Response to Editor

We would like to sincerely thank you for allowing us to resubmit our manuscript. We feel that this version has addressed all the major problems pointed out by Referee's #3, #4, and #5. Specifically, in this version, we have expanded our surface paleo response to include the western Great Plains region as several major sand dunes reactived around the same time we see unique changes in vegetation composition at our study site. As such, we redid our analyses in order to find the best analogues that best represent the paleo-surface conditions that occurred ~4200 cal yr BP. Lastly, as requested, we now have a new discussion section, '4.3 Limitation of the modern climate analogue technique' which specifically addresses the limitations of using the modern climate analogue technique as a method for analyzing past synoptic dynamics. As pointed out by Referee #4, the largest assumption, in our case, is that our two analogues are reflective of megadrought conditions that occur on decadal-to-centennial timescales. In addition, we now express more uncertainty in the language of our manuscript. We hope it is now clearer in the language that this method simply offers a scenario of the 4.2 ka drought in our study region. We hope that our research presents an opportunity for the modeling community to test whether the results of our study are valid representations of megadrought conditions on decadal-to-centennial timescales.

Response to Reviewer #3

Dear Reviewer #3. Thank you for your kind comments in Comment #1, as well as your input and suggestions in Comments #2 through 4. We believe your suggestions have improved the manuscript.

Comment #2: The conclusion is rather long. The middle paragraph should be removed from there, and possibly merged in the discussion section.

Response to comment #2: Thank you for your suggestion. We have deleted the middle paragraph from the conclusion section, and incorporated it into the discussion section where needed.

Comment #3: Line 26 "Yet, the exact timing of drought conditions based on different proxy varies spatially and temporally" needs more details. For example, what are the main causes for the spatial and temporal variations?

Response to comment #3: We apologize this was unclear. The previous paragraph was supposed articulate how the different proxies discussed varied spatially and temporally. We have removed this sentence from the manuscript since it was confusing for the reader.

Comment #4: P9-line 5: Need a brief introduction to 'Bond event 3".

Response to comment #4: Per recommendation to stream line the discussion, we have deleted segments of the discussion, including the paragraph this sentence was included in. Thus, we did not introduce Bond events in the manuscript.

Additional comment #1: You use the modern 5-anomaly dry years as representation to discuss the 4200 years climate mechanism. Does it mean that you can draw the same conclusion for the other droughts in your sedimentary core if there is any?

Response to Additional comment #1: Yes, we can draw the same conclusion. Carter et al. (2017a) also observed this same lagged vegetation response in response to the 1930s or 1950s drought. The 1930s and 1950s droughts experienced anomalous high-pressure ridges over the central US. Anomalous high-pressure ridges were experienced in our analogues. Thus, we hypothesize that the synoptic processes present during the 1930s/1950s drought must have been present during the 4.2ka drought as both cases resulted the brief increase in quaking aspen.

Additional comment #2: How do you deal with the fact that while around 4200 the vegetation is dominated by Populus, and that now it is dominated by conifers. That means the climatic conditions are very different, yet your reconstruction of the 4.2 dry event is based on pollen.

Response to Additional comment #2: We believe the previous response also helps answer this comment. You are correct in that the vegetation composition is currently different, yet, the aspen ecotone is ~200 m downslope from Long Lake. This means that at present, conditions are not conducive for quaking aspen to dominate at Long Lake. However, in the 1950s and ~4000 cal yr BP, we see a brief increase in quaking aspen, likely in response to the 1930/1950s drought and the 4.2ka drought. The relationship between drought, increased temperatures and widespread quaking aspen mortality has been observed across western North American, thus we hypothesize that because of drought conditions, quaking aspen (which makes up the lower treeline in the Medicine Bow Range) migrated upslope to cooler conditions. We briefly discuss both of these additional points on Page 2 in the Introduction section.

<u>Response to Reviewer #4</u>

Dear Reviewer #3. Thank you for stepping in the editorial process of this article. We feel that your comments and suggestions greatly improved the direction of the new revised manuscript. Specifically, we now explicitly state the degrees of freedom used in the Student t-test in the Methods section (see page 5 lines 27-29). In addition, we now state in plain language, the objective of the approach in the last paragraph of the Introduction (see page 4 line 10), as well as have added a new discussion section '4.3. Limitations of the modern climate analogue technique' (see page 11) where we discuss the largest assumption in our paper; the assumption that our two analogues represent megadrought conditions that occur on decadal-to-centennial timescales. In this new discussion section, we offer words of encouragement to the modelling community to further explore the scenario presented in this study.

Comment #1: the column “Purpose of Climate Variable” in Table 1 is appallingly trivial.

Response to comment #1: Thank you for pointing this out. Since we state in the results section, the objective of each climate variable, we have removed Table 1 from the manuscript.

Comment #2: There is also a mistake in the numbering of sections and subsections starting at subsection 4.1

Response to comment #2: We apologize about this mistake. We have fixed the numbering of all sections and subsections.

Comment #3: p.12 l. 33: The citation ‘Using a complex numerical weather-prediction model with data from May 1987 to May 1988. Palmer and Brankovic (1989) had significant skill in prediction an anomalous high pressure ridge over North American during the summer of 1988” is about a trained prediction model, and is irrelevant in the present context.

Response to comment #3: We have deleted this sentence from the manuscript.

Comment #4: Citation “By applying the modern climate analogue technique to paleoenvironental proxies from the mid-continent, Shinker et al. (2006) found that regional moisture influx and small-scale vertical motions in the atmosphere (i.e. subsidence or uplift) provide better information regarding precipitation than large-scale general circulation alone.” The wording is inaccurate. Shinker examined modern climatological data, to indeed observe better predictor of precipitation than large-scale circulation in the modern climate. They then used this insight to help and contribute to the interpretation of paleoclimate data. It is only at the latter stage that the hypothesis of an analogy applies.

Response to comment #4: We have reworded this sentence, which now states ‘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.’

Response to Reviewer #5

Dear Reviewer #5. Thank you for your kind words of support. We are pleased to hear you enjoyed the paper.

Comment #1: This paper relies heavily on the pollen reconstruction in Carter et al 2013. I realized this data has already been published, but it seems very awkward that the pollen in not shown in a figure, as it is a major part of the manuscript. Perhaps the authors think this is redundant (as it is already published elsewhere), however to the reader (especially in the paleo community) it would make visualizing the changes at Long Lake through time much easier. I would encourage the authors to consider including the relevant pollen data from Long Lake either incorporated into an existing figure, or as a new figure itself.

Response to comment #1: Thank you very much for your suggestion. You are absolutely correct in that it would help the reader better visualize the changes seen at Long Lake. We now include the necessary pollen data, as well as have included the climate reconstruction from Carter et al. (2017a) to help the reader visualize the response of aspen to the megadrought identified ~4200 cal yr BP. This data is now in Figure 1 (see below). In addition, we have included a larger spatial area in this version of the manuscript to include several regional dune fields that reactivated around this time period. This paleo data is also included in the new Figure 1.

