Clim. Past Discuss., https://doi.org/10.5194/cp-2017-107
Manuscript under review for journal Clim. Past
Discussion started: 29 September 2017

Drought and vegetation change in the central Rocky Mountains: Potential climatic mechanisms associated with the mega drought at 4200 cal yr BP.

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Abstract. Droughts are a naturally re-occurring phenomena that result in economic and societal losses. Yet, the most historic droughts that occurred in the 1930s and 1950s in the Great Plains and western United States were both shorter in duration, and less severe than mega droughts that have plagued the region in the past. Roughly 4200 years ago, a ~150-year long mega drought occurred in the central Rocky Mountains, as indicated by pollen evidence from lake sediments from Long Lake, south-eastern Wyoming. However, pollen evidence does not record the climate mechanisms that caused the drought; they only provide evidence that the drought occurred. A modern climate analogue technique using North American Regional Reanalysis data was applied to the sedimentary data in order to identify possible synoptic and dynamic patterns that may have caused the mega drought at 4200 cal yr BP. Our results demonstrate the warm and dry conditions were a result of anomalously higher-than-normal geopotential heights that were centred over the Great Plains beginning in spring and persisting until the fall. Drought conditions during the growing seasons was the result of the anomalous high-pressure ridge, which suppressed moisture transport via the low level jet from the Gulf of Mexico, as well as brought in dry continental air from in the interior region of North America. Conditions associated with the mega drought likely led to the changes in vegetation composition as evidenced by the pollen record.

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1 Introduction

Throughout the 20th century, droughts have caused both economic and societal losses throughout the Great Plains and the western United States (US) (Diaz, 1983; Karl and Koscielny, 1982; Karl, 1983; Woodhouse and Overpeck, 1998). However, these most recent droughts were both shorter in duration, and less severe than mega droughts that have plagued the region in the past (Woodhouse and Overpeck, 1998). Unfortunately, because of the rise in globally averaged land and ocean temperatures, changes in the hydrological cycle and moisture availability have occurred in these regions (IPCC, 2014). Subsequently, drought vulnerability has increased in both the Great Plains and western US (Garfin et al., 2013). In the North Platte River drainage basin (our area of interest for this study), there has been a 1.44ºC increase in temperature since 1916, leading to the earlier onset of spring snowmelt by approximately 11 days (Shinker et al, 2010). Global climate change is projected to yield continued changes in moisture availability, and the frequency and/or intensity of drought (Breshears et al., 2005; Cayan et al., 2010; Seager et al., 2007; Sterl et al., 2008). Such changes in the hydrological cycle have the potential to influence hydrologic systems, ecosystem processes, and vegetation distribution in the future.

Unfortunately, changes in vegetation distribution are already occurring. Allen et al. (2010) documented widespread global forest mortality since 1970 as a result of water and/or heat stress. In western North America, mortality has increased among certain quaking aspen (*Populus tremuloides* Michx.) communities as a result of drought and increased temperatures (Anderegg et al., 2013a; 2013b; Hanna and Kulakowski, 2012; Hogg et al., 2008; Kashian et al., 2007; Rehfeldt et al., 2009; Worrall et al., 2008; 2010; 2013). Quaking aspen is the most widely distributed deciduous tree species in North American, and is considered a keystone species in the Intermountain West region (Kay, 1997; Little, 1971; Perala, 1990). While the recent decline of quaking aspen appears to be influenced by increased temperatures, the relationship between climate variability and quaking aspen mortality remains poorly understood prior to the 20th century (Anderegg et al., 2013b; Hanna and Kulakowski, 2012; Worrall et al., 2010). However, Carter et al. (2013) documented a unique change in vegetation composition ~4000 cal yr BP from sedimentary proxy evidence from Long Lake, south-eastern Wyoming in the North Platte River drainage basin. Proxy evidence from Long Lake documents a change from a pine-dominated forest to a mixed-pine-quaking aspen forest, which the authors have coined as the '*Populus* period.' Subsequently, Carter et al. (2017) investigated the role that climate variability and wildfire activity had on the persistence of quaking aspen during the *Populus* period, and determined that increased temperatures associated with a mega drought centred on 4200 cal yr BP (Booth et al., 2005) likely influenced the upslope migration of quaking aspen stands in the Medicine Bow Range of south-eastern Wyoming.

While sedimentary proxy data provide a record of past mega droughts, they do not provide a record of the climatic mechanisms that caused such extreme events. Therefore, understanding modern climate mechanisms and processes that cause drought conditions, and the sensitivity and range of ecological responses to drought are fundamental to ecosystem management (Mock and Shinker, 2013). Improving our understanding of the climate processes associated with modern drought will provide better insight about past drought variability, and the mechanisms that caused mega droughts evident in paleoecological records. A better understanding about drought and ecological responses, especially in regions with high topographic and climatic variability is important information that can be applied to land managers (Shinker et al., 2006). One tool we use can use to understand the climate processes associated with drought is the modern climate analogue technique (Mock and Shinker, 2013), which relies on the principle of uniformitarianism and assumes that modern synoptic and dynamic climate processes operated similarly in the past as they do today. The modern climate analogue technique is an effective way to identify climate mechanisms associated with past environmental changes (e.g. as seen in reconstructed sedimentary pollen analyses) (Edwards et al., 2001; Mock and Brunelle-Daines, 1999; Shinker et al., 2006; Shinker, 2014). A modern climate analogue is simply a conceptual model that uses modern extremes (e.g. drought) as analogs of past events (e.g. vegetation disturbance associated with drought in the palaeo-sedimentary record) as a means to understand palaeoclimate patterns that may have caused extremes in the past (Diaz and Andrews, 1982; Ely, 1997; Edwards et al., 2001; Shinker, 2014). Such conceptual models of dynamic processes can provide examples of modern climatic mechanisms in order to explain historic palaeoclimate variability (Mock and Bartlein, 1995; Mock and Brunelle-Daines, 1999; Mock and Shinker, 2013; Shinker et al. 2006).

The purpose of this study was to apply a modern climate analogy technique to a palaeoecological reconstruction from Long Lake, Wyoming using an environment-to-circulation approach (Barry and Carleton, 2001; Mock and Shinker, 2013; Shinker, 2014; Yarnal, 1993; Yarnal et al., 2001), which considers the surface conditions based on information gained from the proxy data collected from lake sediments (Carter et al., 2013). By identifying extremes (i.e. anomalously dry) in the modern record, the environment-to-circulation approach will help identify dominant synoptic processes that may have created the persistent mega drought centred on 4200 cal yr BP. This paper focuses on the relationship between atmospheric and surface climate mechanisms, and synoptic processes, and their influence on the ecological changes recorded during the *Populus* period identified by Carter et al., (2013).

