Drought and vegetation change in the central Rocky Mountains and western Great Plains: Potential climatic mechanisms associated with megadrought conditions 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 megadroughts that have plagued the region in the past. Roughly 4200 years ago, a ~150-year long megadrought occurred in the central Rocky Mountains, as indicated by sedimentary pollen evidence from Long Lake, south-eastern Wyoming and resulted in a brief and unique change in vegetation composition. Neighbouring the central Rocky Mountains, several dune fields reactivated in the western Great Plains around this time period illustrating a severe regional drought. While sedimentary pollen provides evidence of past drought, paleoecological evidence does not provide context for the climate mechanisms that may have caused the drought. Thus, a modern climate analogue technique was applied to the sedimentary pollen and regional dune reactivation evidence identified from the region to provide a conceptual framework for exploring possible mechanisms responsible for the observed ecological changes. The modern climate analogues of 2002/2012 illustrate that warm and dry conditions persisted through the growing season and were associated with anomalously higher-than-normal heights centred over the Great Plains. In the spring, higher-than-normal heights suppressed moisture transport via the low level jet from the Gulf of Mexico creating a more south-westerly component of flow. In the summer, higher-than-normal heights persisted over the northern Great Plains resulting in a wind shift with an easterly component of flow, drawing in dry continental air into the study region. In both cases, lower-than-normal moisture in the atmosphere (via 850 mb specific humidity) inhibited uplift and potential precipitation. Thus, if the present scenario existed during the 4.2ka drought, the associated climatic responses are consistent with local and regional proxy data suggesting regional drought conditions in the central Rocky Mountains and central Great Plains.

1. Introduction

Droughts are a regular climatic feature in the Great Plains and western United States (US). As global temperatures continue to rise as a result of anthropogenically induced climate change (IPCC, 2014), drought vulnerability is predicted to increase in the Great Plains and western US (Garfin et al., 2013). Of the 20th century droughts, the 1930s and 1950s droughts were the most extensive and long lasting (Schubert et al., 2004), which caused both economic and societal losses throughout the regions (Diaz, 1983; Woodhouse and Overpeck, 1998). Yet, when compared to proxy data, modern era droughts were both shorter in duration and less severe than megadroughts that have plagued the region in the past (Woodhouse and Overpeck, 1998; Cook et al., 2010). Megadroughts can be defined as persistent drought events that last decades to centuries and generally have a large spatial extent (Woodhouse and Overpeck, 1998). However, little is known about what causes megadroughts. Droughts and likely megadroughts are climatically complex processes that are typically not attributed to a single cause, but rather to multiple causes (Namias, 1991). Yet, it is postulated that processes responsible for modern droughts, such as sea-surface temperatures (SSTs), land-atmosphere interactions, and internal atmospheric variability (see Cook et al., 2016 and references therein) may have mechanistically contributed to historic megadroughts. Understanding the mechanisms involved with megadroughts is of critical importance due to the potential for similar extreme drought events to occur in the future (Coats et al., 2013).

One such megadrought was identified approximately 4200 cal yr BP via sedimentary proxy data from Long Lake, south-eastern Wyoming located in the eastern-most extent of the Central Rocky Mountains (CRM) (Carter et al., 2013; 2017a). Proxy evidence from Long Lake documents the lagged ecological response of a pine-dominated forest turning to a mixed-forest with pine and quaking aspen (Figure 1A), which the authors coined as the '*Populus* period' (Carter et al., 2013). This same ecological response was also recorded in the modern record from Long Lake likely in response to the 1930s drought (Carter et al., 2017a). The relationship between drought, increased temperatures and widespread quaking aspen mortality has been observed across western North American (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). Carter et al. (2017a) further 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 ~150-year long megadrought (Figure 1B-D), likely caused the upslope migration of quaking aspen stands in the Medicine Bow Range of south-eastern Wyoming. The timing of the reconstructed drought at Long Lake may be associated with the 4.2 ka climatic event which was a prominent dry period at primarily low-to-mid latitudes that was responsible for cultural collapses globally (deMenocal, 2001; An et al., 2005; Weiss, 2016; 2017a; 2017b). Neighbouring the CRM, drought conditions were also recorded in the Great Plains region approximately 4200 cal yr BP (Booth et al., 2005). Of particular interest to this study are the numerous dune fields that reactived in the western Great Plains (Figure 1E-Q), indicating geographically extensive droughts around this same time period (Halfen and Johnson, 2013); the Ferris and Casper dune fields of eastern Wyoming (Stokes and Gaylord, 1993; Halfen et al., 2010), the White River Badlands dunes of south-western South Dakota (Rawling et al., 2003), and the Nebraska Hills dunes of central Nebraska (Schmeider et al., 2011; Miao et al., 2007; Mason et al., 2004; Goble et al., 2004; Stokes and Swinehart, 1997; Loope et al., 1995; Ahlbrandt et al., 1983; Madole, 1995). Yet, Miao et al. (2007) acknowledge that sand dune reactivation could also be a lagged effect of drought.

Regardless, prehistoric dune activation follows two assumptions; first, that aeolian transport occurs when particles are abundant and freely available to transport via strong winds; and second, that vegetation cover is reduced leaving sand particles easily exposed to strong winds (Halfen and Johnson, 2013). Thus, it is hypothesised that persistently dry growing season conditions between ~4200 and ~4000 cal yr BP likely led to lagged changes in vegetation composition at Long Lake, as well as reduced dune stabilising vegetation across the western Great Plains region.

While sedimentary proxy data such as pollen and charcoal provide a record of changes in past vegetation and disturbances (e.g. fires or drought), they do not provide a record of the climatic mechanisms that initially caused such extreme events. Thus, improving our understanding of the climate processes associated with modern drought will provide better insight about past drought variability and the mechanisms associated with megadroughts evident in paleoecological records. One tool we use can use to understand the climate processes associated with past drought seen in proxy data is through the use of the modern climate analogue technique (Mock and Shinker, 2013), which assumes that modern synoptic and dynamic climate processes operated similarly in the past as they do today. The modern climate analogue technique is a conceptual model that uses modern extremes (e.g. drought) as analogues of past events (e.g. vegetation change associated with drought) as a means to understand palaeoclimate patterns that may have caused historic paleoecological variability (Diaz and Andrews, 1982; Ely, 1997; Edwards et al., 2001; Shinker, 2014;Mock and Bartlein, 1995; Mock and Brunelle-Daines, 1999; Mock and Shinker, 2013; Shinker et al. 2006; Carter et al., 2017b).The modern climate analogue approach has been previously used to understand past synoptic processes and ecological changes recorded in paleoenvironmental data. For example, Mock and Brunelle-Daines (1999) investigated how summer synoptic climatology and external forcing (i.e. Milankovich cycles) impacted effected moisture in the western US during the mid-Holocene (~6000 cal yr BP). Shinker et al. (2006) also examined the mid-Holocene drought, but focused on the mid-continent of North America to provide potential climate processes and mechanisms associated with low lake levels during the prolonged mid-Holocene drought. They found that regional moisture influx and small-scale vertical motions in the atmosphere help explain low lake levels during that time. Similarly, Shinker (2014) investigated climatic controls on water resources in the headwaters of the Upper Arkansas River basin in west-central Colorado and found that local-scale variations in moisture availability and the absence of uplift mechanisms were key in explaining hydroclimate variability evidenced in paleo lake-level reconstructions (Shuman et al., 2009). Edwards et al. (2001) used the same technique to understand how specific atmospheric circulation patterns could have caused surface temperature and effective moisture anomalies during the past 12,000 years in the interior of Alaska. Finally, Carter et al. (2017b) used modern climate analogues to investigate how atmospheric conditions could have potentially contributed to the unique spatial patterns of wildfire activity over the past 1200 years in the northern and southern Rocky Mountains.

In lieu of climate simulations for the 4.2 ka event, the objective of this paper is to examine modern climate analogues as an alternative approach for understanding circulation patterns and potential heterogeneous surface responses between ~4,200 and ~4000 cal yr BP in the CRM and western Great Plains region. The purpose of using the modern climate analogue in this study is not to reconstruct circulation patterns that may have prevailed during the 4.2 ka climatic event, rather, the purpose is to offer insights into potential synoptic processes that may have facilitated the paleoecological responses evidenced in the both the CRM and Great Plains at that time (Mock and Bartlein, 1995). Climate analogues were selected on the basis that they best represented the environment-to-circulation approach (Barry and Carleton, 2001; Mock and Shinker, 2013; Shinker, 2014; Yarnal, 1993; Yarnal et al., 2001), i.e. anomalously dry conditions similar to those experienced during the 4.2 ka event identified in the sedimentary proxy data at Long Lake, south-eastern Wyoming (Carter et al., 2017a), as well as by clusters of radiocarbon and luminescence dates that indicate drought conditions in the western Great Plains (Stokes and Gaylord, 1993; Halfen et al., 2010; Rawling et al., 2003; Schmeider et al., 2011; Mason et al., 2004; Goble et al., 2004; Stokes and Swinehart, 1997; Loope et al., 1995; Ahlbrandt et al., 1983; Madole, 1995). Present day climatology of south-eastern Wyoming (Mock, 1996; Shinker, 2010) indicates that the region exhibits similar precipitation influences as the western Great Plains (e.g. springtime precipitation maximum). Thus, we hypothesize that due to Long Lake's geographical position i.e. the eastern-most extent in the CRM, our study site is sensitive to broad-scale climatic processes influencing the western Great Plains.