Comment #2: The authors should include the reference “Oxygen isotope records of Holocene climate variability in the Pacific Northwest” (Steinman et al., 2016) reference in line 30 on page 8 and perhaps in some other section in the paper. Steinman et al 2016 presents high-res oxygen isotopes records from three lakes that suggests the middle Holocene winters were wetter in western North America. This paper also provides model-based evidence and a robust review of paleoclimate literature from the Pacific Northwest. This may be of use to the authors during revision.

Response to comment #2: Thank you for pointing out this paper. We have included it alongside the other references on page 8 that indicate cool and wet climatic conditions during this time.

Comment #3: Lines 14-15, page 9: Steinman et al 2016 suggest a shift to more ENSO-like condition (i.e. drier winters) in the Pacific Northwest from approximately 3000-2000 cal yr BP. The references and discussion in this section needs to be updated to include other regional records.

Response to comment #3: 1. Thank you for the suggestion. However, we did not discuss this point in the manuscript for two reasons; 1) the time period 3000-2000 is beyond the inflection point of the 4.2 ka event; and 2) the PNW and its teleconnection to ENSO are very different than the CRM and Great Plains. We did include the Steinman et al. (2016) citation on page 10 line 10 as we discuss how the different regional precipitation anomalies could be the result of proxies more sensitive to winter-precipitation i.e. ENSO teleconnections.

Comment #4: I believe this was added to satisfy a reviewer, but why is the principle of uniformitarianism even stated. I feel that this is understood. I would defer to the authors discretion, but this is also awkward wording. I think something like “assuming similar conditions as modern” or something comparable would suffice.

Response to Comment #4: We have removed all discussion regarding the principle of uniformitarianism from the manuscript.

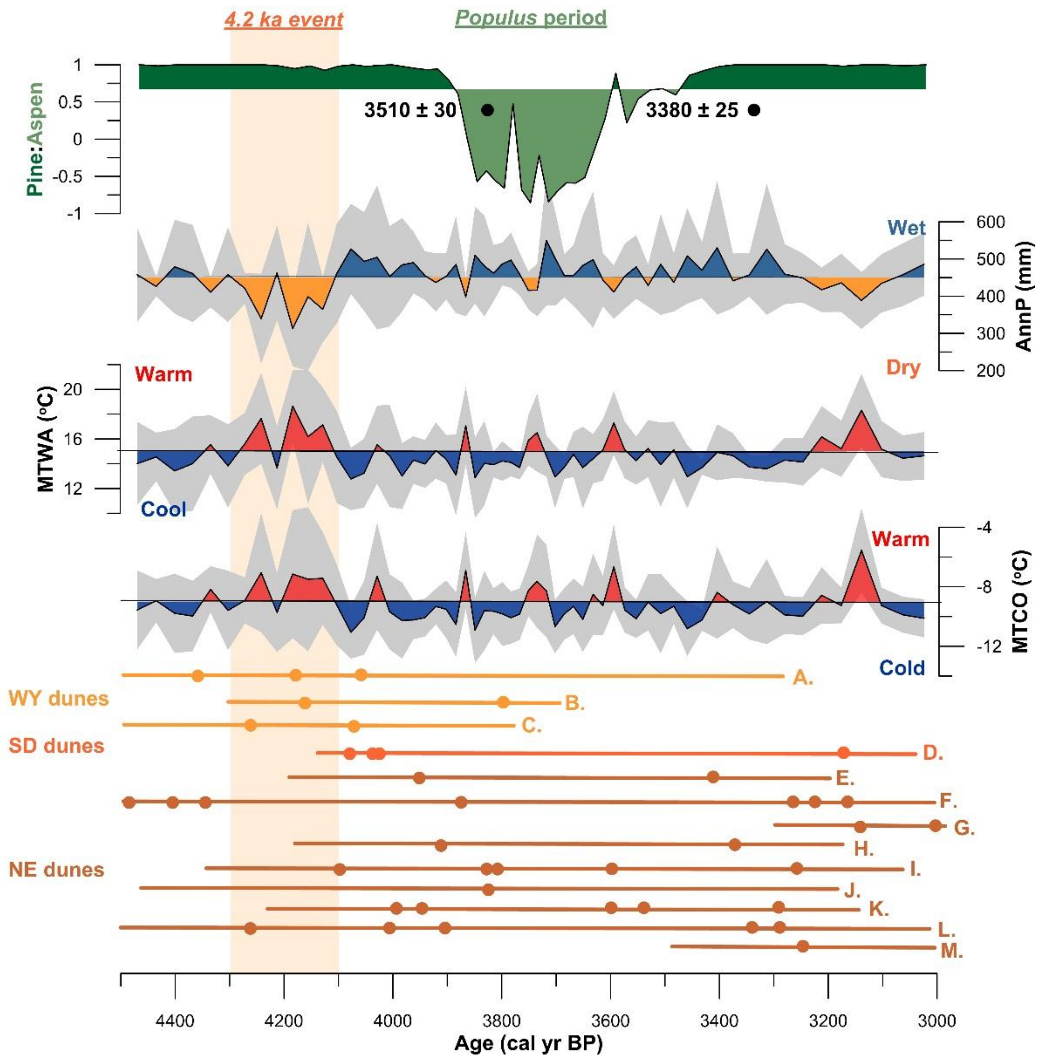
Comment #5: Lines 6-9, page 3: Two uses of the word ‘analogue’ in the sentence. Confusing wording.

Response to Comment #5: This sentence is describing what the modern climate analogue technique is. I believe because we forgot to include the word ‘technique’ after the first analogue, the reader was unable to determine the context of the sentence. We have reworded this sentence in the hopes that it is now more easily understandable; “The modern climate analogue technique is a conceptual model that uses modern extremes (e.g. drought) as analogues of past events (e.g. vegetation disturbance associated with drought in the sedimentary record) 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).”

Comment #6: There is a typo at the end of Line 8 on page 2.

Response to Comment #5: Thank you for pointing out this mistake. However, we have removed this paragraph from the new version.

Proposed Figure 1.



Proposed Figure 1 figure caption. Regional paleo-proxy evidence supporting drought conditions ~4200 and ~4000 cal yr BP. From Long Lake, south-eastern Wyoming, Carter et al. (2013) identified a brief change in vegetation composition from a lodgepole pine dominated forest to a mixed forest of lodgepole pine-quaking aspen, known as the *Populus* period (top), likely in response to the 4.2 ka drought (orange shading). Using the modern climate analogue technique, Carter et al. (2017a) reconstructed persistently dry (reduced annual precipitation (AnnP)), and warm (increased Mean Temperature of the Warmest Month (MTWA); Mean Temperature of the Coldest Month (MTCO)) conditions between 4300 – 4100 cal yr BP. These drought conditions temporally correspond to the 4.2 ka event. Regionally, several dune fields reactivated around this time period, as demonstrated by clusters of radiocarbon and luminescence dates; Age data error bars reflect those reported by the original authors—typically 1 to 2r; A-C represent dunes located in Wyoming near Long Lake, Wyoming; A. Ferris dunes (Stokes and Gaylord, 1993); B-C. Casper dunes (Halfen et al., 2010); D represents South Dakota dune fields relatively near

Long Lake, Wyoming; D. White River Badlands dunes (Rawling et al., 2003); E-M represent dunes located in Nebraska relatively near Long Lake, Wyoming; E. Nebraska Hills dunes (Schmeider et al., 2011); F. Nebraska Hills dunes (Miao et al., 2007); G-H. Nebraska Hills dunes (Mason et al., 2004); I. Nebraska Hills dunes (Goble et al., 2004); J. Nebraska Hills dunes (Stokes and Swinehart, 1997); K. Nebraska Hills dunes (Loope et al., 1995); L. Nebraska Hills dunes (Ahlbrandt et al., 1983); M. Nebraska Hills dunes (Madole, 1995). Data was modified from Carter et al. (2013; 2017a), and Halfen and Johnson (2013).