2 Study area

Long Lake (41° 30.099′ N, 106° 22.087′ W; 2700 m a.s.l.) is located within the North Platte River watershed in the Medicine Bow Range of south-eastern Wyoming (Figure 1). The lake lies within a closed drainage basin behind a Pinedale-aged terminal moraine with no inlets or outlets (Atwood, 1937). The study site experiences a snow-dominated winter precipitation with a spring precipitation maximum (Mock, 1996; Shinker, 2010). Interpolated January and July precipitation and temperatures from the nearest weather station suggests an average of 330 and 690 mm, and -9.7°C and 11°C, respectively (NRCS, unpublished data). Using the modern pollen analogue technique, Carter et al. (2017) reconstructed both the mean temperature of the coldest month (MTCO) (i.e, January), and mean temperature of the warmest month (MTWA) (i.e., July) which average -9°C and 15°C over the past ~2000 years. Carter et al., (2017) also reconstructed annual precipitation, which averages ~443 ± 39 mm over the past 2000 years. Both the modern and reconstructed climate from the area highlights that the Medicine Bow Range receives a high degree of precipitation variability. Additionally, the Medicine Bow Range are located within the region that currently does not experience seasonal precipitation patterns associated with ENSO phases (Wise, 2010; Heyer et al., 2017).

Modern vegetation at the study site is comprised mostly of lodgepole pine (*Pinus contorta*), with Engelmann spruce (*Picea englemanni*) and subalpine fir (*Abies lasiocarpa*) on more mesic soils. Lodgepole pine has been the dominant canopy cover type for the past ~8000 years (Carter et al., 2013). However, the region has experienced rapid changes in vegetation composition from a lodgepole pine dominated forest to a mixed forest of lodgepole pine and quaking aspen between ~4000 and 3450 cal yr BP in response to warmer-than-average temperatures as a result of a mega drought centred ~4200 cal yr BP (Carter et al., 2017). Currently, the modern geographical location of the aspen ecotone is roughly 200 m a.s.l. downslope from Long Lake (Carter et al. 2017).

3 Methods

3.1 Sedimentological analysis

Carter et al. (2013; 2017) describe the sedimentary collection that took place from Long Lake in 2007. Additionally, Carter et al. (2017) describe age-depth relations, charcoal and pollen analysis, and the modern pollen analogue technique.

3.2 Modern climate analogue

In order to identify potential climatic mechanisms associated with changes in vegetation composition, a time series of modern precipitation anomalies was calculated from Wyoming Climate Division 10, the Upper River Platter basin using data from the National Climate Data Centre (NCDC) (Figure 2). The Upper Platte River basin was chosen because it encompasses the Medicine Bow Range, where our study site Long Lake is located. The times series was calculated for 1979-2014, which is the common period for the North American Regional Reanalysis (NARR) dataset. From the time series, potential analogues (i.e., selected case years) were chosen that best represent similar conditions (e.g. anomalously dry) that would have potentially caused the ecological response found in the sedimentary analyses conducted by Carter et al. (2013; 2017) (Mock and Brunelle-Daines, 1999). Case years were selected that were greater than or equal to -1.5 standard deviations from the long-term average.

Once the modern climate analogue case years were selected, anomalies were calculated by subtracting the five case years that were less than or equal to -1.5 standard deviations from the long-term average (1979-2014). For the purpose of understanding modern synoptic processes that may have influenced vegetation change, a variety of surface and atmospheric climate variables were used from the NARR dataset (Mesinger et al., 2006) to calculate and map anomalous patterns (Table 1). Use of the NARR dataset is advantageous for two reasons; 1) it provides a variety of climate variables that represent atmospheric synoptic processes (e.g. atmospheric pressure, wind direction and speed, moisture availability, and vertical motion) as well as surface conditions (e.g. precipitation rate and temperature); and 2) The spatial resolution (32-km grids) of the NARR is at a finer scale than large-scale GCMs. The 32-km resolution of the NARR is valuable for our area of geographic study because it captures topographic and climatic diversity of the central Rocky Mountains. The seasonal value (e.g. winter = December, January, and February; or DJF) of the selected modern analogue case years were averaged together (composited) and compared to the long-term mean (1981-2010) to create composite-anomaly values for each season. These composite-anomaly values were mapped in order to analyse and assess the spatial and temporal variability of our selected modern climate analogues to identify surface and atmospheric conditions that would support vegetation change identified in the sedimentary

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record. Atmospheric variables (e.g. atmospheric pressure and wind vectors) were mapped at a continental scale to illustrate the large spatial scales in which such variables operate. Similarly, the surface variables (e.g. precipitation rate) were mapped at the local or regional level to illustrate the spatial heterogeneity of such processes. Composite-anomaly values were calculated using the NAAR Monthly/Seasonal Climate Composites plotting and analysis page (https://www.esrl.noaa.gov/psd/cgi-bin/data/narr/plotmonth.pl.). The resultant netCDF (Network Common Data Form) files were downloaded from the NAAR Monthly/Seasonal Climate Composites plotting and analysis page and were plotted graphically using the NASA/GISS software, Panoply, a netCDF, HDF, and Grib Data Viewer (https://www.giss.nasa.gov/tools/panoply/). The resulting maps are plotted using the NARR 32-km gridded format and have not been interpolated in order to maintain the native spatial representation of the data. As described by Heyer et al., (2017) the 32-km gridded NARR dataset is useful for assessing hydroclimatic impacts at high spatial resolution such as within a watershed as presented here.

4 Results

Five case years (2012, 2002, 2001, 1988, and 1994) that were 1.5 standard deviations below the long-term average were chosen because they were found to be the most suitable analogues for dry conditions in the North Platte River Basin. These case years offer potential synoptic and dynamic processes that led to the ecological responses from the central Rocky Mountains.

4.1 Modern climate analogues of extreme dry conditions in the North Platte River Basin

Surface modern climate analogues

The composite-anomaly maps for precipitation rate provide the spatial representation of the information shown in the time series of annual precipitation. Here we illustrate seasonal composite-anomaly values for precipitation rate from all dry year cases (Figure 3). Winter (DJF) composite-anomaly values for precipitation are slightly above normal in the study region (Figure 3a). However, the overall annual average (based on the time series) was lower-than-average throughout the case years. Spring (MAM) composite-anomaly values for precipitation rate indicate a shift toward slightly drier-than-normal conditions (Figure 3b). Summer (JJA) composite-anomaly values indicate an increase in aridity for the case years (Figure 3c) that persisted in the region through the fall (SON) (Figure 3d).

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Seasonal composite-anomaly maps for temperature (Figure 4) provide information on local surface conditions during the anomalous case years. Winter (DJF) composite-anomaly values are slightly cooler-than-normal in the region (Figure 4a). Temperatures increased during the spring, enhancing during the summer months, and persisted through the fall (Figure 4d).

4.2 Atmospheric modern climate analogues

In the atmosphere, 500mb geopotential height anomalies are aligned with surface temperature anomalies. Figure 5 illustrates 500mb geopotential height composite anomalies during the anomalous case years, which is shown on a continental scale because it captures regions of lower-than-normal atmospheric pressure (associated with enhanced troughs) and higher-than-normal atmospheric pressure (associated with enhanced ridges). Winter (DJF) composite anomaly values for 500mb geopotential height show slightly lower-than-normal pressure centred over the interior of Canada and extending down over the Great Plains, and a higher-than-normal ridge in the north Pacific (Figure 5a). Spring (MAM) composite anomaly values indicates a higher-than-normal pressure centred over the central Great Plains (Figure 5b), which shifted to a more northerly position centred over the northern Great Plains during the summer (JJA) (Figure 5c). Fall (SON) composite anomaly values show a slightly higher-than-normal pressure over the western US.

