 500 hPa flow and the dashed lines identify significant ($p < 0.05$) regime shifts in the 500 hPa flow using the Rodionov regime shift test.

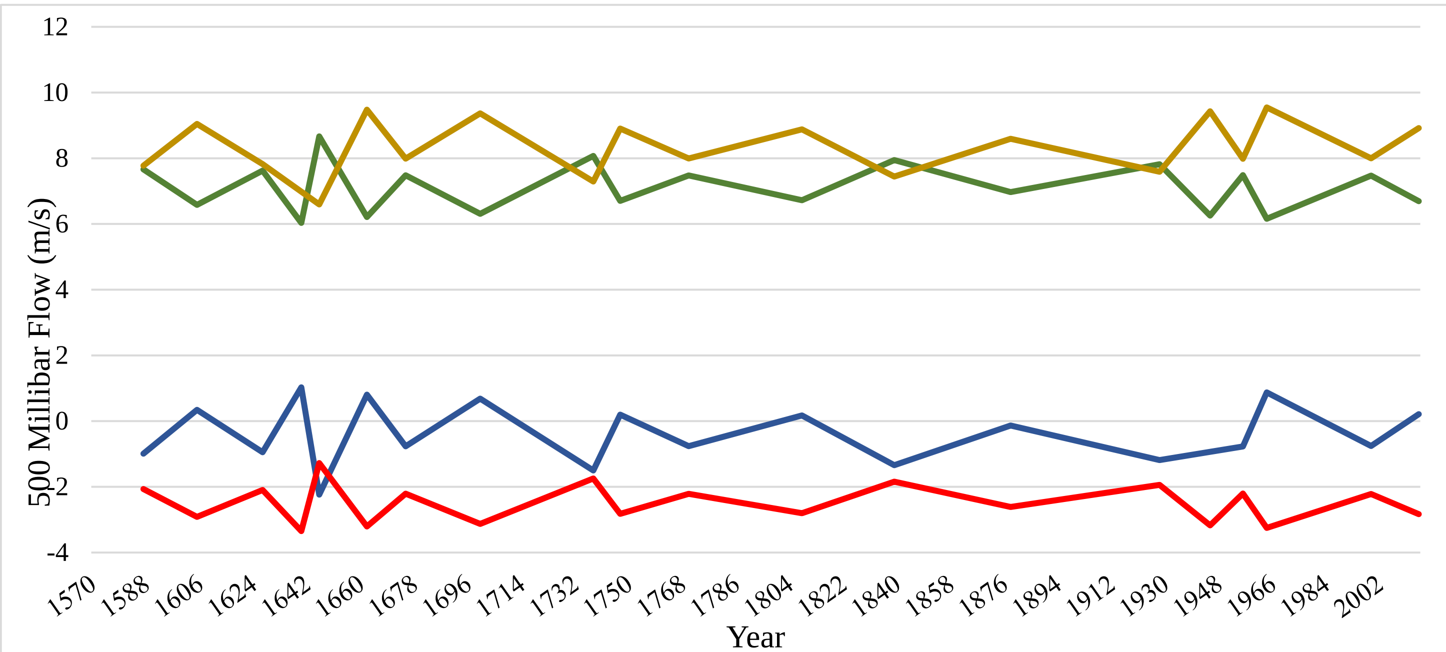

Figure 5 North (gold), south (green), east (red), and west (blue) Rodionov regime shifts from the upper-level (500 hPa) climate reconstructions. The slope of the lines was generated by connecting the mean values of the identified regimes.