Please see the reference list for citations included in the new Figure 1 caption.

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.

Vachel A. Carter[1,2], Jacqueline J. Shinker[3], Jonathon Preece[3]

[1]RED Lab, Department of Geography, University of Utah, Salt Lake City, UT, 84112, USA
[2]Department of Botany, Charles University, Prague, 12801, Czech Republic
[3]Department of Geography and Roy J. Shlemon Center for Quaternary Studies, University of Wyoming, Laramie, WY, 82071, USA

Correspondence to: Vachel A. Carter (vachel.carter@gmail.com)

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. ~~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 sedimentary pollen evidence 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 pollen data to provide a conceptual framework for exploring possible mechanisms responsible for the observed ecological changes. The modern climate analogues illustrate that persistent warm and dry conditions throughout the growing season were a result of anomalously higher-than-normal geopotential heights centred over the Great Plains, which suppressed moisture transport via the low level jet from the Gulf of Mexico, as well as brought in dry continental air from the interior region of North America. Associated climatic responses are consistent with local and regional proxy data suggesting regional drought conditions ~4200 cal yr BP in the central Rocky Mountains and central Great Plains. Persistent drought-like conditions provide insight as to the mechanisms that facilitated abrupt changes in vegetation composition in the past in our study region of south-eastern Wyoming.~~

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~~Throughout the 20th century,~~ 1930s and 1950s droughts were the most extensive and long lasting (Schubert et al., 2004), which~~ droughts~~ ~~have~~ caused both economic and societal losses throughout the regions ~~Great Plains and the western United States (US)~~ (Diaz, 1983; ~~Karl and Koscielny, 1982; Karl, 1983;~~ Woodhouse and Overpeck, 1998). ~~However,~~Yet, when compared to proxy data, modern ~~these most~~ era ~~recent~~ 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 1), 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 1), 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 1A-M), 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.

~~Globally averaged land and ocean temperatures have increased in recent decades, which have affected the hydrological cycle and subsequent moisture availability in these regions (IPCC, 2014). Subsequently, drought vulnerability has increased in both the Great Plains and western US (Garfin et al., 2013). In the Upper Platte River drainage basin (the region of interest in this study), there has been a 1.44°C 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 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.

Since 1970, widespread forest mortality on a global-scale has occurred as a result of water or heat stress (Allen et al., 2010). Drought and increased temperatures have resulted in widespread mortality among certain western North American , quaking aspen (*Populus tremuloides* Michx.) communities (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). 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 Upper Platte River drainage basin. Proxy evidence from Long Lake documents a change from a pine-dominated forest to a mixed-forest with pine and quaking aspen which the authors have coined as the '*Populus* period.' Subsequently, Carter et al. (2017a) 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 temporally constrained ~150-year long drought between 4300 and 4100 cal yr BP likely influenced the upslope migration of quaking aspen stands in the Medicine Bow Range of south-eastern Wyoming, while frequent fire activity may have led to the ~500-year persistence of quaking aspen. This ~150-year long drought may be associated with the 4.2 ka 'megadrought' that occurred throughout the Great Plains region (Booth et al., 2005).

While sedimentary proxy data such as pollen and charcoal provide a record of changes in past vegetation and disturbances (e.g.such as fires or drought), they do not provide a record of the climatic mechanisms that initially 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). events. Thus, iImproving our understanding of the climate processes associated with modern drought will provide better insight about past drought variability, and the mechanisms associated with 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 past drought seen in proxy data is through the use of 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 goal of the modern climate analogue technique is to provide examples of how synoptic processes work in order to explain paleoclimatic variations in the past (Mock and Shinker, 2013), and is therefore 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; Carter et al., 2017b). TheA modern climate analogue technique is a conceptual model that uses modern extremes (e.g. drought) as analogues of past events (e.g. vegetation change disturbance associated with drought in the sedimentary record) as a means to understand palaeoclimate patterns that may have caused historic paleoecological variability 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; Shinker, 2014; 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.. By applying the modern climate analogue technique to paleoenvironnmental proxies from the mid-continent, Shinker et al. (2006) found that regional moisture influx and small-scale vertical motions in the atmosphere (i.e. subsidence or uplift) provide better information regarding precipitation than large-scale general circulation alone. The authors' stress that controls of surface and atmospheric processes must also be addressed in paleoclimate reconstructions as these can override the influence of broad circulation patterns (Shinker et al., 2006).Similarly, Edwards et al. (2001) used the modern climate analogue 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. 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. By applying the modern climate analogue technique to paleoenvironnmental proxies from the mid-continent, Shinker et al. (2006) found that regional moisture influx and small-scale vertical motions in the atmosphere (i.e. subsidence or uplift) provide better information regarding precipitation than large-scale general circulation alone. The authors' stress that controls of surface and atmospheric processes must also be addressed in paleoclimate reconstructions as these can override the influence of broad circulation patterns (Shinker et al., 2006). Similarly, Shinker (2014) investigated used the modern climate analogue technique to understand 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 in the Upper Arkansas River basin (Shuman et al., 2009; 2010). Edwards et al. (2001) used the same modern climate analogue 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 describe how atmospheric conditions could have potentially created contributed to the unique spatial patterns of wildfire activity over the past 1200 years in the northern and southern Rocky Mountains, as seen in 37 sedimentary charcoal records.

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.

Here we apply a modern climate analogue approach similar to Shinker et al. (2006; 2014) to a paleoecological reconstruction from Long Lake, Wyoming by using an environment-to-circulation approach (Barry and Carleton, 2001; Mock and Shinker, 2013; Shinker, 2014; Yarnal, 1993; Yarnal et al., 2001). An environment-to-circulation approach considers the surface conditions based on information gained from the proxy data collected from lake sediments (Mock and Shinker, 2013). In this study, the proxy data were collected from Long Lake, Wyoming (Carter et al., 2013; 2017a). By identifying extremes in the modern record (e.g. anomalous dry conditions), the environment-to-circulation approach will be used to investigate potential climate mechanisms associated with drought conditions reconstructed from sedimentary proxy data from Long Lake, Wyoming. This paper focuses on the relationship between atmospheric synoptic processes and surface climate mechanisms and their influence on the ecological changes recorded during the *Populus* period identified by Carter et al., (2013; 2017a).