While the 500mb geopotential height composite anomaly maps provide a continental perspective of broad scale anomalous ridges and troughs, the variable, 500mb Omega (vertical velocity), offers a more local scale perspective on secondary sinking and rising motions that occur within ridges and troughs. Specifically, positive 500mb Omega composite anomaly values indicate anomalous sinking motions (motions that suppress precipitation) and negative 500mb Omega composite anomaly values indicate anomalous rising motions (motions that enhance precipitation). Therefore, seasonal maps of 500mb Omega composite-anomaly values illustrate local scale sinking and rising motions (Figure 6). Winter (DJF) composite-anomaly maps for 500mb Omega indicate weak rising motions in the study region (Figure 6a). Spring (MAM) and Fall (SON) composite-anomaly maps indicate strong sinking motions in the study region (Figure 6b and 6d). Summer (JJA) composite-anomaly maps show a mixture of weak rising and sinking motions in the study region (Figure 6c).

The 850mb specific humidity composite anomaly values were plotted on a continental scale to provide context on the spatial extent of available moisture during each season (Figure B). Winter (DJF) 850mb specific humidity composite anomaly values are slightly below normal in the study region (Figure 7a). Spring (MAM) 850mb specific humidity composite anomaly values indicate below normal moisture availability (Figure 7b), which persisted into the summer (JJA) and fall (SON) (Figure 7c and 7d).

The 500mb vector winds composite anomaly maps provide information on the anomalous component of flow (Figure 8), which is associated with the 500mb geopotential height composite anomaly maps. For winter (DJF), the anomalous component of flow is northerly into the study region (Figure 8a), largely dictated by the higher-than-normal heights seen in the 500mb geopotential heights (Figure 6a). During the spring (MAM), the anomalous component of flow is from the south and southwest (Figure 8b) associated with the clockwise flow of air around the anomalous ridge seen in Figure 6b. During the summer (JJA), the anomalous component of flow is from the east (Figure 8c) associated with the clockwise flow of air around the anomalous ridge seen in Figure 6c. For fall (SON), the anomalous component of flow is northerly into the study region (Figure 8d).

5 Discussion

5.1 Holocene evidence of mega drought conditions in the central Rocky Mountains and central Great Plains, USA

Carter et al. (2013; 2017) found palynological evidence that documents a shift in vegetation composition beginning around 4000 cal yr BP at Long Lake, Wyoming. These changes can be attributed to the increase in temperatures associated with the ~150-yr long (Carter et al., 2017) mega drought centred over the Great Plains ~4200 cal yr BP (Booth et al., 2005). Reconstructed MTCO and MTWA variables suggest January and July temperatures averaged -8ºC and 16ºC, while reconstructed annual precipitation averaged 394 ± 58 mm at Long Lake during the mega drought (Carter et al., 2017). Additional palaeoclimate evidence from the region that supports an ecological response to the mega drought include reactivation of multiple aeolian dune fields located in Wyoming and across the central Great Plains (Halfen et al., 2009; Mayer and Mahan, 2004; Stokes and Gaylord, 1993), lower lake levels at Upper Big Creek Lake in northern Colorado (Shuman et al., 2015), and changes in both $\delta^{13}C$ and $\delta^{18}O$ isotopes from a speleothem record from Minnetonka Cave on the Utah/Idaho border (Lundeen et al., 2013).

One of the hypothesized causal factors of the mega drought centred on 4200 cal yr BP were more "persistent La Niña-like conditions", which have been linked to other severe and prolonged droughts during the Holocene (Booth et al., 2005; Forman et al., 2001; Menking and Anderson, 2003), as well as the Dust bowl drought in the 1930s (Schubert et al., 2004), and the recent drought between 1998 and 2002 (Hoerling and Kumar, 2004). However, the prescription of persistent La Niña-like conditions does not address the atmospheric processes at a local and regional scale that may have led to the widespread mega drought conditions centred on 4200 cal yr BP. By identifying extreme dry years from modern precipitation data near Long Lake, the modern climate analogue technique is used in this study in order to identify atmospheric circulation mechanisms that supported hydrologic extremes in the modern record as analogues for synoptic climate processes of past hydrologic extremes evident in the pollen record (Mock and Brunelle-Daines, 1999; Shinker et al., 2006; Shinker, 2014).

5.2 A seasonal modern climate analogue explanation for the mega drought in the central Rocky Mountains and central Great Plains of North America

From the five case years that were found to be the most suitable analogues to describe palaeoclimate patterns (Mock and Brunelle-Daines, 1999), the surface climate variables, precipitation and temperature, indicate slightly wetter-than-normal and slightly cooler-than-normal conditions during the winter seasons in the Medicine Bow Range and surrounding region (Figures 3 and 4). While winters were slightly wetter-than-normal, the overall annual precipitation values for the selected case years were greater-than -1.5 standard deviations below average, which illustrates the within-year and between-year variability of precipitation that occurs in the central Rocky Mountains (Mock, 1996; Shinker, 2010). Nevertheless, slightly wetter-than-average conditions can be expected during the cool season in mountainous regions as a result of orographic uplift and a dominant westerly storm track from the Pacific Ocean (Mock, 1996; Shinker, 2010). However, while the 500mb Omega show enhanced vertical motions in the study area during the winter, there was a lack of moisture present in the atmosphere which inhibited above average precipitation during the winter, as illustrated by the 850mb specific humidity. The cooler-than-normal temperatures during the winter months can be explained by several factors; First, the 500mb vector winds indicate an anomalous component of flow of cold and dry air being drawn from the interior region of Canada to south-eastern Wyoming (Figure 8a); second, the slightly higher-than-normal precipitation (Figure 3a) likely increased the possibility of greater-than-normal cloud cover; third, the moisture present at the surface likely reduced that amount of sensible heat; and finally, the 500mb geopotential height pattern also indicates a weak trough in the northern Great Plains region (Figure 5a), which explains the anomalous component of flow that was moving cold, dry air from the interior region of Canada toward the study region.

During the spring months, warm and dry conditions prevailed in the region (Figure 3b). The 500mb geopotential height pattern indicates an enhanced high-pressure ridge centred over the Great Plains region, which subsequently brought an anti-cyclonic component of flow from the continental interior of North America, as demonstrated by the 500mb vector winds (Figure 8). However, dry conditions during the spring can be attributed to a combination of enhanced atmospheric sinking, and a lack of atmospheric moisture, as illustrated by the 500mb Omega and 850mb specific humidity (Figures 6 & 7).

Temperature and precipitation anomaly maps (Figures 3 & 4) show that enhanced warm and dry conditions continued throughout the summer months. During the summer, the 500mb geopotential height pattern indicates that the anomalous high pressure ridge had migrated slightly northward over the northern Great Plains region, and into the study region (Figure 5). The anti-cyclonic flow around the high-pressure ridge indicates that the anomalous component of flow was more horizontal, bringing anomalously dry air from the interior of the continent towards Long Lake (Figure 8). While there was a mixture of anomalous sinking and rising motions during the summer months (Figure 6c), the 500mb height pattern indicates that the overall large scale atmospheric control was the anomalous high-pressure ridge centred over the Great Plains (Figure 5c). Additionally, the 850mb specific humidity anomaly map shows lower-than-normal atmospheric moisture in the study region during the summer (Figure 7c), which resulted in drought conditions in the study area.