2. Study Area

Long Lake (41° 30.099′ N, 106° 22.087′ W; 2700 m a.s.l.) is located within the Upper Platte River watershed in the Medicine Bow Range of south-eastern Wyoming (Figure 2). The study site experiences a snow-dominated winter precipitation with a May precipitation maximum (Mock, 1996; Shinker, 2010), albeit that the May precipitation maximum only accounts for 12-15% of the total annual precipitation (Shinker, 2010). Interpolated modern January and July precipitation and temperatures from the nearest weather station suggests an average of 330 and 690 mm, and -9.7ºC and 11ºC, respectively (NRCS, unpublished data). Using the modern pollen analogue technique (Overpeck et al., 1985), Carter et al. (2017a) reconstructed the mean temperature of the coldest month (MTCO; i.e. January), mean temperature of the warmest month (MTWA; i.e. July), and annual precipitation, which averaged -9ºC, 15ºC, and ~443 ± 39 mm over the past ~2000 years. During the drought between 4300 and 4100 cal yr BP, MTCO, MTWA and annual precipitation averaged -8ºC, 16ºC, and 394 ± 58 mm (Figure 1B-D; Carter et al., 2017a). Both the modern and reconstructed climate from the area highlights that the Medicine Bow Range has a high degree of precipitation variability likely related to natural fluctuations in the strength and position of the jet stream. Currently, the study region does not experience statistically significant seasonal precipitation patterns associated with ENSO phases (Wise, 2010; Heyer et al., 2017).

Modern vegetation at Long Lake 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). Currently, the modern geographical location of the aspen ecotone is roughly 200 m a.s.l. downslope from Long Lake, yet the modern upper limit of aspen on north-facing slopes in the Medicine Bow Mountains is similar to the elevation at Long Lake (Carter et al. 2017a).

Carter et al. (2013; 2017a) describe the sedimentary collection that took place at Long Lake in 2007, while Carter et al. (2017a) describe age-depth relations, charcoal and pollen analysis, and the modern pollen analogue technique which was used to reconstruct local temperature and precipitation values. Additionally, Carter et al. (2017a) updated the age-depth relations from Carter et al. (2013) with the addition of an AMS radiocarbon date that was used to temporally constrain the upper and lower ages of the '*Populus*' period (Figure 1A; also see Carter et al., 2017a), as well as provides an upper age constraint on the drought at 4200 cal yr BP.

3. Methods

Modern climate analogues and calculation of composite-anomaly values

To investigate potential climate mechanisms that may be associated with the ecological changes at Long Lake, Wyoming, a time series of modern precipitation anomalies was calculated from Wyoming Climate Division 10, the Upper Platte River basin, using data from the National Climate Data Centre (NCDC) (Figure 3). Time series of modern precipitation anomalies were also calculated from Wyoming Climate Division 8, South Dakota Climate Division 5, and Nebraska Climate Division 2 (Figure 3), as these climate divisions encompass the Ferris and Casper dune fields, the White River Badlands dune fields, and the Nebraska Hills sand dunes. For all four time series, annual average precipitation values from 1979-2014, the common period for the North American Regional Reanalysis (NARR) dataset, were compared to the long-term mean (1981-2010). From the time series, potential analogues were selected based on a few criteria; first, anomalously dry conditions must have occurred during the same year(s) in all four climate divisions; and second, case years were greater than -1 standard deviations (one SD equals 58.89 mm at Wyoming 10; 59.73 mm at Wyoming 8; 91.61 mm at South Dakota 5; and 101.43 mm at Nebraska 2) below the long-term average i.e. within the 10^{th} percentile of dry years. These case years thus represent the driest conditions across all four climate divisions, and are clearly representative of highly anomalously widespread dry conditions, as likely occurred during the 4.2 ka climatic event at Long Lake, the Ferris and Casper dune fields, White River Badlands dune fields, and Nebraska Hills sand dunes. Once the case years were identified (2002 and 2012), annual precipitation of each case year were compared to the 1981-2010 climate normal at each grid point in our study region using a two-tailed Student's t-test with an alpha of 0.05. The degrees of freedom (30) were calculated as $n1 + n2 - 2$, where $n1 = 30$ and corresponds to the number of years in the climate normal, and $n2 = 2$, for the number of case years. Precedence for using a t-test to calculate statistical significance of anomalies in climatological analyses is well established in the existing literature (Cayan, 1996; Shabbar and Khandekar, 1996; Taschetto and England, 2009). The results are presented in a map depicting the spatial distribution of significant p-values across our study region (Figure 4).

A variety of surface and atmospheric climate variables from the NARR dataset (Mesinger et al., 2006) were analysed and mapped to assess potential linkages among synoptic processes and ecological changes between ~4,200 and ~4000 cal yr BP. 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 motions), as well as surface conditions (e.g. precipitation rate and temperature); and 2) the spatial resolution (32-km grids) of the NARR dataset is at a finer scale than large-scale GCMs making the NARR dataset useful for assessing hydroclimate impacts at high spatial resolution (Heyer et al., 2017). Additionally, the 32-km resolution is valuable for capturing the topographic and climate diversity of the geographic study region. The seasonal values (e.g. winter = December, January, February (DJF); spring = March, April, May (MAM); summer = June, July, August (JJA); and fall = September, October, November (SON)) 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. Surface variables were mapped at a regional level to illustrate the spatial heterogeneity of such processes. Atmospheric variables were mapped at a continental scale to illustrate the large spatial scales in which such variables operate. 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 plotted graphically using the NASA/GISS software, Panoply, a netCDF 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.

4. Results

Modern climate analogues of extreme dry conditions in the CRM and western Great Plains

4.1 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 seen in Figure 3. Winter (DJF) precipitation rate composite-anomaly values are above normal near Long Lake, as well as near both the Ferris and Casper dune fields, but slightly below normal near the White River Badlands and Nebraska Hills sand dunes (Figure 5a). Spring (MAM) precipitation rate composite-anomaly values indicate a shift toward significantly drier-than-normal conditions across the entire study region (Figure 5b), which persisted through the summer (JJA) (Figure 5c) and into the fall (SON) (Figure 5d).

Composite-anomaly maps for winter (DFJ) temperature indicate cooler-than-normal conditions near Long Lake, as well as near both the Ferris and Casper dune fields, but warmer-than-normal conditions near the White River Badlands and Nebraska Hills sand dunes (Figure 6a). Positive temperature anomalies increased during the spring (Figure 6b), and became increasingly warmer-than-normal during the summer across the entire study region (JJA) (Figure 6c). Temperatures were slightly warmer-than-normal across the entire study region during the fall (SON) (Figure 6d).

4.2 Atmospheric modern climate analogues

Geopotential height at the 500mb level provides information about atmospheric pressure in the mid-troposphere. Thus, it was used in this study to examine the influence of lower-than-normal atmospheric pressure (associated with enhanced troughs), and higher-than-normal atmospheric pressure (associated with enhanced ridges) on surface conditions. Winter (DJF) 500mb geopotential height composite-anomaly values show slightly higher-than-normal heights centred off both US coasts (Figure 7a). Spring (MAM) composite-anomaly values indicate a higher-than-normal heights centred over the central Great Plains and south-eastern US region (Figure 7b), which shifted north over the Midwest and northern Great Plains region during the summer (JJA) (Figure 7c). Fall (SON) composite-anomaly values show higher-than-normal heights off the coast of British Columbia, and lower-than-normal pressure centred over interior Canada (Figure 7d).

The 500mb vector wind composite anomaly maps provide information about wind direction and anomalous component of flow (Figure 8), which is associated with the 500mb geopotential height composite-anomaly values. For winter (DJF), there is no anomalous component of flow into the study region (Figure 8a) as the study region resides in between two anomalous high-pressure centres centred over the eastern and western US coasts (Figure 7a). During the spring (MAM), the anomalous component of flow is from the south-west (Figure 8b) associated with the clockwise flow of air around the anomalous ridge centred over the central Great Plains and south-eastern US region (Figure 7b). During the summer (JJA), the anomalous component of flow is from the east, south-east (Figure 8c) associated with the clockwise flow of air around the anomalous ridge over the Midwest and northern Great Plains region seen in Figure 7c. For fall (SON), the anomalous component of flow is northerly into the study region (Figure 8d).

While the 500mb geopotential height and 500mb vector wind composite-anomaly maps provide a continental perspective of broad-scale anomalous ridges and troughs and subsequent advection of wind, 500mb Omega (vertical velocity) offers a more local-scale perspective on secondary sinking and rising motions that occur within ridges and troughs, respectively. Specifically, positive 500mb Omega composite-anomaly values show anomalous sinking motions indicating suppression of precipitation, and negative 500mb Omega composite-anomaly values indicate anomalous rising motions that enhance precipitation (Figure 9). Winter (DJF) 500mb Omega composite-anomaly values indicate slight rising motions over both Long Lake, and the Ferris and Casper dune fields, and slight sinking motions over the White River Badlands and Nebraska Hills sand dunes (Figure 9a). However, rising motions become anomalously positive over Long Lake, and the Ferris and Casper dune fields during the spring (MAM) and fall (SON) (Figure 9b and 9d). Sinking motions prevail over the White River Badlands and Nebraska Hills sand dunes during the growing season i.e. spring through fall. Summer (JJA) composite-anomaly values show a mixture of weak rising and sinking motions over Long Lake and the Ferris and Casper dune fields (Figure 9c).