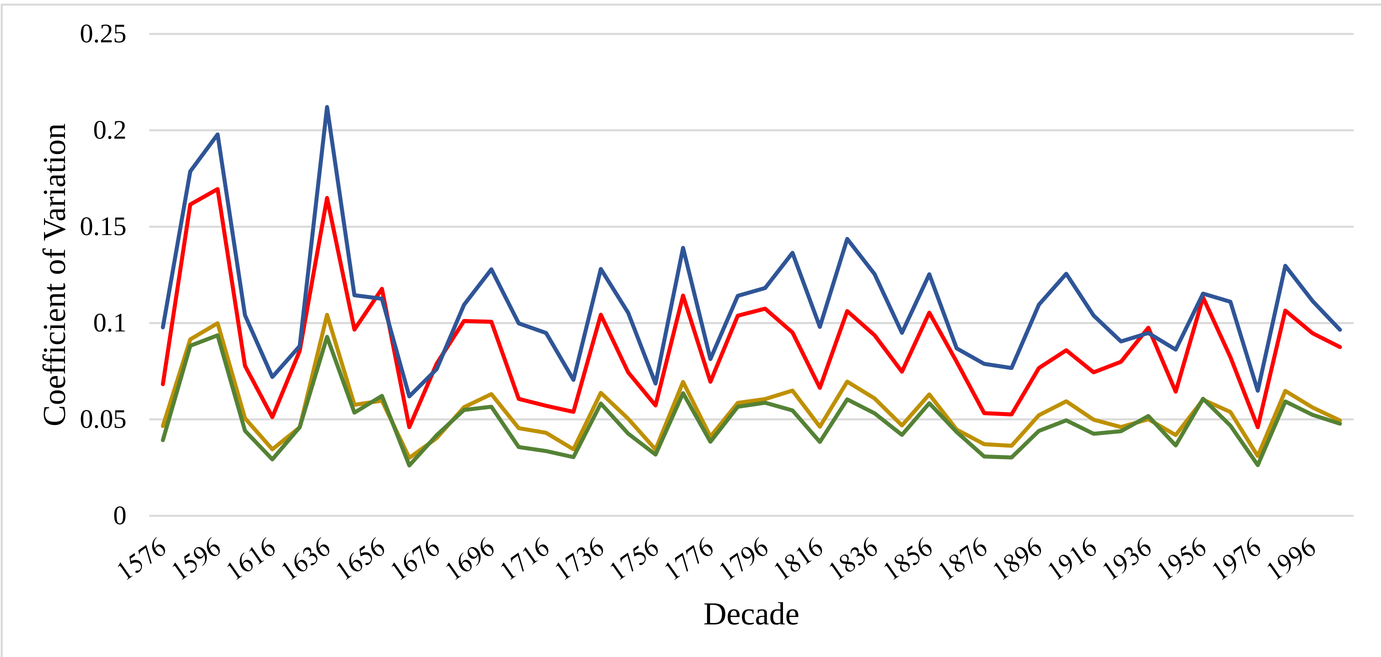

Figure 6 North (gold), south (green), east (red), and west (blue) decadal coefficient of variation (CoV) variables from the upper-level (500 hPa) climate reconstructions. CoV values were determined by calculating mean and standard deviation per decade working backwards (e.g., 2015-2006, 2005-1996, etc.).