Warm and dry conditions persisted into the fall (Figures 3 and 4) as a result of slightly higher-than-normal geoptential heights that were centred over Idaho and the northern Rocky Mountain region. The anomalous 500mb geopotential heights created an anti-cyclonic air flow pattern that brought dry air from the interior of Canada into the study region, as demonstrated by the 500mb vertical winds (Figure 8). Additionally, the 500mb Omega composite anomaly maps indicates enhanced sinking motions in the atmosphere (Figure 6), which inhibited the delivery of atmospheric moisture transport into the region, as illustrated by the 850mb specific humidity composite anomaly maps (Figure 8).

5.3 Paleowinds and the application of the modern climate analogue technique during the mega drought at 4200 cal yr BP

During the winter months in the Great Plains region of North America, conditions are relatively dry (Schmeisser et al., 2010). From our modern climate analogue, this can be explained by cold, dry northerly winds from the interior of Canada that follow the western edge of the 500mb geopotential low-pressure trough centred over the interior region of Canada.

However, during the spring and early summer months, a high-pressure ridge positions over the Great Plains region shifts the winds, creating more of a southerly-to-southwesterly component of flow. Typically, southerly winds are responsible for bringing in moist latent air from the Gulf of Mexico to the Great Plains region (Sridhar et al., 2006), which is known as the Great Plains low-level jet (Schmeisser et al., 2010). The southerly winds are associated with the anti-cyclonic flow around the Bermuda High off the coast of eastern North America. However, if the Great Plains low-level jet is closed off from its moisture source (the Gulf of Mexico), the Great Plains region will essentially be dry during the summer months. Schmeisser et al. (2010) suggest that in order for drought to develop and persist in the Great Plains region during the summer months, the Bermuda High must be reduced or positioned either more easterly or southerly, which would create a more south-westerly component of flow. However, our 500mb geopotential height composite anomaly maps for both spring and summer (Figures 5b & c) documents the development, and persistence of an anomalous 500mb high-pressure ridge over the Great Plains region, which likely inhibited the Great Plains low-level jet from transporting moisture from the Gulf of Mexico into the region. Reconstructed palaeowinds using optical luminescence dating from sand dunes in the Great Plains region suggest a more south-westerly component of flow during periods of drought, such as during the mega drought centred on 4200 cal yr BP (Schmeisser et al., 2010). Therefore, the development and persistence of anomalously 500mb high-pressure ridges over the Great Plains region and the subsequent anti-cyclonic component of flow offers one hypothetical explanation to the widespread ecological responses from the Great Plains and central Rocky Mountain regions during the mega drought centred on 4200 cal yr BP.

Additionally, we investigated whether the current hypothesis that more 'persistent La Niña-like conditions' may have caused the mega drought centred on 4200 cal yr BP (Booth et al., 2005). Our identified five case years with anomalously dry conditions that were less than -1.5 standard deviations below the long-term average, include 2012, 2002, 2001, 1988, and 1994 (Figure 3). When compared to historic La Niña and El Niño events (post 1950), the five selected case years in the time series occurred in all phases of ENSO; negative/cool (La Niña), positive/warm (El Niño) and neutral (NOAA, 2015). Wise (2016) created a standardized precipitation index (SPI) for western North America using Climate Research Unit (CRU) data from October through March (i.e. the cool season) in order to reconstruct atmospheric circulation patterns associated with drought from western North America. The reconstructed SPI data that are typical during La Niña-like events over North America document an enhanced trough positioned in the interior of Canada, and an enhanced ridge positioned off the coast of California

(Wise, 2016). However, while our composite anomaly maps for the winter and spring seasons (which encompasses the reconstructed cool season also used in Wise, 2016) document an anomalous trough of low pressure in the interior of Canada, the anomalous ridge of high pressure is positioned further north in the Pacific Ocean during the winter months. Additionally, the development and persistence of an anomalously high-pressure ridge over the Great Plains region during the spring, and lasting into the summer differs from the reconstructed La Niña-like atmospheric patterns documented by Wise, 2016. Therefore, the results from our study suggest that dry conditions in the region can occur during any phase of ENSO, and that there may be more to the story than the "persistent La Niña-like conditions" proposed by Booth et al. (2005) to explain the regional mega drought centred on 4200 cal yr BP.

6 Conclusion

Paleoecological reconstructions are valuable for understanding how ecosystems and disturbance regimes respond to both gradual and abrupt changes in climate. However, proxies preserved in sedimentary records fail to record mechanisms that caused the ecological responses; the proxies only record that there was a change in vegetation composition or a change in disturbance regimes. We applied a modern climate analogue technique to explain potential climatic mechanisms that occurred during the mega drought centred on 4200 cal yr BP, and that led to the ecological changes recorded in the paleoecological reconstruction from Long Lake, Wyoming.

The surface modern climate analogues document anomalously warm and dry conditions during the growing season in the Medicine Bow Mountains of south-eastern Wyoming. The atmospheric modern climate analogues provide climatic mechanisms that resulted in the warm and dry conditions, which were recorded in the sedimentary proxies from Long Lake, Wyoming. However, the atmospheric modern climate analogues document the mechanisms that created the warm and dry conditions. The atmospheric modern climate analogues illustrate anomalously high-pressure ridge positioned over the Great Plains region, which coincidently have been associated with the most recent droughts of the 20th century. However, while the modern case years show weak rising motions during the summer months, there wasn't enough moisture available in the atmosphere (i.e. lower-than-normal moisture in the atmosphere does not support precipitation at the study region). In other words, the mechanism for uplift was present over the study region, but the moisture availability was not present as a result of a persistent high-pressure ridge which drew warm and dry air into region in a southerly-to-south-westerly direction from the interior region of North America towards the study region. Additionally, the persistent high-pressure ridge positioned directly over the Great Plains/northern Great Plains and northern Rocky Mountains during the growing season likely interrupted the normal moisture of flow from the Gulf of Mexico via the low level jet into the region, drawing warm and dry air from the interior of North America to the study region in a southerly manner. The combination of higher-than-normal geopotential heights, an anomalous southerly-to-south-westerly component of flow, and lack of moisture transport to the study region created the anomalously warm and dry conditions in the study region during the mega drought at 4200 cal yr BP. Together, these could potentially explain the change in vegetation composition seen in the pollen record at Long Lake, and the widespread reactivation of dunes recorded from the region (Halfen et al., 2009; Mayer and Mahan, 2004; Stokes and Gaylord, 1993), as well as lowered lake levels in the central Rocky Mountain region (Shuman et al., 2015).

Mega droughts such as the one centred on 4200 cal yr BP, as well several droughts in the 13th and 16th centuries were more severe and of longer duration than the more recent droughts of the 20th century (Woodhouse and Overpeck, 1998). Understanding the climate processes associated with modern drought will provide better insight about past drought variability and the mechanisms that caused mega droughts evident in paleoecological records. This study demonstrated the benefits of applying a modern climate analogue technique to the paleoecological reconstruction from Long Lake in order to better understand the potential climatic mechanisms that impacted the quaking aspen populations in the Medicine Bow Range.

7 Data Availability

Modern climate analogue years were selected based on NOAA/NCDC Wyoming Climate Division 10 from the Earth System Research Laboratory Physical Science Division of NOAA (https://www.esrl.noaa.gov/psd/data/timeseries/). Surface and atmospheric variables used in the composite-anomaly analysis are available through the Earth System Research Laboratory Physical Science Division of NOAA (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr). The charcoal data has been uploaded to the Global Charcoal Database web page: https://www.paleofire.org/index2.php. The pollen data has been uploaded to the Neotoma Paleoecology Database web page: https://www.neotomadb.org/groups/category/pollen. Pollen and charcoal data are interpreted at 1-cm resolution between depths 94 and 176 cm, as described by Carter et al. (2017).