Lastly, the 850mb specific humidity composite anomaly values provide context on the spatial extent of atmospheric moisture available for uplift by Omegas during each season (Figure 10). Seasonal 850mb specific humidity composite anomaly-values are above normal across the entire study region throughout the year (Figure 10a-d).

5. Discussion

5.1 The 4.2 ka event and associated regional climate variability

Multi-decadal- to centennial-scale droughts were common phenomena in the Great Plains and western US during the late Holocene (Woodhouse and Overpeck, 1998; Cook et al., 2004; Schmieder et al., 2011; Cook et al., 2016), and were likely common phenomena throughout the Holocene. As previously noted, several ecological changes were recorded throughout the CRM and western Great Plains region in response to a severe and long-lasting drought between ~4200 and ~4000 cal yr BP (Carter et al., 2017a; Stokes and Gaylord, 1993; Halfen et al., 2010; Rawling et al., 2003; Schmeider et al., 2011; Mason et al., 2004; Goble et al., 2004; Stokes and Swinehart, 1997; Loope et al., 1995; Ahlbrandt et al., 1983; Madole, 1995). These regional ecological responses temporally coincide with drought conditions throughout the Great Plains region (see Booth et al., 2005). Other proxy evidence that supports regional dry conditions around this time are the high concentrations of sand influx between 4200 and 3800 cal yr BP in the Sand Hills of Nebraska (Schmieder, 2009), and lower reconstructed lake levels between ~5000 and ~3400 cal yr BP from several lakes in the CRM near Long Lake (Shuman et al., 2014; 2015). Additionally, Shuman and Marsicek (2016) synthesized paleoclimate data from the mid-latitudes of North America (i.e. northern Great Plains), which also support extensive drought conditions between 4700 and 4000 cal yr BP. However, the 4.2 ka event itself was a not predominant feature in their syntheses. Widespread and severe drought conditions were also recorded across western North America between 4700 and 4000 cal yr BP based on pollen, charcoal, diatom, grain-size analysis, testate amoebae assemblages, and speleothem stable isotopes, (Dean, 1997; Bernal et al., 2011; Schmieder et al., 2011; Lundeen et al., 2013; Morris et al., 2013; Wanner et al., 2015; Carter, 2016).

Conversely, cool and wet conditions have also been proposed throughout North America between 5500 – 3800 cal yr BP based on stable isotopes, pollen, tree-ring data, as well as by advances in glaciers (Menounos et al., 2008; Grimm et al., 2011; Mayrer et al., 2012; Anderson et al., 2016; Steinman et al., 2016). Namely, Grimm et al. (2011) did not record extensive drought conditions at 4200 cal yr BP in the northern Great Plains. Rather, the authors suggest a regime shift towards wet conditions around 4400 cal yr BP, which counters the finding presented by Booth et al. (2005). Similarly, in south-central Colorado, negative excursions in $\delta^{18}O$ values from Bison Lake, Colorado ~4200 cal yr BP, coupled with increases in spruce (*Picea*) pollen are interpreted as being indicative of colder-than-previous temperatures and increased snowfall (Anderson, 2012; Anderson et al., 2015). Lastly, treeline abruptly declined ~4200 cal yr BP in the Great Basin region further suggesting cool conditions (Salzer et al., 2014).

The ecological variability in proxy data across the western US and Great Plains at this time can be explained by several factors; 1) it could be a function of either site or proxy sensitivity, response time, or temporal resolution; 2) variable ecological responses may be due to surface climate responses to large-scale changes in the polar jet stream or even local-scale variability associated with topographic diversity (Mock, 1996; Shinker, 2010); 3) changes in composite anomalies for point locations can reveal different synoptic conditions (Mock and Anderson, 1997), thus it is to be expected that regions near the study region (i.e. the SRM and northern Great Plains) have different climatological responses; and 4) the 4.2 ka event was imbedded within a period of broad-scale climate reorganization which experienced several important climatic events. The most important climatic events to occur prior-to the 4.2ka event were the onset and intensification of the El Niño Southern Oscillation (ENSO) between 5000 and 4000 cal yr BP (Shulmeister and Lees, 1995; Barron and Anderson, 2010), and the documented switch from a more negative Pacific North-American (PNA) phase (i.e. more enhanced zonal circulation) to a more positive PNA phase (i.e. more enhanced meridional circulation) between 4200 and 4000 cal yr BP (Fisher et al., 2008; Anderson et al., 2016; Liu et al., 2014). Both ENSO and the PNA are primary controls of modern winter climate variability, primarily in the western US (Müller and Roeckner, 2006; Notaro et al., 2006; Allen et al., 2014), although impacts of ENSO in our study region of south-eastern Wyoming are minimal (see Heyer et al., 2017 and Wise, 2010). Positive PNA patterns are typically associated with positive winter temperature and negative precipitation anomalies over the Pacific Northwest (Wallace and Gutzler, 1981; Leathers et al., 1991; Allen et al., 2014). Together, these two modes of variability can influence the position of the jet stream which subsequently influences both modern, and likely past, regional temperature and precipitation in certain parts of western North America. Additionally, a weakening of the North American Monsoon (NAM) system is proposed to have occurred between 5000 and 4000 cal yr BP (Metcalfe et al., 2015). The NAM is another source of seasonal precipitation variability in the west, albeit largely in the southwest portion of North America (Adams and Comrie, 1997, Mock 1996, Shinker 2010). While our study region occasionally benefits from advection of moisture recycled from the southwest (Dominguez et al., 2009), the overall atmospheric circulation controls within the CRM is dominated by westerly winds via the polar jet stream, even in the summer (Mock 1996; Shinker 2010), versus the shift in circulation-driven winds in the southwest associated with the NAM (Adams and Comrie, 1997).

5.2 Regional climate variability at 4200 cal yr BP based on modern climate analogues of drought

Analysing proxy responses is crucial for identifying potential analogues (Fischer et al., 2018). By identifying extreme dry years from modern precipitation data, the modern climate analogue technique is used here to provide a potential scenario of the 4.2 ka drought that occurred in the CRM and western Great Plains. Identified dry case years for our study region illustrate slightly cooler-than-normal and slightly wetter-than-normal winter conditions in Wyoming, yet warmer-than-normal and drier-than-normal conditions across South Dakota and Nebraska (Figures 5 and 6). Great Plains winter precipitation, specifically January precipitation, is typically dry due to predominant north-westerly flow across the region (Mock, 1996). The slightly wetter than normal conditions in Wyoming cannot be explained by phases of ENSO as the study region is currently positioned within the ENSO dipole transition zone between 40º – 42ºN (Dettinger et al., 1998; Wise 2010) where consistently low correlation values between Pacific sea-surface temperature anomalies and cool season precipitation occur (Dettinger et al., 1998; Wise, 2010; Heyer et al., 2017). Thus, winter conditions in south-eastern Wyoming and the western Great Plains are currently not impacted by phases of ENSO (Heyer et al., 2017, Wise 2010), and likely haven't been impacted by phases of ENSO throughout the Holocene (Wise, 2016; Carter et al., 2013; Mensing et al., 2013). Therefore, while Barron and Anderson (2010) concluded an enhanced ENSO pattern c. 4.0 ka BP may have been associated with an increase in winter precipitation in the southern Rocky Mountains (Anderson et al., 2012), it is likely that the enhanced ENSO pattern contributed to an increase in variability of the polar jet stream (Heyer et al., 2017). This may have affected proxy-data that is more sensitive to winter-time precipitation (e.g. stable isotopes), and thus may have created the spatial inconsistencies of winter precipitation anomalies in the region in the past i.e. cool and wet conditions identified in the southern Rocky Mountains (Anderson et al., 2015) and Pacific Northwest (Steinman et al., 2016).