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 21). 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 -precipitationMay precipitation maximum in May (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 have 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 1; 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 Lakethe 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). 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). Lodgepole pine has been the dominant canopy cover type for the past ~8000 years (Carter et al., 2013). However, the region experienced a rapid change 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 drought conditions centred on 4200 cal yr BP (Carter et al., 2017).

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) also updated the age-depth relations from Carter et al. (2013) with the additions of an AMS radiocarbon date that was used to temporally constrain the upper and lower ages of the '*Populus*' period (Figure 1; also see Carter et al., 2017a), as well as provides an upper age constraint on as well as temporally constraint the drought at 4200 cal yr BP (see Table 1, Carter et al., 2017a).

3. Methods

Modern climate analogues and calculation of composite-anomaly values

To investigate In order to identify potential climate mechanisms that may be associated with the ecological changes in vegetation composition 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~~2~~);~~.~~ ~~The~~ Upper Platte River basin ~~was chosen because it~~ encompasses the Medicine Bow Range where Long Lake and the sedimentological analyses were collected from (Carter et al., 2013; 2017a). Additionally, 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, a~~A~~nnual 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)~~ to create a time series of annual precipitation anomalies~~. ~~The time 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 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 10th 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. ~~(e.g. dry case years) that were identified to be the most statistically dry years were selected to represent similar conditions (e.g. anomalously dry) that would have potentially caused the ecological response identified in the sedimentary analyses conducted by Carter et al. (2013; 2017a) . In this study, case years that were -1 standard deviations below the long-term average (one standard deviation being equivalent to 58.89 mm per year) were selected as modern analogues.~~ 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. ~~Statistical significance of each case year were evaluated at each grid point in our study region using a two-tailed Student's t-test with an alpha of 0.05 to quantify significance.~~ 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 ~~of south-western Wyoming~~ (Figure 4~~2b~~).

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. ~~For the purpose of understanding modern synoptic processes that may have influenced vegetation change, a variety of surface and atmospheric climate variables from the NARR dataset (Mesinger et al., 2006) were used to calculate and map anomalous patterns (Table 1).~~ 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) t~~T~~he 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, t~~T~~he 32-km resolution is ~~therefore~~ valuable for capturing the topographic and climate diversity of the geographic study region. The seasonal values (e.g. winter = December, January, ~~and~~ February (~~; or~~ 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. ~~These composite-anomaly values were mapped in order to analyze and assess the spatial and temporal variability of both the surface and atmospheric variables to identify conditions that would support vegetation change identified in the sedimentary record.~~ 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

~~4.1~~ Modern climate analogues of extreme dry conditions in the CRM and western Great Plains~~Upper Platte River Basin~~

4.1~~.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 ~~for precipitation~~ are ~~slightly~~ 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 ~~in the study region~~ (Figure 5~~3~~a). ~~However, based on the time-series, the overall annual average was lower-than-average throughout the case years.~~ Spring (MAM) precipitation rate composite-anomaly values ~~for precipitation rate~~ indicate a shift toward significantly ~~slightly~~ drier-than-normal conditions across the entire study region (Figure 5~~3~~b), which persisted through the~~. s~~S~~ummer (JJA) ~~composite-anomaly values indicate an increase in aridity~~ (Figure 5~~3~~c) and into the ~~that persisted in the region through the~~ fall (SON) (Figure 5~~3~~d).

~~Seasonal C~~Composite-anomaly maps for winter (DFJ) temperature ~~(Figure 4) provide information on local surface conditions during the anomalous case years. Winter (DJF) composite-anomaly values~~ indicate ~~are slightly~~ 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 ~~in the region~~ (Figure 6~~4~~a). 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)persisted from summer into the fall (Figure 64d).

44.1.2 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. 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) 500mb geopotential height composite-anomaly values for 500mb geopotential height show- slightly higherlower-than-normal heightspressure centred off both US coasts over the interior of Canada and extending down over the Great Plains, and higher-than-normal pressure in the north Pacific (Figure 75a). Spring (MAM) composite-anomaly values indicate a higher-than-normal heightspressure centred over the central Great Plains and south-eastern US region (Figure 75b), which shifted north over the Midwest and northern Great Plains region during the summer (JJA) (Figure 75c). Fall (SON) composite-anomaly values show slightly higher-than-normal heightspressure off the coast of British Columbia, and lower-than-normal pressure centred over interior Canada the western US (Figure 75d).

The 500mb vector wind composite anomaly maps provide information about wind direction and on the anomalous component of flow (Figure 86), which is associated with the 500mb geopotential height composite-anomaly valuesmaps. For winter (DJF), there is no anomalous component of flow is northerly into the study region -(Figure 86a). 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 to south-east (Figure 86b) associated with the clockwise flow of air around the anomalous ridge centred over the central Great Plains and south-eastern US region seen in (Figure 75b). During the summer (JJA), the anomalous component of flow is from the east, south-east (Figure 86c) associated with the clockwise flow of air around the anomalous ridge over the Midwest and northern Great Plains region seen in Figure 75c. For fall (SON), the anomalous component of flow is northerly into the study region (Figure 86d).

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~~ing~~ anomalous rising motions that enhance precipitation (Figure 9~~7~~). Winter (DJF) 500mb Omega composite-anomaly values ~~maps for 500mb Omega~~ indicate ~~weak~~ slight ~~anomalous~~ 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 ~~in the study region~~ (Figure 9~~7~~a). However, rising motions become anomalously positive over Long Lake, and the Ferris and Casper dune fields during the spring ~~Spring~~ (MAM) and f~~F~~all (SON) ~~composite-anomaly maps indicate strong anomalous sinking motions in the study region~~ (Figure 9~~7~~b and 9~~7~~d). 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 ~~maps~~ show a mixture of ~~anomalous~~ weak rising and sinking motions over Long Lake and the Ferris and Casper dune fields ~~in the study region~~ (Figure 9~~7~~c).

Lastly, t~~T~~he 850mb specific humidity composite anomaly values ~~were plotted on a continental scale to~~ provide context on the spatial extent of atmospheric moisture available for uplift by Omegas during each season (Figure 10~~8~~). Seasonal ~~Winter (DJF)~~ 850mb specific humidity composite anomaly-values are ~~slightly~~ above~~below~~ normal across the entire ~~in the~~ study region throughout the year (Figure 10~~8~~a-d). ~~Spring (MAM) 850mb specific humidity composite anomaly values indicate below normal moisture availability (Figure 8b), which persisted into the summer (JJA) and fall (SON) (Figure 8c, d).~~

5. Discussion

5.1 The 4.2 ka event and associated ~~Proxy evidence for~~ 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 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).