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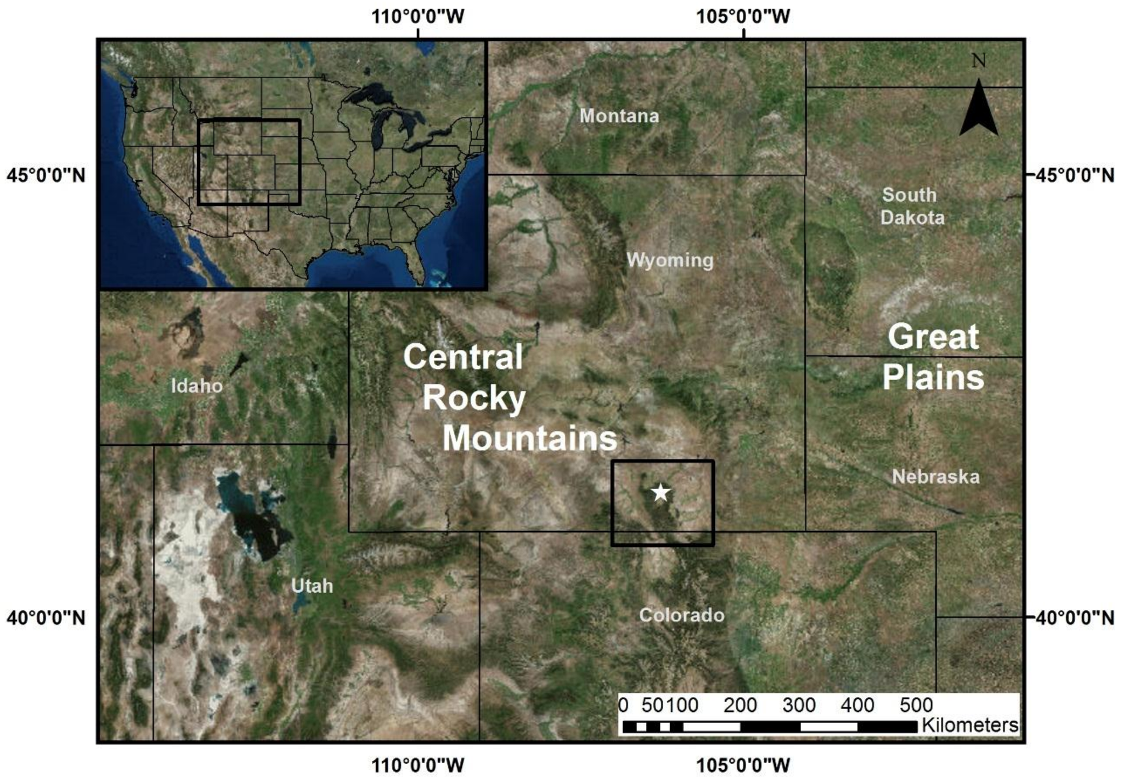

Figure 1. Location map of the study region in the western United States (small panel; black box). Long Lake, Wyoming (white start inside the black box indicating the study area) is located in south-eastern Wyoming within the central Rocky Mountain region on the edge of the Great Plains.

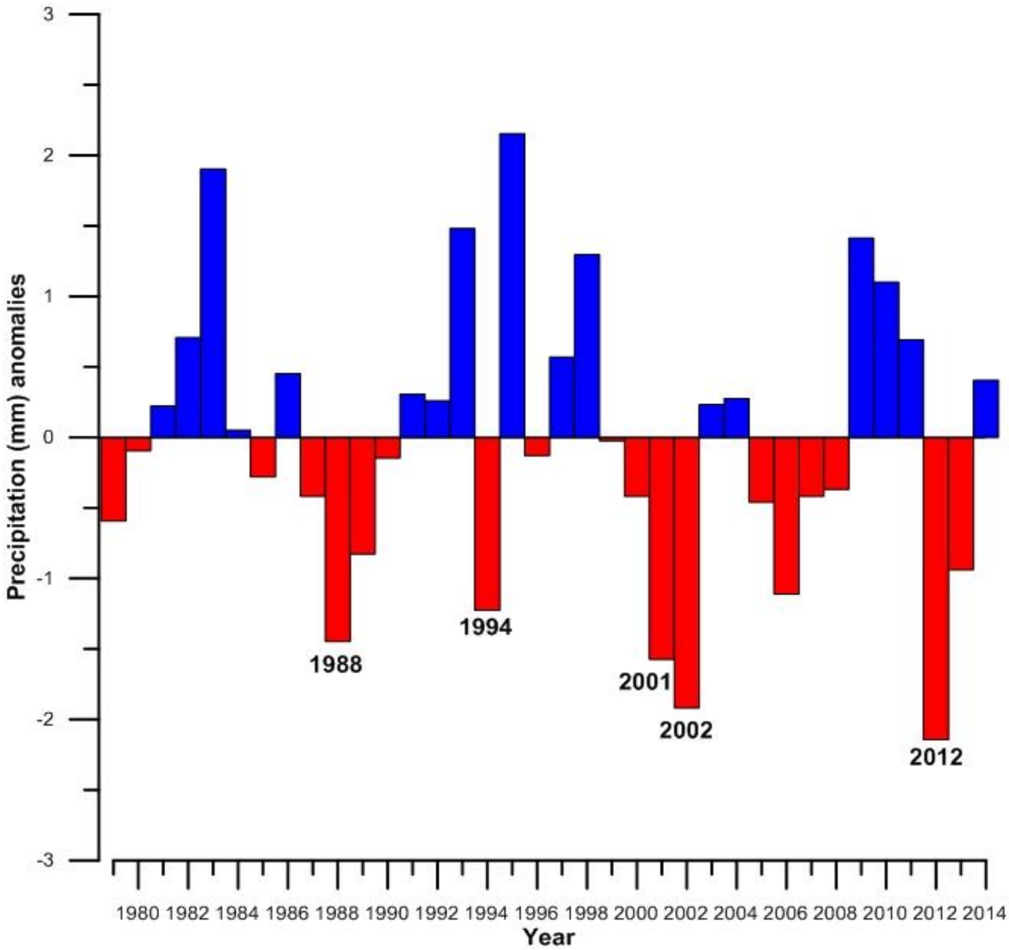

Figure 2. Time series of annual precipitation anomalies for 1979-2014 compared to the long-term average (1981-2010) in Wyoming climate division 10, Upper Platte River Basin. The first 5 years with -1.5 or more standard deviations below the long-term average include 2012, 2002, 2001, 1998, and 1994. Climate division data collected from http://www.esrl.noaa.gov/psd/cgi-bin/timeseries/timeseries1.pl.