Winter precipitation is beneficial for vegetation during the growing season in the form of soil recharge via snowpack accumulation, yet peak precipitation maximum in the study region occurs during the late spring i.e. May (Mock, 1996). Thus, changes in late spring/early summer conditions are more likely to impact vegetation and soil recharge across the CRM and western Great Plains. Typically, southerly winds known as the Great Plains low-level jet (Schmeisser et al., 2010) are responsible for bringing in moist air from the Gulf of Mexico to the Great Plains region during late spring/early summer (Sridhar et al., 2006). These southerly winds are associated with the anticyclonic 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. Change and Smith (2000) suggest several other factors are involved with drought formation in the Great Plains region. First is the prominent anticyclonic feature positioned over the central portion of North America; second, the midtropospheric westerly winds weaken and become easterly winds in association with the anticyclonic high-pressure positioned over the Great Plains; and third, the Bermuda high-pressure has a westward displacement rather than a reduced or more easterly or southerly position, as suggested by Schmeisser et al. (2010). This westward displacement of the Bermuda high-pressure causes the enhancement of a low-level warm flow into the central Great Plains region causing the region to experience negative specific humidity anomalies. Drought conditions proposed by Schmeisser et al. (2010) were experienced during the spring of 2002/2012. Specifically, modern climate analogues clearly demonstrate that the low-level jet was closed off during the spring as a result of an anomalous ridge of high-pressure over the southern US/Central Great Plains region (Figure 7b), which resulted in a south-westerly component of flow into CRM and western Great Plains region (Figure 8b). This climatic situation likely inhibited growing season moisture from the Gulf of Mexico via the low level jet, which is especially important for dune stabilizing grasses and vegetation in the central Great Plains (Schmieder et al., 2011). In addition, the drought conditions proposed by Change and Smith (2000) were also experienced during the summer of 2002/2012. Modern climate analogues demonstrate an anticyclonic feature over the north-central Great Plains (Figure 7c), which resulted in an easterly to- south-easterly component of flow into the study region (Figure 8c). In both scenarios, we can speculate that the Bermuda High was strongly reduced and/or positioned in a way that allowed for the development and persistence of anomalous high-pressure ridges over the central region of the US throughout the growing season. While there were rising motions present in Great Plains region throughout the growing season (Figure 9), lower-than-normal moisture in the atmosphere (via 850 mb specific humidity) inhibited uplift and potential precipitation (Figure 10), thus further supporting dry conditions in the study region.

Modern climate analogues clearly demonstrate how drought conditions prevailed during the 2002/2012 growing season, as suggested by Schmeisser et al. (2010) and Change and Smith (2000), thus offering a potential analogue for drought conditions ~4200 cal yr BP. Therefore, based on the geographical proximity of our study region to the central Great Plains region, our hypothesis that severe and persistent droughts have the ability to affect the eastern most parts of the CRM is supported by the results of the modern climate analogue technique. Thus, these results offer a potential scenario to mechanistically explain the drought conditions documented at Long Lake ~4200 cal yr BP, and subsequent lagged ecological changes at Long Lake (Carter et al., 2013; 2017a), and at the Ferris and Casper dune fields of eastern Wyoming **(**Stokes and Gaylord, 1993; Halfen et al., 2010), the White River Badlands dunes of south-western South Dakota (Rawling et al., 2003), and the Nebraska Hills dunes of central Nebraska (Schmeider et al., 2011; Miao et al., 2007; Mason et al., 2004; Goble et al., 2004; Stokes and Swinehart, 1997; Loope et al., 1995; Ahlbrandt et al., 1983; Madole, 1995) ~4000 cal yr BP.

5.3 Limitations of the modern climate analogue technique

The modern climate analogue is beneficial in that it offers a way of understanding synoptic processes in the past (Barry, 1981). However, it does have a few limitations. The first and foremost is the assumption that the analogues used in this study represent megadrought conditions that persisted on decadal-to-centennial timescales. The current state of research is in general agreement that anomalous and persistent high pressure ridges over the Great Plains are one of the most common contributors of drought (Basara et al., 2013). Persistent high pressure ridges support subsidence (e.g. sinking vertical motions) which suppresses precipitation. Additionally, the clockwise flow of air associated with high pressure ridges prevent the typical southward movement of cold fronts from Canada which serve to organize spring rains, block delivery of moisture from the Gulf of Mexico, as well as inhibit convective thunderstorms which would normally contribute to summer precipitation in the Great Plains region (Hoerling et al., 2014). The role of anticyclones during drought has been observed in decadal to- multi-decadal model simulations (Herweijer et al., 2006). In addition enhanced anticyclonic circulation over the Great Plains was found to be a prominent feature causing mid-Holocene droughts in the region (Diffenbaugh et al., 2006). Thus, we presume the scenario presented in this study may be representative of droughts on longer timescales. Yet, we acknowledge that slow ocean dynamics and Pacific and Atlantic teleconnections, which are important components involved with Great Plains drought, may have been factors involved with megadroughts in the past. Yet, our analogues may not be representative of such dynamics, just as those teleconnections may lack mechanistic linkages. While it has been suggested from both modern observation and modelled data that a relationship exists between SSTs and drought (Trenberth et al., 1988; Palmer and Brankovic, 1989; Kalnay et al., 1990; Schubert et al., 2004; Basara et al., 2013; Cook et al., 2016), Hoerling et al. (2014) found weak evidence to support SST as a strong forcing on major droughts in the central Great Plains because droughts occurred in each phase of ENSO. As the relationship between Pacific and Atlantic teleconnections and slow ocean dynamics are not very well understood (Basara et al., 2013), our study does not investigate nor address internal variability or SSTs, both of which have been shown to contribute to droughts in these regions (Schubert et al., 2004; Herweijer et al. 2006). Future opportunities to test the synoptic drivers of prolonged drought presented here include data-model comparisons and regional climate modelling to investigate whether the analogues and the resulting climate scenario are reflective of decadal-to-centennial megadrought conditions.

6. Conclusion

Paleoecological reconstructions are valuable for understanding how ecosystems and disturbances respond to both gradual and abrupt changes in climate. However, proxy evidence preserved in sedimentary records are unable to record climatic mechanisms that caused the ecological responses. Using the modern climate analogue technique, our results offer potential climatic mechanisms that explains how persistent drought may have affected the vegetation composition at Long Lake, Wyoming, as well as impacted dune stabilising vegetation across the western Great Plains. Specifically, the modern climate analogues illustrate how drought conditions prevailed during the 2002/2012 growing season. Unique to all seasons are the anomalous high-pressure ridges positioned over the central region of the US which coincidently have been associated with the most recent droughts of the 20th century. In the spring, as suggested by Schmeisser et al. (2010), higher-than-normal geopotential heights over the southern US/Central Great Plains region resulted in the south-westerly component of flow, which inhibited moisture transport to the study region. As late spring/early summer precipitation is crucial for the region, the scenario presented by the 2002/2012 analogues would mechanistically explain how persistently dry conditions could result in the reduction of dune stabilising vegetation across the western Great Plains region identified by Stokes and Gaylord (1993), Halfen et al. (2010), Rawling et al. (2003), Schmeider et al. (2011), Mason et al. (2004), Goble et al. (2004), Stokes and Swinehart (1997), Loope et al. (1995), Ahlbrandt et al. (1983), and Madole (1995). The 2002/2012 analogues also illustrate an anticyclonic feature over the north-central Great Plains during the summer which resulted in an easterly to- south-easterly component of flow, prolonging drought conditions in the region (Chang and Smith, 2000). If the present scenario of persistently dry conditions existed between 4300 and 4100 cal yr BP, the 2002/2012 analogues also offer a mechanistic explanation that supports the surface paleoecological responses identified by Carter et al. (2013) i.e. the *Populus* period. The 2002/2012 analogues support the working hypothesis that due to the geographical proximity of the CRM (i.e. Long Lake, Wyoming) to the western Great Plains, synoptic processes causing widespread drought in the region influence the CRM. However, we acknowledge that the present study assumes that the 2002/2012 analogues are reflective of megadrought conditions that persist on decadal-to-centennial timescales. Future data-model comparisons should investigate whether the synoptic processes presented in this study hold true on decadal-to-centennial timescales.

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 provide better insight of past drought variability and the mechanisms that caused megadroughts evident in paleoecological records. This study demonstrated the benefits of applying a modern climate analogue technique to the paleoecological reconstruction from the CRM and the western Great Plains in order to better understand the potential climatic mechanisms that impacted ecological changes.

7. **Data Availability**

Modern climate analogue years were selected based on NOAA/NCDC Wyoming Climate Division 10, Wyoming Climate Division 8, South Dakota Climate Division 5, and Nebraska Climate Division 2 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). Pollen and charcoal data have been uploaded to the Neotoma Paleoecology Database web page: https://www.neotomadb.org/groups/category/pollen; https://apps.neotomadb.org/Explorer/?datasetid=24878. Pollen and charcoal data are interpreted at 1-cm resolution between depths 94 and 176 cm, as described by Carter et al. (2017a). Dune reactivation data was graciously obtained from the Supplemental Material uploaded by Halfen and Johnson (2013).