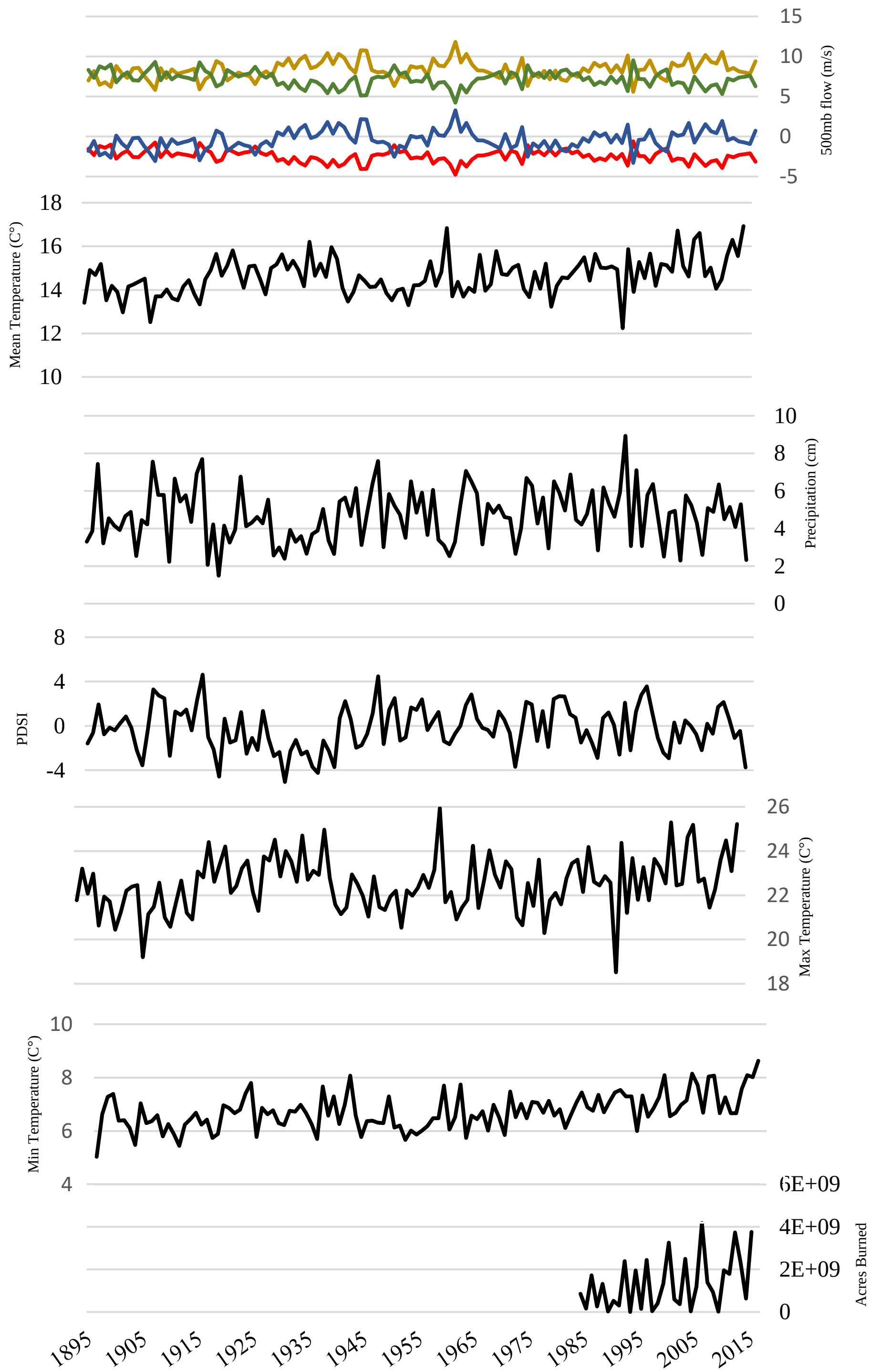

Figure 7 Temporal pattern (1895-2015) of a. north (gold), south (green), east (red), and west (blue) climate reconstruction, b. Montana Climate Division 1 mean temperature (JJA), c. Montana Climate Division 1 precipitation (JJA), d. Montana Climate Division 1 Palmer Drought Severity Index (August), e. Montana Climate Division 1 maximum temperature (JJA), f. Montana Climate Division 1 minimum temperature (June), and g. Montana and Idaho hectares burned (August).

Vita

Evan Emmerson Montpellier was born in St. Catharines, Ontario, but at the age of two moved to Greensboro, North Carolina, after his parents were relocated for work. Evan was raised in a home that encouraged him to spend his days outside exploring the neighborhood forests. His young inventive mind transformed the backyard forest into an expansive world and his first laboratory. As he grew older, he sought greater adventure and the ability to push his intellectual boundaries. The Boy Scouts of America offered a place where he could expand his view of the natural world through continued experiential learning. In 2011, Evan received his Eagle Scout award and upon graduation from Lucy Ragsdale High School in 2013, chose to attend Appalachian State University. Evan was not immediately introduced to geography upon arrival at Appalachian State, but after taking a survey course in the department, he knew that he had found the right field of study. Many aspects of geography struck a chord with his childhood self. During his senior year at Appalachian State, Evan enrolled in the accelerated admissions program. He graduated with honors in Geography in May of 2016. In 2017, Evan started graduate research under the guidance of Dr. Peter Soulé.

Upon graduation with a M.A. from Appalachian State University in May 2018, Evan plans to continue working with trees as an arborist in Boone, NC or Philadelphia, PA. During this time Evan hopes to apply to Ph.D. programs and other jobs in the field of Geography.