Clim. Past Discuss., https://doi.org/10.5194/cp-2017-107
Manuscript under review for journal Clim. Past
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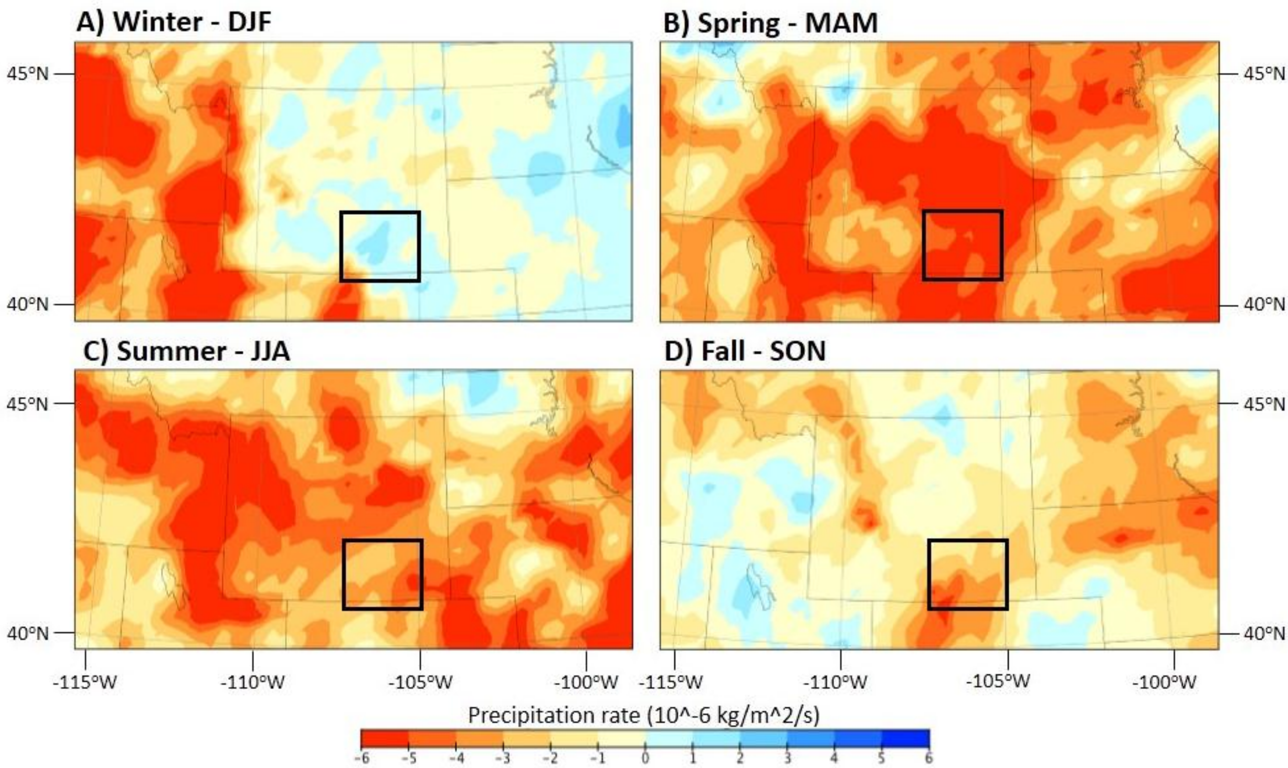

Figure 3. Composite anomaly maps for precipitation rate at the surface. A) Precipitation rate at the surface for winter (DJF); B) Spring (MAM); C) Summer (JJA); D) Fall (SON). Positive values (cool colours) for precipitation rate indicate wetter-than-normal conditions. Negative values (warm colours) indicate dryer-than-normal conditions. The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. Light grey lines depict lines of latitude/longitude.

Clim. Past Discuss., https://doi.org/10.5194/cp-2017-107
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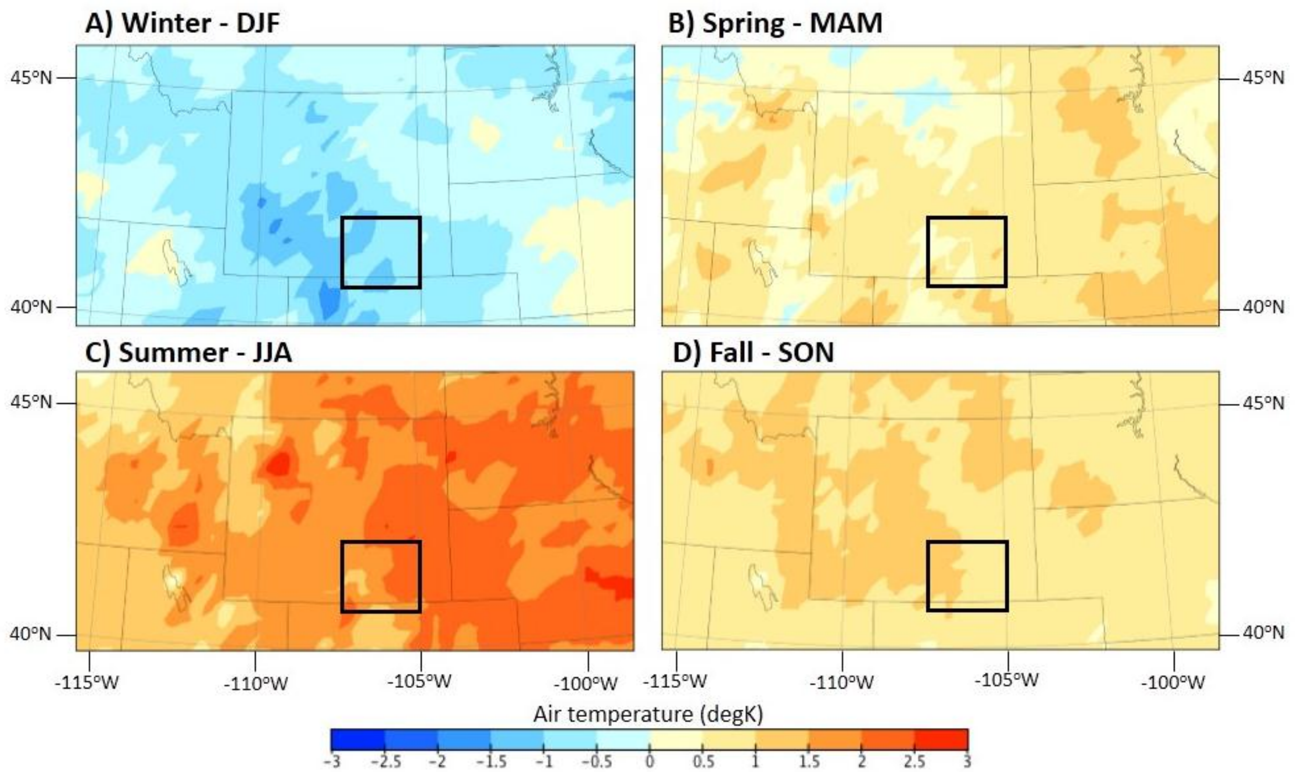

Figure 4. Composite anomaly maps for air temperature at the surface. A) Air temperature during the winter (DFJ); B) Spring (MAM); C) Summer (JJA); D) Fall (SON). Positive values (warm colours) for air temperature indicate warmer-than-normal conditions. Negative values (cool colours) indicate cooler-than-normal conditions. The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. Light grey lines depict lines of latitude/longitude.