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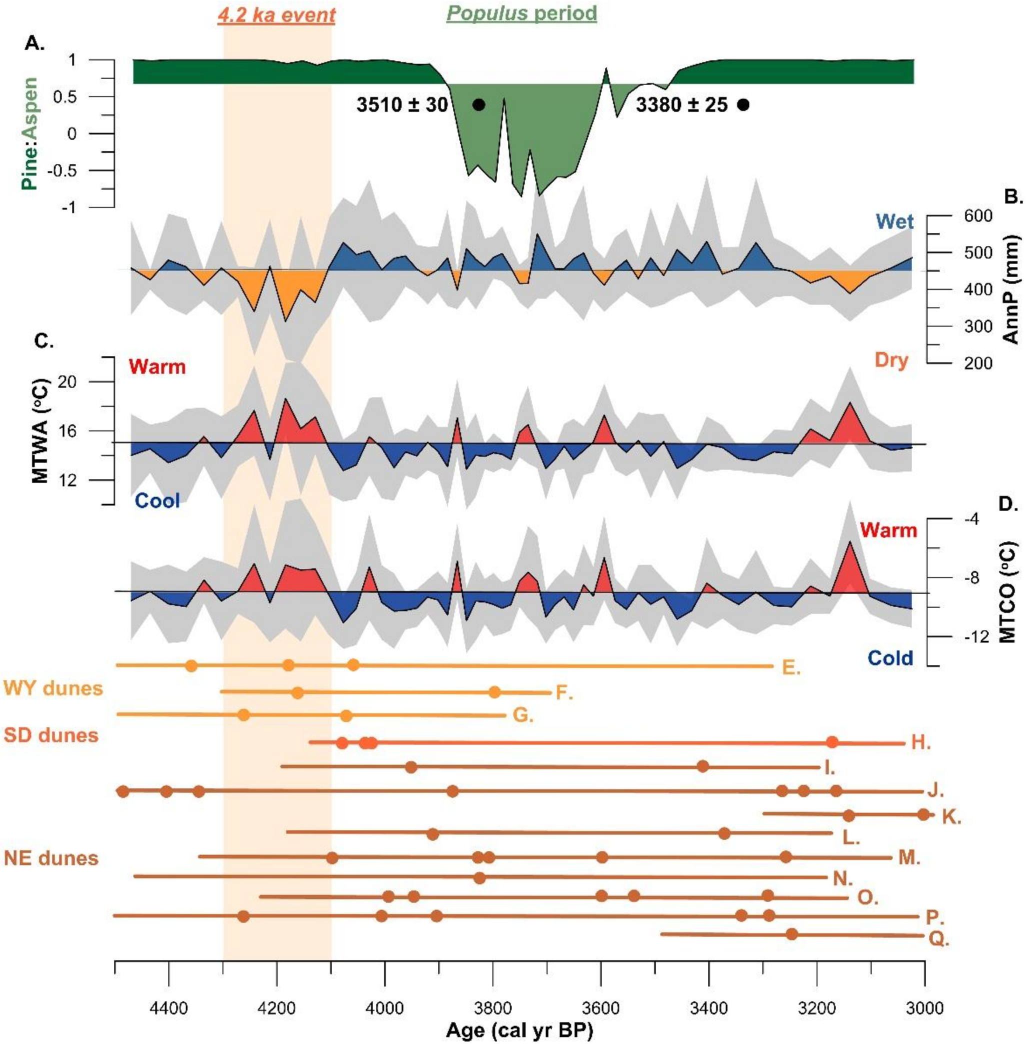

Figure 1. Regional paleo-proxy evidence supporting drought conditions between ~4200 and ~4000 cal yr BP. A. Pine:Aspen pollen ratio showing the *Populus* period - a change from a lodgepole pine dominated forest to a mixed forest of lodgepole pine-quaking aspen – from Long Lake, south-eastern Wyoming (Carter et al., 2013). Black circles illustrate radiocarbon dates that were used to temporally constrain the *Populus* period; B-D. Reconstructed climate variables from Long Lake, south-eastern Wyoming - annual precipitation (AnnP)), mean temperature of the warmest month (MTWA); mean temperature of the coldest month (MTCO) (Carter et al., 2017a); E-Q show clusters of radiocarbon and luminescence dates – age data error bars reflect those reported by the original authors, typically 1 to 2r; E. Ferris dunes, Wyoming (Stokes and Gaylord, 1993); E-G. Casper dunes, Wyoming (Halfen et al., 2010); H. White River Badlands dunes, South Dakota (Rawling et al., 2003); I. Nebraska Hills dunes, Nebraska (Schmeider et al., 2011); J. Nebraska Hills dunes (Miao et al., 2007); K-L. Nebraska Hills dunes (Mason et al., 2004); M. Nebraska Hills dunes (Goble et al., 2004); N. Nebraska Hills dunes (Stokes and Swinehart, 1997); O. Nebraska Hills dunes (Loope et al., 1995); P. Nebraska Hills dunes (Ahlbrandt et al., 1983); Q. Nebraska Hills dunes (Madole, 1995). Orange shading denotes the 4.2ka drought. Data was modified from Carter et al. (2013; 2017a), and Halfen and Johnson (2013).

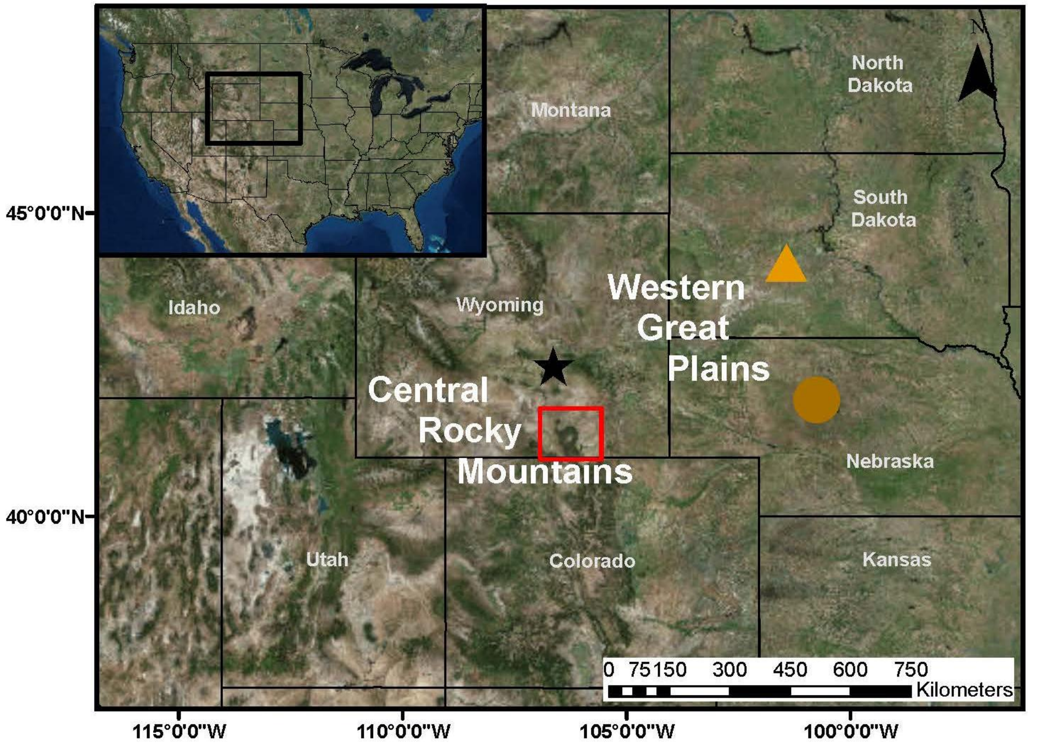

Figure 2. Location map of the study region in the western United States (small panel; black box). Sedimentary proxy data analysed in this study come from Long Lake, Wyoming (red box) located in south-eastern Wyoming within the central Rocky Mountain region on the edge of the western Great Plains. Long Lake experienced a unique change in vegetation composition ~4000 cal yr BP in response to persistent drought conditions ~4200 cal yr BP. Regionally, several dune fields reactivated in response to regional droughts ~4000 cal yr BP; the black star depicts the region where the Ferris dunes (Stokes and Gaylord, 1993) and Casper dunes (Halfen et al., 2010) are located. The orange triangle depicts the White River Badlands dunes (Rawling et al., 2003) of South Dakota. Lastly, the brown circle indicates the Nebraska Hills dune field (Schmeider et al., 2011; Miao et al., 2007; Mason et al., 2004; Goble et al., 2004; Stokes and Swinehart, 1997; Loope et al., 1995; Ahlbrandt et al., 1983; Madole, 1995).