Ecological responses can vary spatially across the central Rocky Mountains and central Great Plains because of different synoptic controls. For example, 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 which was attributed to a ~150-year long drought between 4300 and 4100 cal yr BP. While the authors were unable to confirm whether the drought was indeed 150-years long, 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). Regardless, the timing of the drought reconstructed from Long Lake, Wyoming occurred during similar conditions identified over the Great Plains region (Booth et al., 2005). Several sites near Long Lake also experienced ecological changes associated with drought conditions; first, clusters of optical luminescence and radiocarbon dates ~4200 cal yr BP suggest widespread dune reactivation in dune fields in Wyoming and in the central Great Plains (Stokes and Gaylord, 1993; Mayer and Mahan, 2004; Halfen et al., 2010). Similarly, Miao et al. (2007) also demonstrate active aeolian activity between 4500 and 2300 cal yr BP, however, the authors acknowledge they cannot rule out aeolian responses lagged to climate (Miao et al., 2007); second, high concentrations of sand influx between 4200 and 3800 cal yr BP also indicates drought conditions in the Sand Hills of Nebraska (Schmieder, 2009); third, lower lake levels were recorded between ~5000 and ~3400 cal yr BP from several lakes in the central Rocky Mountains near Long Lake, further supporting regionally dry conditions during this time period (Shuman et al., 2014; Shuman et al., 2015); lastly, reconstructed paleoclimate data from the mid-latitudes of North America (i.e. northern Great Plains) suggest extensive drought conditions persisted between 4700 and 4000 cal yr BP (Shuman and Marsicek, 2016). However, this was a not predominant feature in their record. Widespread and severe drought conditions were also recorded across the Rocky Mountains and Great Plains region 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). Yet, the exact timing of drought conditions based on different proxy varies spatially and temporally.

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). 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; Anderson et al., 2016). Lastly, treeline abruptly declined ~4200 cal yr BP in the Great Basin region further suggesting cool conditions (Salzer et al., 2014). Such variability in climate reconstructed from proxy data across North America could be a function of site or proxy sensitivity, response time, and temporal resolution making it difficult to pinpoint the exact timing and spatial extent of major climatic shifts experienced during this time period (Schmieder, 2009). For example, Higuera et al. (2014) suggest that significantly shorter fire return intervals between 4000 and 3500 cal yr BP in Rocky Mountain National Park correspond with above-average lake levels from Hidden Lake, Colorado (Shuman et al., 2009). The authors suggest that higher lake levels indicate snow-dominated winters, but increased fire activity indicates drier summers. However, variability in climate may also, represent surface climate responses to both large-scale changes in the polar jet stream, as well as small-scale controls such as topography (Barry, 1970; 1982; Mock, 1996; Shinker, 2010; Mock and Shinker, 2011) that are inherent to the heterogeneous climate throughout the topographical complex interior intermountain west.

The spatial and temporal heterogeneity in proxy data during this time period is likely the result of broad-scale reorganization in climate. Specifically, the time period between 5000 and 4000 cal yr BP is when the onset and intensification of the El Niño Southern Oscillation (ENSO) occurred (Shulmeister and Lees, 1995; Barron and Anderson, 2010), as well as a 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 in some parts of North America (Müller & 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 more meridional flow, positive winter temperature and negative precipitation anomalies over the Pacific Northwest, and have been linked to wildfire activity in the Southern Canadian Rocky Mountains (Wallace & Gutzler, 1981; Leathers et al., 1991; Fauria & Johnson, 2008; 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.

Another source of seasonal precipitation variability in the west is associated with the North American Monsoon system (NAM), albeit largely in the southwest portion of North America (Adams and Comrie, 1997, Mock 1997, Shinker 2010). A weakening of the NAM system is proposed between 5000 and 4000 cal yr BP (Metcalfe et al., 2015). 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 central Rocky Mountains is still dominated by westerly winds via the polar jet stream even in summer (Mock 1996; Shinker 2010) versus the shift in circulation-driven winds in the southwest associated with the NAM (Adams and Comrie, 1997).

Imbedded within the period of climate organization described above was the '4.2 ka event' which was a prominent dry period found primarily at low-to-mid latitudes and was responsible for cultural collapses globally (deMenocal, 2001; An et al., 2005; Weiss, 2016; 2017a; 2017b). This climatic event has been suggested to be the formal boundary between the mid- and late-Holocene (Walker et al., 2012). Currently, there is no clear mechanistic explanation behind the 4.2 ka event (Walker et al., 2012), but several hypotheses exist. The first hypothesis is that the 4.2 ka event was the result of Bond event 3 (Bond et al., 1997; 2001). Yet, there is currently no precise mechanistic explanation for the Bond cycles (Wanner et al., 2014). The second hypothesis is that the drought was caused by the general southward migration of the Intertropical Convergence Zone (ITCZ) due to decreased late-Holocene summer/annual insolation (Liu et al., 2014). A southward migration of the ITCZ offers a potential climatic mechanism because of its influence on the position of the jet stream, which as previously discussed, significantly impacts North American winter temperature and precipitation patterns (see Mock, 1996). Finally, persistent La Niña-like conditions have been proposed as one of the hypothesized causal factors of drought centred on 4200 cal yr BP. La Niña-like conditions 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 here 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 via the environment-to-circulation approach (Mock and Brunelle-Daines, 1999; Shinker et al., 2006; Shinker, 2014).

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 Modern climate analogues in this paper 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 the Medicine Bow Range (Figures 53 and 64). Great Plains winter precipitation, specifically January precipitation, is typically dry due to predominant north-westerly flow -across the region (Mock, 1996). Cooler-than-normal winter temperatures during the winter months can be explained by several factors; first, cold and dry air from the interior region of Canada was drawn to the study region by anomalous flow associated with the anomalous high-pressure ridge centred off the coast of the Pacific Northwest (Figures 5a, 6a); and second, the slightly higher-than-normal precipitation (Figure 3a) likely increased the possibility of greater-than-normal cloud cover. Slightly wetter-than-normal during the cool season in mountainous regions are likely a result of local orographic uplift (Mock, 1996; Shinker, 2010), demonstrated by anomalous rising vertical motions in the study area

(Figure 7a). However, while winters were slightly wetter-than-normal, While the overall annual precipitation values for the selected case years were lower-than-average in all seasons of all case years, with the exception of a couple of seasons used to calculate the composite anomaly values. Overall, the interior intermountain west experiences both within-year and between-year variability of precipitation (Mock, 1996; Shinker, 2010). This within- and between-year variability is likely a result of variations in the polar jet during winter months. 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). ThusTherefore, 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 conditions at Long Lake are currently not impacted by phases of ENSO (Heyer et al., 2017, Wise 2010), as it is positioned within the transition zone (between 40º – 42ºN) that include consistently low correlation values between Pacific sea-surface temperature anomalies and cool season precipitation (Dettinger et al., 1998; Wise, 2010; Heyer et al., 2017). Analysis of this transition zone of low correlation values between sea-surface temperature anomalies and cool season precipitation over the past 500 years suggest it has been stable ~40ºN latitude (Wise, 2016). Paleoecological studies from the study region have also suggested a relatively stable transition zone throughout the Holocene (Carter et al., 2013; Mensing et al., 2013). Thus, 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) creating spatial inconsistencies of winter precipitation anomalies in the region in the past. Based on the modern climate analogues presented here, winter conditions are supportive of proxy data demonstrating the time period between 5000 and 4000 cal yr BP as being climatically variable likely in response to variations in the polar jet stream. Furthermore, our selected modern analogue case years represent a mixture of ENSO modes (e.g. El Niño, La Niña and Neutral conditions) indicating that these modes of variability, while statistically significant in the Southwest (as described by Wise, 2010 and Heyer et al., 2017) do not impact our study area in a consistent manner.