Clim. Past Discuss., https://doi.org/10.5194/cp-2017-107
Manuscript under review for journal Clim. Past
Discussion started: 29 September 2017

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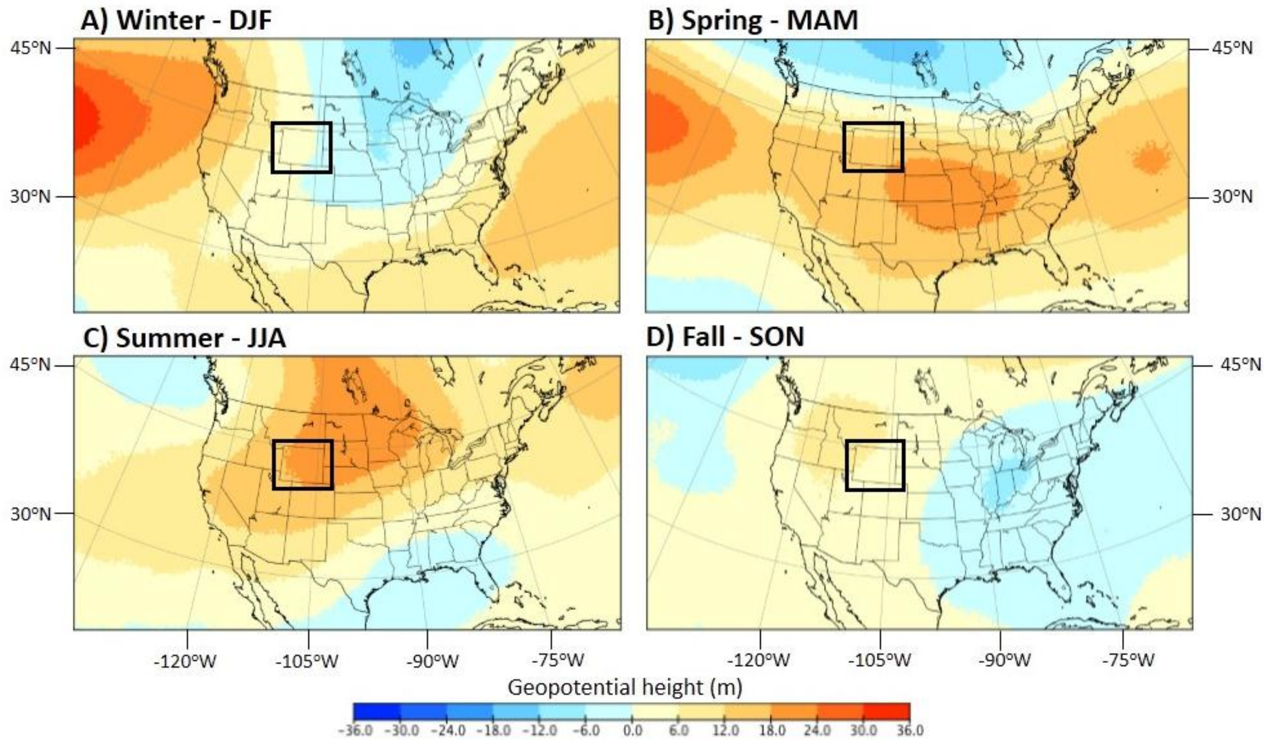

Figure 5. Composite anomaly maps for 500mb geopotential height during A) the winter season (JJA); B) spring (MAM); C) summer (JJA); and D) fall season (SON). Positive values (warm colours) for 500mb geopotential heights indicate a stronger-than-normal ridge. Negative values (cool colours) indicate a strong-than-normal trough. The black box denotes the study region, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. Light grey lines depict lines of latitude/longitude.

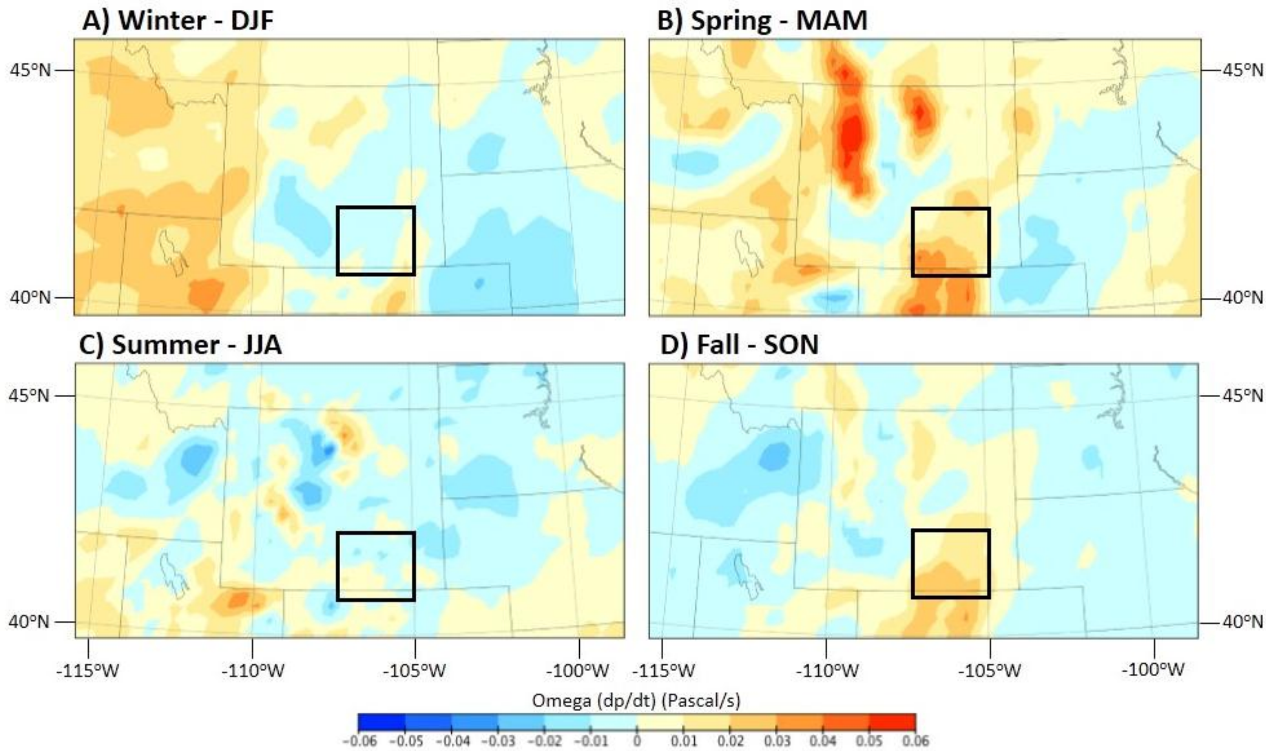

Figure 6. Composite anomaly maps for 500-mb Omega (vertical velocity) during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) the fall season (SON). Positive values (warm colours) for omega indicate enhanced sinking motions (suppress precipitation). Negative values (cool colours) indicate enhanced rising motions (enhanced precipitation). The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. Light grey lines depict lines of latitude/longitude.