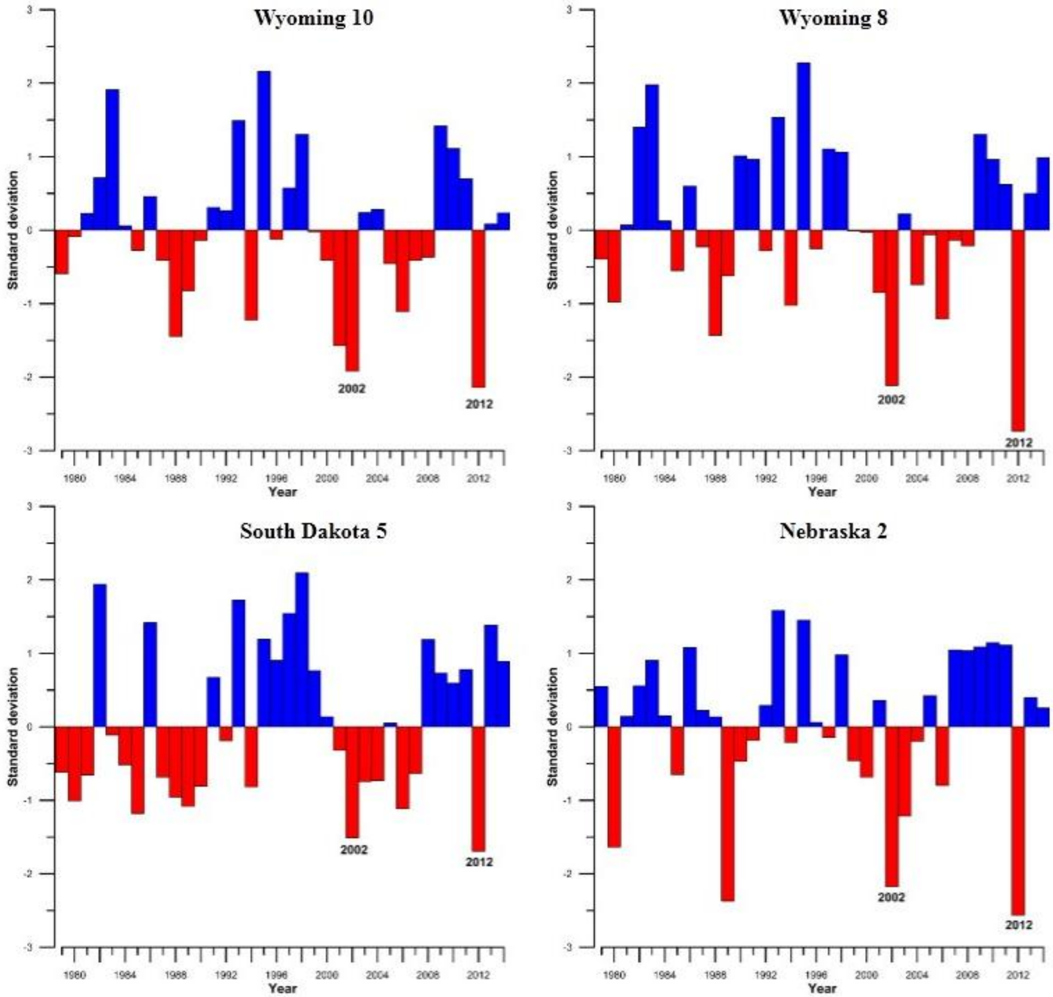

Figure 3. Time series of precipitation anomalies from Wyoming Climate Divisions 10 (top left) and 8 (top right), South Dakota Climate Division 5 (bottom left), and Nebraska Climate Division 2 (bottom right). Annual precipitation anomalies for 1979-2014 were compared to the long-term average (1981-2010) from each Climate Division. Case years that were greater than -1 standard deviations below the long-term average, or in the 10th percentile, were chosen as modern analogues to investigate dry conditions during the 4.2 ka megadrought in the central Rocky Mountains (Carter et al., 2017a), and western Great Plains (Stokes and Gaylord, 1993; Halfen et al., 2010; Rawling et al., 2003; Schmeider et al., 2011; Miao et al., 2007; Mason et al., 2004; Goble et al., 2004; Stokes and Swinehart, 1997; Loope et al., 1995; Ahlbrandt et al., 1983; Madole, 1995). Climate division data were collected from http://www.esrl.noaa.gov/psd/cgi-bin/timeseries/timeseries1.pl.

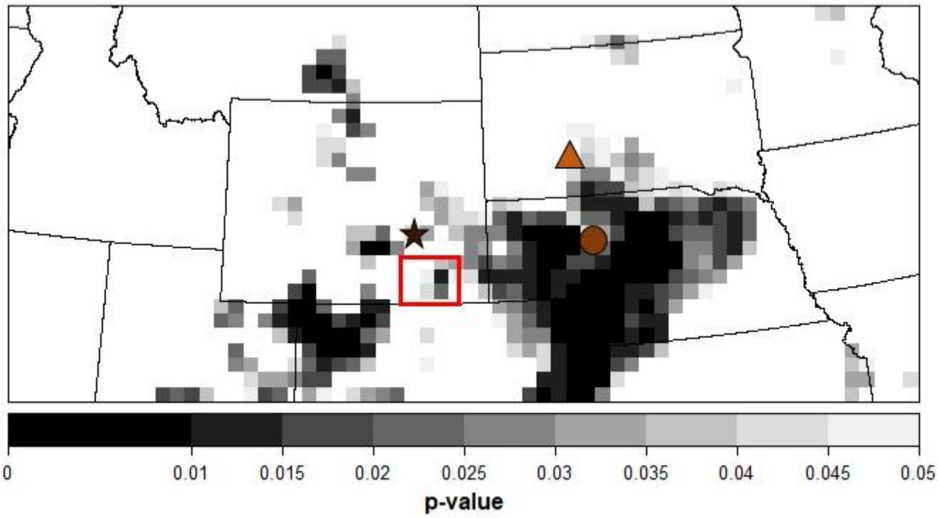

Figure 4. Map showing the spatial distribution of significant p-values ($p < 0.05$) during the two case years (2002 and 2012) across the central Rocky Mountains and western Great Plains, USA. P-values were evaluated using a two-tailed Student's t-test with an alpha of 0.05. Sedimentary proxy data from Long Lake, Wyoming (red box), as well as clusters of radiocarbon and luminescence dates from the Ferris and Casper dune fields (black star), the White River Badlands dunes (orange triangle), and the Nebraska Hills sand dunes (brown circle) all recorded severe drought conditions ~4200 cal yr BP (Carter et al., 2017a; Stokes and Gaylord, 1993; Halfen et al., 2010; Rawling et al., 2003; Schmeider et al., 2011; Miao et al., 2007; Mason et al., 2004; 2011; Goble et al., 2004; Stokes and Swinehart, 1997; Loope et al., 1995; Ahlbrandt et al., 1983; Madole, 1995).

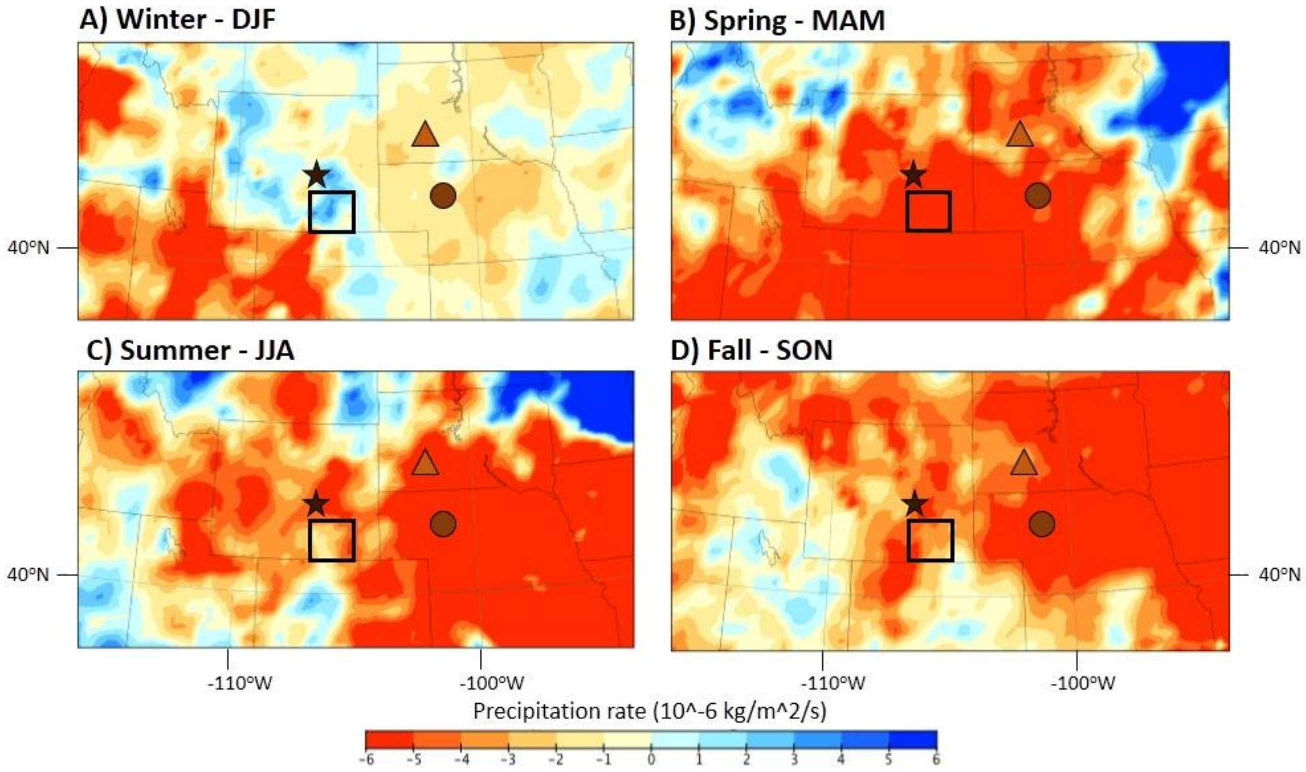

Figure 5. Composite anomaly maps for precipitation rate at the surface. A) Precipitation rate at the surface for winter (DJF); B) spring (MAM); C) summer (JJA); and D) fall (SON). Positive values (cool colours) for precipitation rate indicate wetter-than-normal conditions. Negative values (warm colours) indicate dryer-than-normal conditions. The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. The black star denotes the Ferris and Casper dune fields; the orange triangle denotes the White River Badlands dunes; and the brown circle denotes the Nebraska Hills sand dunes. Light grey lines depict lines of latitude/longitude.