~~While ~~W~~w~~inter 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 ~~of south-eastern Wyoming ~~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. ~~in the study area.~~ 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 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.

This is demonstrated by modern climate analogues which illustrate anomalously warm and dry conditions beginning in the spring and persisting throughout the growing season (Figures 3 and 4) not only at Long Lake, but also across the entire west-central Great Plains. The warmer-than-average temperatures are directly related to an anomalous and persistent high-pressure ridge centred over the central Great Plains region in the spring, which persists over the northern Great Plains and study region during the summer (Figures 5b, c). As a result of anomalous anti-cyclonic winds, dry continental air from the interior of North America were delivered into the study region (Figure 6b, c). The delivery of anomalously dry air (Figure 8b) into the study region in conjunction with enhanced local sinking motions in the atmospheric (Figure 7b) ultimately suppressed precipitation in the spring. While some anomalous rising motions were present in the summer via 500mb Omega values (Figure 7c), there was lower-than-normal moisture in the atmosphere (via 850 mb specific humidity) to be uplifted and precipitated (Figure 8c). The lack of atmospheric moisture further supported the enhancement of drought conditions in the study region during the growing season.

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 (Wilhite and Hubbard, 1998; Sridhar et al., 2006). These 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. Change and Smith (2000) suggest several other factors are involved with drought in the Great Plains region. First, the prominent feature is an anticyclone positioned over the central portion of North America; second, the midtropospheric westerly winds weaken and become easterly winds in association with the anti-cyclonic 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 relative humidity anomalies. The 500mb geopotential height composite-anomaly maps (Figure 5b) for both spring and summer illustrate a high-pressure ridge centred over the central Great Plains in the spring, and shifting north during the summer (Figure 5c). As a result, midtropospheric winds, as seen in 500mb vector winds (Figure 6b, c), illustrate an easterly- to south-easterly component of flow around the anomalous high-pressure ridges which 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). Modern climate analogues visibly illustrate a reduced, yet northward displacement of the western ridge of the Bermuda high-pressure which likely contributed to dry conditions in the region. And finally, modern climate analogues clearly illustrate a lack of relative humidity in the western Great Plains and study region of south-eastern Wyoming (Figure 8b, c). These results offer a climatic explanation that resulted in the ecological changes ~4000 cal yr BP, as recorded in the sedimentary data at Long Lake, as well as provide a mechanistic explanation regarding the reactivation of dunes in Wyoming and the central Great Plains during this time.

5.3 Limitations of the modern climate analogue technique Model simulations and implications for drought in the central Rocky Mountains and central Great Plains

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 lead to subsidence (e.g. sinking vertical motions) which suppresses precipitation. Additionally, the clockwise flow of air associated with high pressure ridges . Persistent high pressure ridges also 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 Using a complex numerical weather-predication model with data from May 1987 to May 1988, Palmer and Brankovic (1989) had significant skill in predicating an anomalous high pressure ridge over North America during the summer of 1988. However, there is less agreement on the boundary conditions required to initiate anomalous and persistent high pressure ridges over the Great Plains. In particular, the relationship between Pacific and Atlantic teleconnections, which are important components involved with and 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. is not very well understood (Basara et al., 2013). 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; ~~Feng et al, 2008;~~ 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.

~~While our study is not able to address, nor model boundary conditions involved in initiating drought within the study region of south-eastern Wyoming ~4200 cal yr BP, the process-based approach of the modern climate analogue can be used to inform future paleoclimatic modelling and drought prediction. For example, as discussed above, both modern observations and simulations have demonstrated that anomalous and persistent high pressure ridges over the Great Plains are important synoptic processes involved in drought conditions over the Great Plains region. Similarly, enhanced anti-cyclonic circulation over the Great Plains was found to be a prominent feature causing mid-Holocene droughts in the region (Diffenbaugh et al., 2006). Thus, using the underlying assumption involved in the modern climate analogue, the principle of uniformitarianism (Barry and Perry, 1973), our results suggest that high pressure ridges and anti-cyclonic circulation over the Great Plains region, likely contributed to the drought identified at 4200 cal yr BP.~~

~~Based on the geographical proximity of our study region to the central Great Plains region, we hypothesize that severe and persistent droughts have the ability to affect the eastern most parts of the central Rocky Mountains.~~

6. Conclusion

~~**5. Conclusion**~~

Paleoecological reconstructions are valuable for understanding how ecosystems and disturbances respond to both gradual and abrupt changes in climate. However, proxy~~ies~~ evidence preserved in sedimentary records are unable ~~fail~~ to record climatic mechanisms that caused the ecological responses~~; the proxies only record that there was a change in vegetation composition or a change in disturbance regimes~~. Using the modern climate analogue technique~~ and the underlying principle of uniformitarianism~~, our results offer potential climatic mechanisms that explains how persistent drought ~~conditions in the central Great Plains~~ may have affected the vegetation composition at Long Lake, Wyoming ~4000 cal yr BP, as well as impacted dune stabilising vegetation across the western Great Plains. Specifically, the ~~atmospheric~~ 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. persistent anomalous high pressure positioned over the Great Plains region, which coincidently have been associated with the most recent droughts of the 20th century, regardless of ENSO mode or any other mode of variability. While the modern case years show weak rising motions during the summer months, there wasn't enough moisture available in the atmosphere via specific humidity at 850mb for precipitation anomalies to occur. 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 the study region in a southerly- to south-easterly direction from the interior region of North America. Additionally, the persistent high-pressure ridge positioned over the Great Plains during the growing season likely interrupted the normal moisture flow from the Gulf of Mexico via the low-level jet into the region, instead drawing warm and dry air from the interior of North America to the study region. The combination of higher-than-normal geopotential heights, anomalous component of flow and lack of moisture transport to the study region created the anomalously warm and dry conditions in the study region, thus providing a potential mechanistic explanation for anomalous dry conditions that support the ecological change, widespread dune reactivation, and lowered lake levels associated with the drought at 4200 cal yr BP in the central Rocky Mountains and central Great Plains (Halfen et al., 2009; Mayer and Mahan, 2004; Stokes and Gaylord, 1993; Shuman et al., 2015).