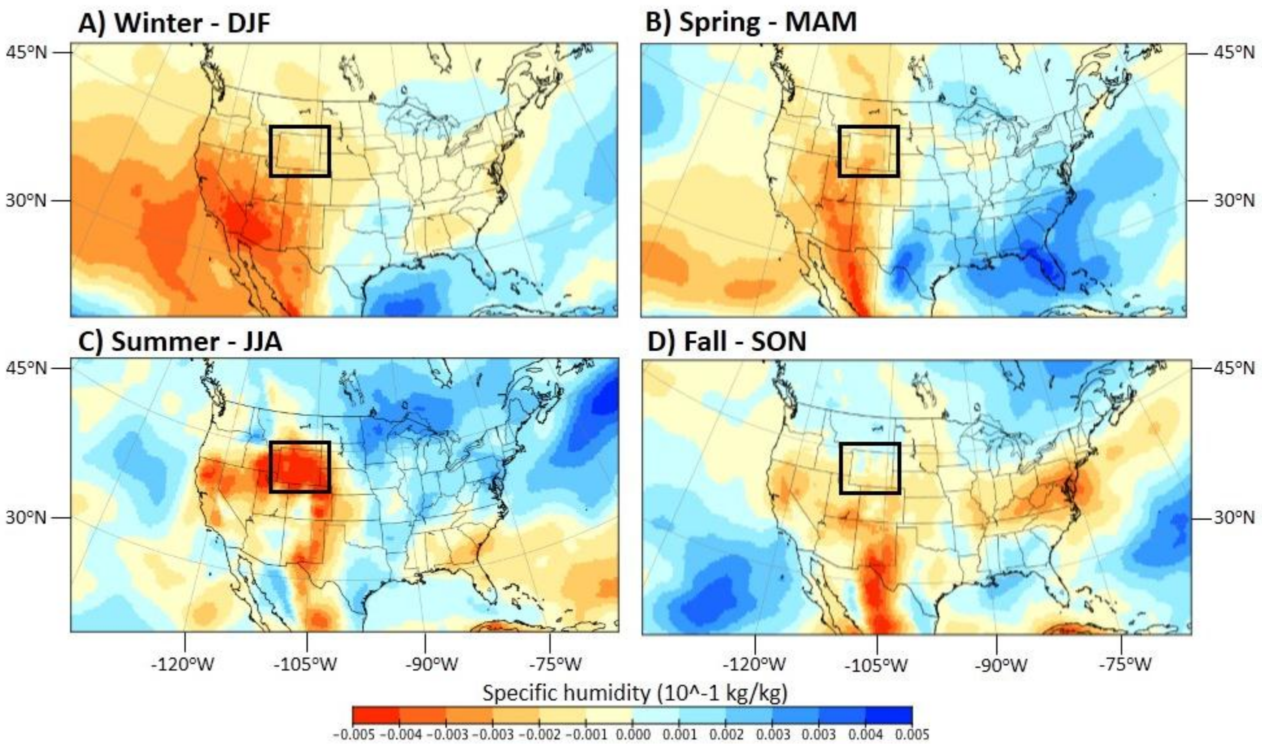

Figure 7. Composite anomaly maps for 850mb specific humidity during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) the fall season (SON). Positive values (cool colours) for 850-mb specific humidity indicate wetter-than-normal conditions in the atmosphere. Negative values (warm colours) indicate dryer-than-normal conditions. The black box denotes the study region, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. Light grey lines depict lines of latitude/longitude.

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Manuscript under review for journal Clim. Past
Discussion started: 29 September 2017

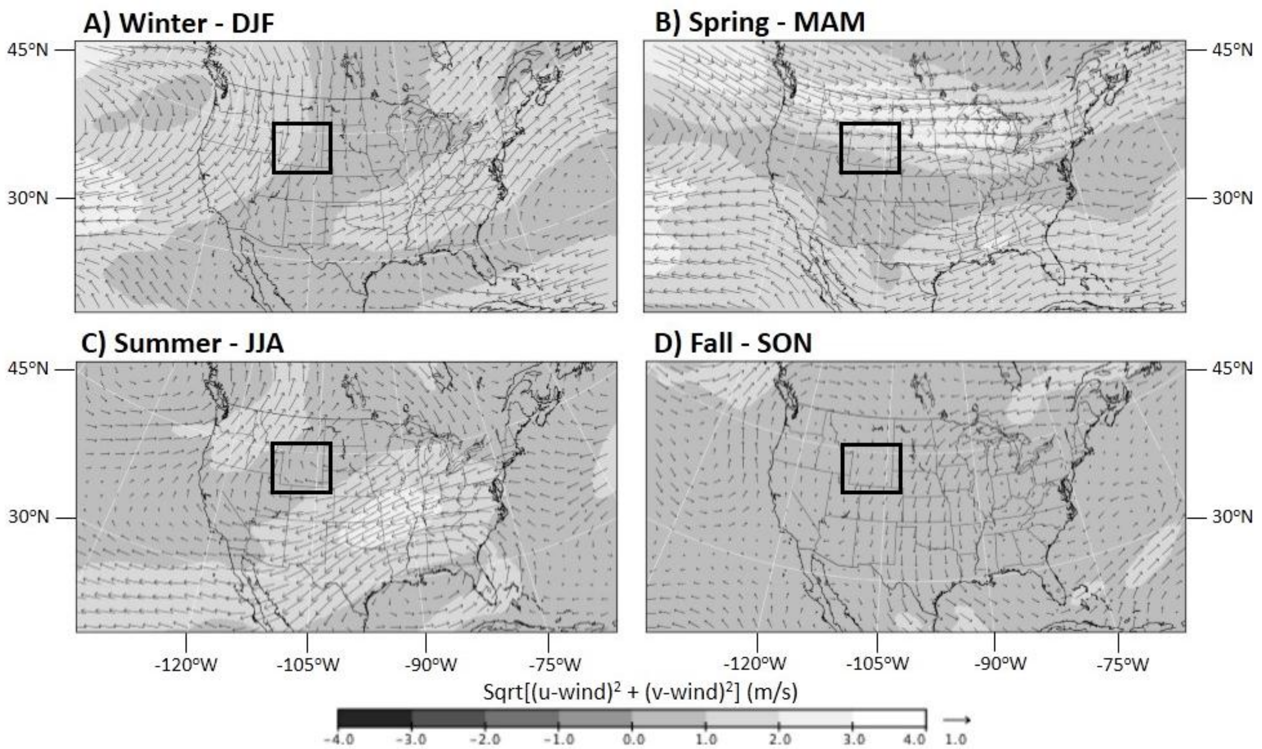

Figure 8. Seasonal composite anomaly maps for 500mb vector winds during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) fall season (SON). The black box denotes the study region, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. White lines depict lines of latitude/longitude.

Clim. Past Discuss., https://doi.org/10.5194/cp-2017-107
Manuscript under review for journal Clim. Past
Discussion started: 29 September 2017

Climate Variable	Level in the Atmosphere	Purpose of Climate Variable
Precipitation Rate	Surface	Provides information on how much precipitation makes it to the surface
Surface temperature	Surface	Provides information on temperatures at the surface
Soil Moisture	Surface	Provides information on surface moisture potentially available for vegetation and the atmosphere.
Geopotential Height	500mb level	Provides information about atmospheric pressure in the mid-troposphere
Vector Winds	500mb level	Provides information about wind direction and anomalous componenet of flow
Specific Humidity	850mb level	Provides information about mositure availablity in the atmosphere
Omega (Vertical Velocity)	500mb level	Provides information about rising or sinking motions in the atmosphere that enhance or suppress precipitation, respectively.

Table 1. Climate variables available in the NARR dataset that this particular study used for this analysis.