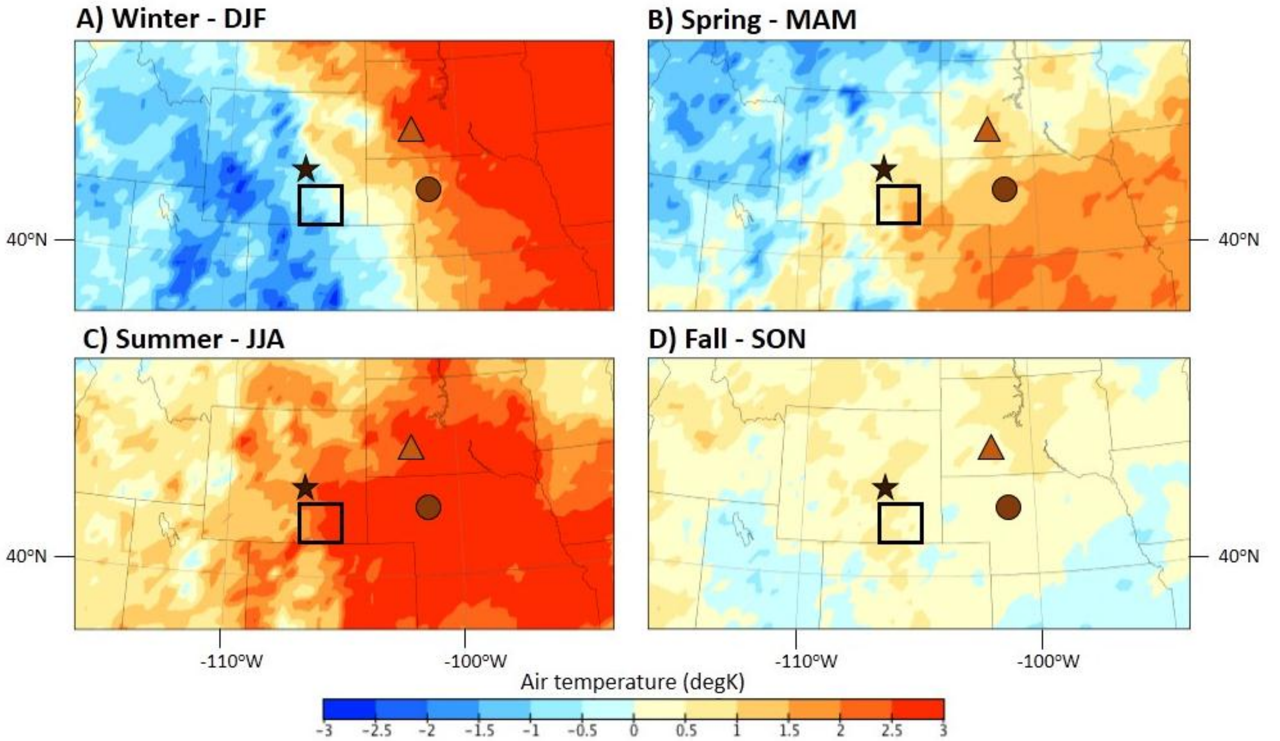

Figure 6. Composite anomaly maps for air temperature at the surface. A) Air temperature during the winter (DJF); B) spring (MAM); C) summer (JJA); D) and fall (SON). Positive values (warm colours) for air temperature indicate warmer-than-normal conditions. Negative values (cool colours) indicate cooler-than-normal conditions. The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. The black star denotes the Ferris and Casper dune fields; the orange triangle denotes the White River Badlands dunes; and the brown circle denotes the Nebraska Hills sand dunes. Light grey lines depict lines of latitude/longitude.

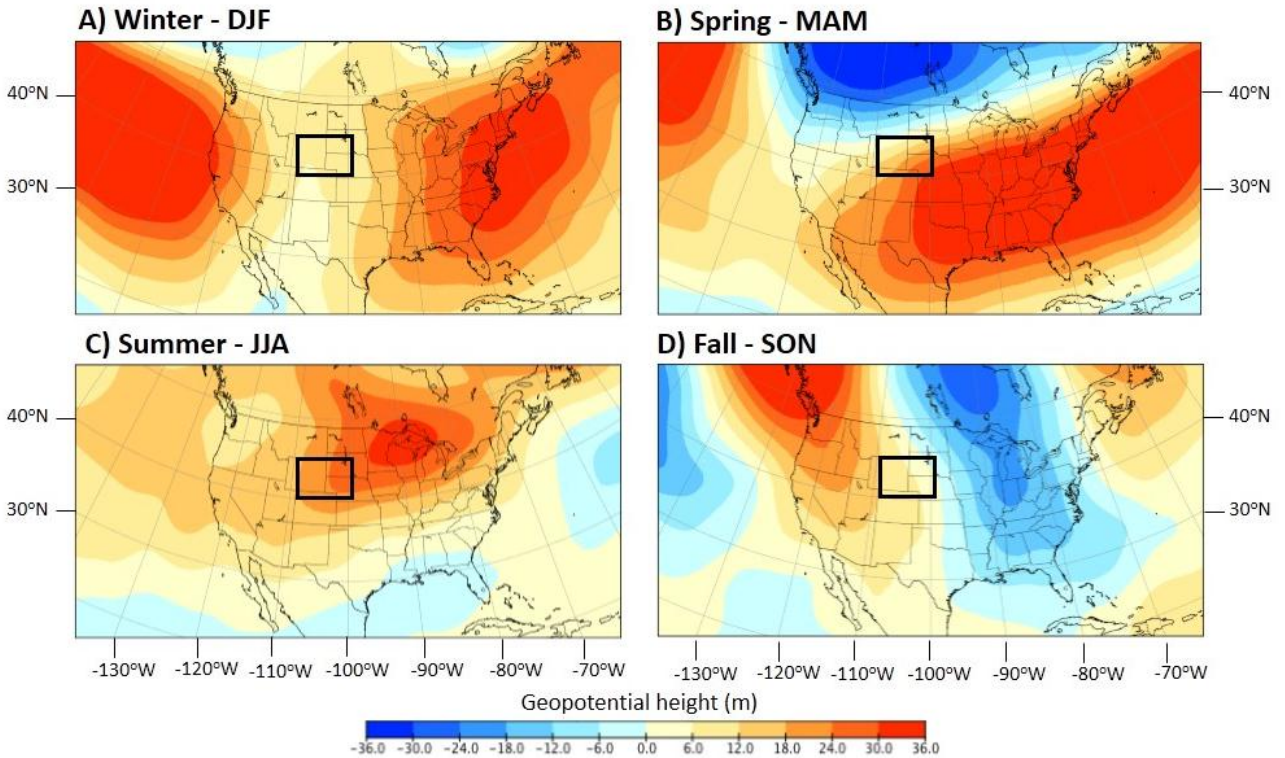

Figure 7. Composite anomaly maps for 500mb geopotential height during A) winter (DJF); B) spring (MAM); C) summer (JJA); and D) fall (SON). Positive values (warm colours) for 500mb geopotential heights indicate a stronger-than-normal ridge. Negative values (cool colours) indicate a strong-than-normal trough. The black box denotes the study region.