Many reconstructions using proxy data from sites within the intermountain west (especially in the western Rocky Mountains) and northern Great Plains indicate a variety of conditions around 4200 cal yr BP (Menounos et al., 2008; Grimm et al., 2011; Mayrer et al., 2012; Anderson, 2012; Anderson et al., 2016). However, because Long Lake, Wyoming is the eastern most record in the central Rocky Mountains with the closest geographic proximity to the central Great Plains, results from Long

~~Lake indicate synchronicity of drought signal during 4200 cal yr BP with the central Great Plains. The anomalous high pressure centred over the central Great Plains likely has little influence in terms of both the northern Great Plains where influences in ground water are important (Grimm et al., 2011), and farther west within the Rocky Mountains where a high degree of spatial and temporal variability of seasonal precipitation occurs driven by fluctuations in the polar jet stream (Mock, 1996; Shinker, 2010). For example, Shinker (2010) illustrated the heterogeneity of precipitation in the interior intermountain west by assessing the monthly contribution of annual precipitation within the region. Even with a lack of distinct precipitation seasonality in any given month within the interior intermountain west, high elevation precipitation events (or lack of) can easily offset (or enhance) water deficit (Shinker 2010). Such variability of precipitation within the interior intermountain west, driven by variations in the strength and position of the jet stream, help to explain the inconsistency in drought across the region~~. ~~Finally, Long Lake experiences similar seasonal precipitation characteristics as the central Great Plains (see Shinker, 2010) rather than sharing seasonal characteristics of other interior intermountain west sites to the west, the northern Great Plains, and the desert southwest. While an out of phase relationship with the desert southwest and Great Plains region has been proposed (i.e. wetter monsoons during drier Great Plains) (Dominguez et al., 2009), our results do not illustrate enhanced monsoon activity. This would agree with previous literature (Metcalfe et al., 2015) suggesting the weakening influence of NAM outside of the true monsoon region (i.e. Arizona, New Mexico, and north-western Mexico region) ~4000 cal yr BP.~~

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 mega-droughts 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 ~~Long Lake~~ in order to better understand the potential climatic mechanisms that impacted ecological changes~~ such as the changes in 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). 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).

References

Adams, D. K., and A. C. Comrie,: The North American monsoon. Bull. Amer. Meteor. Soc., 78, 2197–2213, doi: 10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2, 1997.

Ahlbrandt, T.S., Swinehart, J.B., Maroney, D.G.: The dynamic Holocene dune fields of the Great Plains and Rocky Mountain basins, USA. In Brookfield, M.E., Ahlbrandt, T.S., editors, *Eolian Sediments and Processes*, Elsevier, New York, 379-406.

Allen, C.D., Macalady, A.K., Chenchouni H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E.H., Gonzalez, P.: global overview of drought and heat-inducted tree mortality reveals emerging climate change risks for forests, Forest Ecol. Manag., 259, 660-684, doi:10.1016/j.foreco.2009.09.001, 2010.

Allen, A.M., Hostetler, S.W., Alder, J.R.: Analysis of the present and future winter Pacific-North American teleconnection in the ECHAM5 global and RegCM3 regional climate models. Clim. Dyn., 42, 1671-1682, doi: 10.1007/s00382-013-1910-x, 2014.

An, C.B., Tang, L., Barton, L., Chen, F.H.: Climate change and cultural response around 4000 cal yr B.P. in the western part of Chinese Loess Plateau. Quat. Res., 63, 347–352, doi:10.1016/j.yqres.2005.02.004, 2005.

Anderegg, L.D.L., Anderegg, W.R.L., Abatzoglou, J., Hausladen, A.M., Berry, J.A: Drought characteristics' role in widespread aspen forest mortality across Colorado, USA, Global Change Biol., 19, 1526-1537, doi:10.1111/gcb.12146, 2013a.

Anderegg, W.R.L., Plavcová, L., Anderegg, L.D.L., Hacke, U.G., Berry, J.A., Field, C.B.: Drought's legacy: multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk, Global Change Biol., 19, 1188-1196, doi: 10.1111/gcb.12100, 2013b.

Anderson, L.: Rocky Mountain hydroclimate: Holocene variability and the role of insolation, ENSO, and the North American Monsoon. Glob. Planet. Change, 92-93, 198-208, doi: 10.1130/G31575.1, 2012.

Anderson, L., Brunelle, A., Thompson, R.S.: A multi-proxy record of hydroclimate, vegetation, fire, and post-settlement impacts for a subalpine plateau, central Rocky Mountains, USA. Holocene, 25, 1-12, doi: 10.1177/0959683615574583, 2015.

Anderson, L., Berkelhammer, M., Barron, J.A., Steinman, B.A., Finney, B.P., Abbott, M.B.: Lake oxygen isotopes as recorders of North American Rocky Mountain hydroclimate: Holocene patterns and variability at multi-decadal to millennial time scales. Global. Planet. Change. 137, 131-148, doi: 10.1016/j.gloplacha.2015.12.021, 2016.

Atwood Jr., W.W.: Records of Pleistocene glaciers in the Medicine Bow and Park Ranges, J. Geol., 45, 113–140, 1937.

Barron, J.A., and Anderson, L: Enhanced Late Holocene ENSO/PDO expression along the margins of the eastern North Pacific. Quat. Int., 235, 3–12, doi: 10.1016/j.quaint.2010.02.026, 2010.

Barry, R. G.: Atmospheric circulation and climatic change, I. Approaches to paleoclimatic reconstruction. In Berger, A. editor, *Climatic Variations and Variability: Facts and Theories*, Reidel, Dordrecht, 333-345, 1981.

Barry, R.G.: Approaches to reconstructing the climate of the steppe-tundra biome. In: Hopkins DM, Matthews JA Jr, Schweger CE, Young SB (eds) Paleoecology of Beringia. Academic Press, New York, USA, pp. 195-204, 1982.

Barry, R.G., and Perry, A.H.: Synoptic Climatology – Methods and Applications. Metheun, London, UK, 1973.

Barry, R.G. and Carleton, A.M.: Synoptic and dynamic climatology, Routledge Psychology Press, London England, 2001.

Basara, J.B., Maybourn, J.N., Pierano, C.M., Tate, J.E., Brown, P.J., Hoey, J.D., Smith, B.R.: Drought and associated impacts in the Great Plains of the United States – A review. Int. J. Geosciences, 4, 72-81, doi: 10.4236/ijg.2013.46A2009, 2013.

Bernal, J.P., Lachniet, M., McCulloch, M., Mortimer, G., Morales, P., Cienfuegos, E.: A speleothem record of Holocene climate variability from southwestern Mexico. Quat. Res., 75, 104–113, doi: 10.1016/j.yqres.2010.09.002, 2011.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G.: A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. Science, 278, 1257–1266, doi:10.1126/science.278.5341.1257, 1997.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evan, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene. Science, 294, 2130-2136, doi: 10.1126/science.1065680, 2001.

Booth, R.K., Jackson, S.T., Forman, S.L., Kutzbach, J.E., Bettis, E.A., Kreigs, J., Wright, D.K.: A severe centennial-scale drought in the mid-continental North America 4200 years ago and apparent global linkages, Holocene 15, 321-328, doi:10.1191/0959683605hl825ft, 2005.

~~Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., Romme, W.H., Kastens, J.H., Floyd, M.F., Belnap, J., Anderson, J.J., Myers, O.B., Meyer, C.W.: Regional vegetation die-off in response to global-change-type drought, Proc. Natl. Acad. Sci., 102, 15144-15148, doi:10.1073/pnas.0505734102, 2005.~~

Carter, V.A., Brunelle, A., Minckley, T.A., Dennison, P.E., Power, M.J.: Regionalization of fire regimes in the Central Rocky Mountains, USA, Quat. Res., 80, 406-416, doi:10.1016/j.yqres.2013.07.009, 2013.