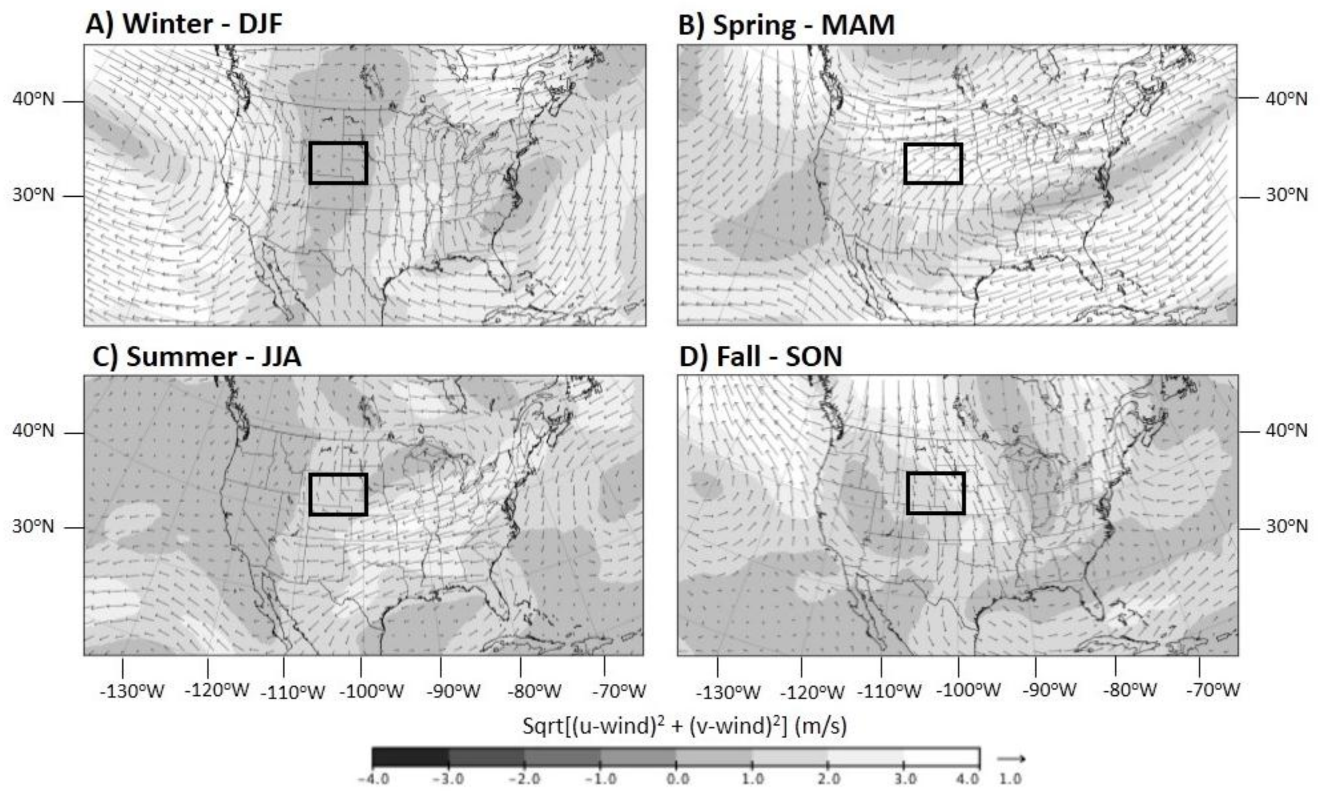

Figure 8. Seasonal composite anomaly maps for 500mb vector winds during A) winter (DJF); B) spring (MAM); C) summer (JJA); and D) fall (SON). The black box denotes the study region.

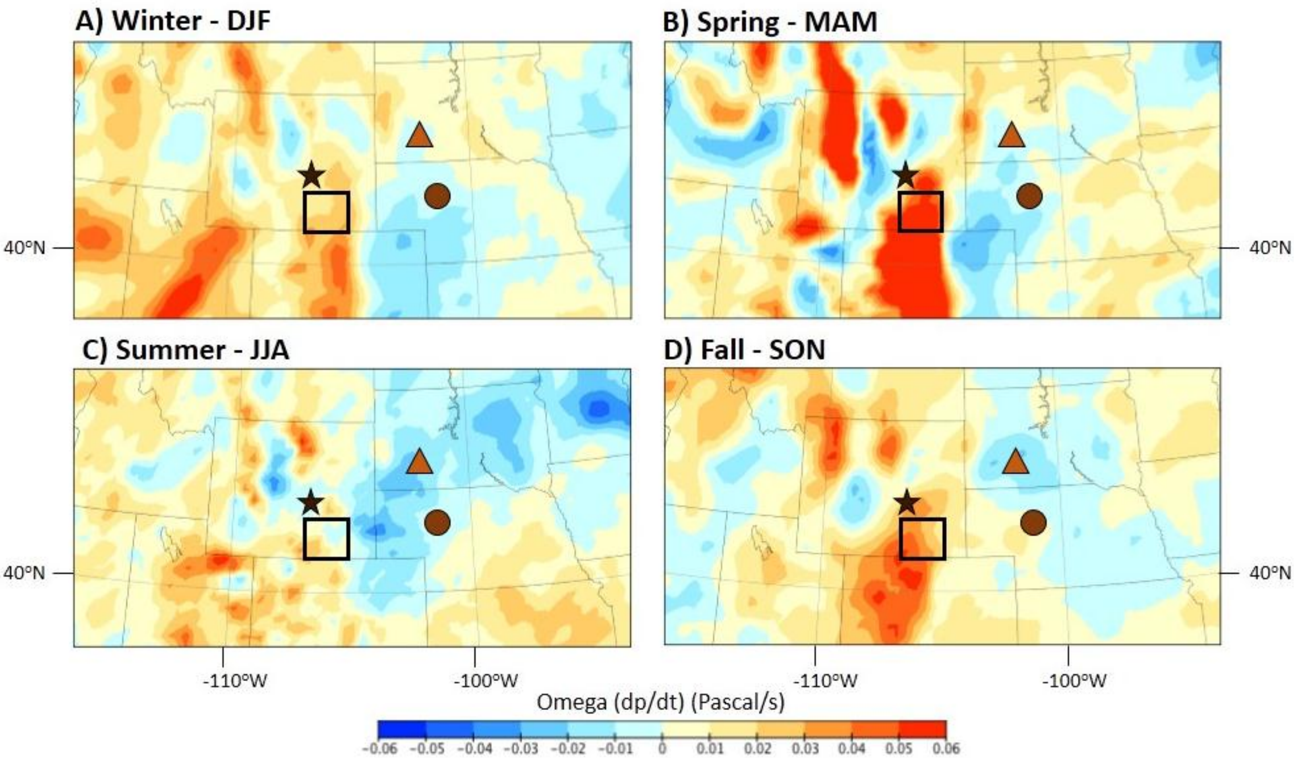

Figure 9. Composite anomaly maps for 500-mb Omega (vertical velocity) during A) winter (DJF); B) spring (MAM); C) summer (JJA); and D) the fall (SON). Positive values (warm colours) for omega indicate enhanced sinking motions (suppress precipitation). Negative values (cool colours) indicate enhanced rising motions (enhanced precipitation). The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. The black star denotes the Ferris and Casper dune fields; the orange triangle denotes the White River Badlands dunes; and the brown circle denotes the Nebraska Hills sand dunes.

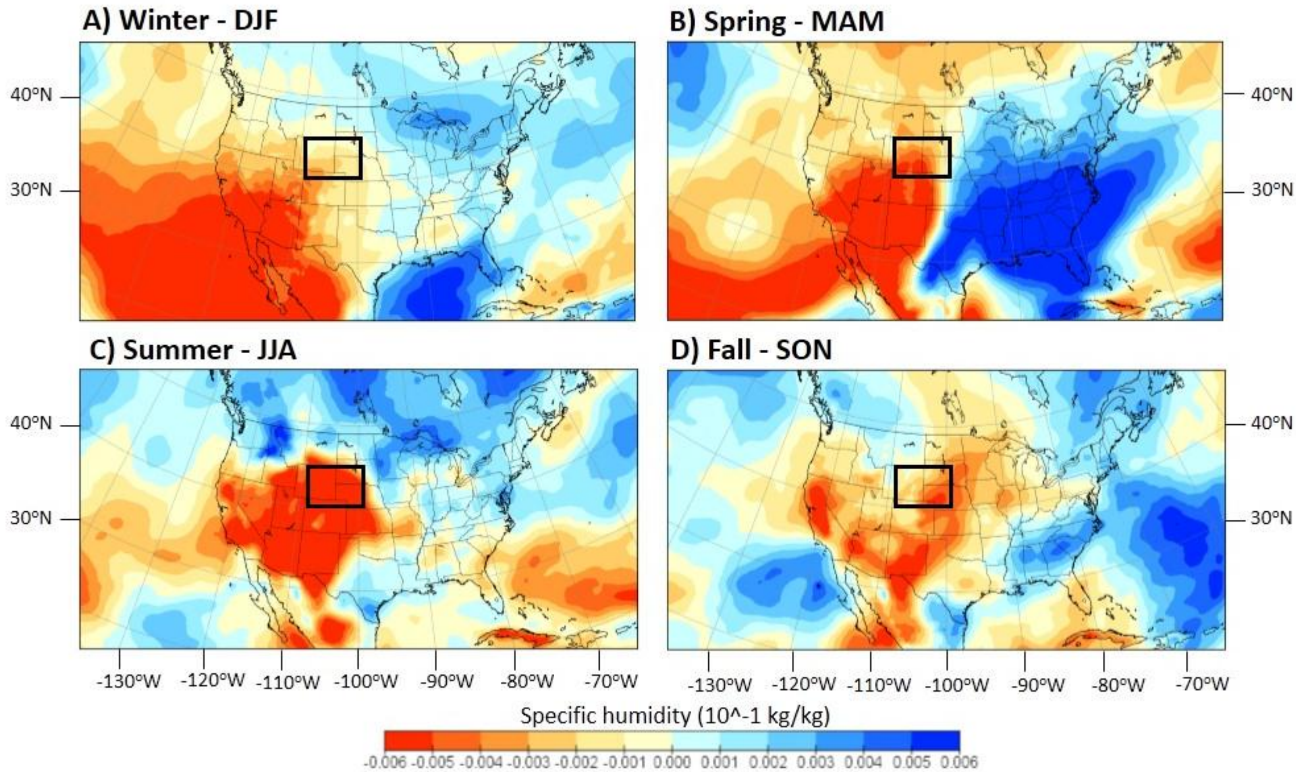

Figure 10. Composite anomaly maps for 850mb specific humidity during A) winter (DJF); B) spring (MAM); C) summer (JJA); and D) fall (SON). Positive values (cool colours) for 850-mb specific humidity indicate wetter-than-normal conditions in the atmosphere. Negative values (warm colours) indicate dryer-than-normal conditions. The black box denotes the study region.