Carter, V.A.: The role of climate variability and disturbances on forest ecology in the intermountain west. PhD dissertation, Department of Geography, University of Utah, 2016.

Carter, V.A., Brunelle, A., Minckley, T.A., Shaw, J.D., DeRose, R.J., Brewer, S.: Climate variability and fire effects on quaking aspen in the central Rocky Mountains, USA, J. Biogeogr., 44, 1280-1293, doi: 10.1111/jbi.12932, 2017a.

Carter, V.A., Power, M.J., Lundeen, Z.J., Morris, J.L., Petersen, K.L., Brunelle, A., Anderson, R.S., Shinker, J.J., Turney, L., Koll, R., Bartlein, P.J.: A 1500-year synthesis of wildfire activity stratified by elevation from the US Rocky Mountains, Quat. Int. in press, doi: 10.1016/j.quaint.2017.06.051, 2017b.

Cayan, D.R.: Interannual climate variability and snowpack in the western United States. J. Clim., 9(5), 928-948, doi: 10.1175/1520-0442(1996)009<0928:ICVASI>2.0.CO;2, 1996.

~~Cayan, D.R., Das, T., Pierce, D.W., Barnett, T.P., Tyree, M., Gershunov, A.: Future dryness in the southwest US and the hydrology of the early 21st century drought, Proc. Natl. Acad. Sci., 107, 21271-21276, doi:10.1073/pnas.0912391107, 2010.~~

Chang, F-C., and Smith, E.A.: Hydrological and dynamical characteristics of summertime droughts over US Great Plains. J. Clim. 14, 2296-2316, doi:10.1175/1520-0442(2001)014<2296:HADCOS>2.0.CO;2, 2001.

Coats, S., Smerdon, J.E., Seager, R., Cook, B.I., Gonzalez-Rouco, J.F.: Megadroughts in Southwestern North America in ECHO-G Millennial Simulations and Their Comparisons to Proxy Drought Reconstructions. J. Clim. 26, 7635-7649, doi: 10.1175/JCLI-D-12-00603.1, 2013.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W.: Long-term aridity changes in the western United States. Science, 306, 1015-1018, doi: 10.1126/science.1102586, 2004.

Cook, E.R., Seager, R., Heim Jr. R.R., Vose, R.S., Herweijer, C., Woodhouse, C.: Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. J. Quat. Sci. 25, 48–61, doi: 10.1002/jqs.1303, 2010.

Cook, B.I., Cook, E.R., Smerdon, J.E., Seager, R., Williams, A.P., Coats, S., Stahle, D.W., Villanueva Díaz, J.: North American megadroughts in the Common Era: reconstructions and simulations. WIREs Clim. Change., 7, 411-432, doi: 10.1002/wcc.394, 2016.

Dean, W.: Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: evidence from varved lake sediments. Geology, 25, 331–334, doi: 10.1130/0091-7613(1997)025<0331:RTACOH>2.3.CO;2, 1997.

deMenocal, P.B.: Cultural responses to climate change during the Late Holocene. Science, 292, 667–673, doi:10.1126/science.1059188, 2001.

Dettinger, M.D., Cayan, D., Diaz, H., Meko, D.: North–south precipitation in western North America on interannual-to-decadal timescales. J. Clim., 11, 3095–3111, doi:10.1175/1520-0442(1998)011<3095:NSPPIW>2.0.CO;2, 1998.

Diaz, H.F. and Andrews, J.T.: Analysis of the spatial pattern of July temperature departures (1943-1972) over Canada and estimates of the 700 mb mid-summer circulation during middle and late Holocene, Int. J. Climatol., 2, 251-265, doi: 10.1002/joc.3370020304, 1982.

Diaz, H.F.: Drought in the United States: Some aspects of major dry and wet periods in the contiguous United States, 1895–1981, J. Appl. Meteorol., 22, 3–16, 1983.

Diffenbaugh, N.S., Ashfaq, M., Shuman, B., Williams, J.W., Bartlein, P.J.: Summer aridity in the United States: Response to the mid-Holocene changes in insolation and sea surface temperature. Geophys. Res. Lett., 33, L22712, doi:10.1029/2006GL028012, 2006.

Dominguez, F., Camilo Villegas, J., Breshears, D.D.: Spatial extent of North American Monsoon: Increased cross-regional linkages via atmospheric pathways, Geophysical Research Letters 36, L07401, doi: 10.1029/2008GL037012, 2009.

Edwards, M.E., Mock, C.J., Finney, B.P., Barber, V.A., Bartlein, P.J.: Potential analogues for paleoclimatic variations in eastern interior Alaska during the past 14,000 yr: Atmospheric circulation controls of regional temperature and moisture response. Quat. Sci. Rev., 20, 189-202, doi:10.1016/S0277-3791(00)00123-2, 2001.

Ely, L.L.: Response of extreme floods in the southwestern United States to climatic variations in the late Holocene, Geomorphology, 19, 175-201, doi:10.1016/S0169-555X(97)00014-7, 1997.

Fauria, M.M., and Johnson, E.A.: Climate and wildfires in the North American boreal forest. Philos. Trans. R. Soc. Lond. B. Biol. Sci., 363, 2315–2327, doi: 10.1098/rstb.2007.2202, 2008.

Fischer, H., Meissner, K.J., Mix, A.C., Abram, N.J., Austermann J., Brovkin, V., Capron, E., Colombaroli, D., Daniau, A-L., Dyez, K.A., Felis, T., Finkelstein, S.A., Jaccard, S.L., McClymont, E.L., Rovere, A., Sutter, J., Wolff, E.W., Affolter, S., Bakker, P., Ballesteros-Cánova, J.A., Barbante, C., Caley, T., Carlson, A.E., Churakova (Sidorova), O., Cortese, G., Cumming, B.F., Davis, B.A.S., de Vernal, A., Emile-Geay, J., Fritz, S.C., Gierz, P., Gottschalk, J., Holloway, M.D., Joos, F., Kucera, M., Loutre, M-F., Lunt, D.J., Marcisz, K., Marlon, J.R., Martinez, P., Masson-Delmotte, V., Nehrbass-Ahles, C., Otto-Bliesner, B.L., Raible, C.C., Risebrobakken, B., Sánchez Goñi, M.F., Saleem Arrigo, J., Sarnthein, M., Sjolte, J., Stocker, T.F., Velasquez Alvárez, P.A., Tinner, W., Valdes, P.J., Vogel, H., Wanner, H., Yan, Q., Yu, Z., Ziegler, M., Zhou, L.: Palaeoclimate constraints on the impact of 2ºC anthropogenic warming and beyond. Nat. Geosci. 11, 474-485, doi: 10.1038/s41561-018-0146-0, 2018.

Fisher, D., Osterberg, E., Dyke, A., Dahl-Jensen, D., Demuth, M., Zdanowicz, C., Bourgeois, J., Koerner, R.M., Mayewski, P., Wake, C., Kreutz, K., Steig, E., Zheng, J., Yalcin, K., Goto-Azuma, K., Luckman, B., Rupper, S.: The Mt. Logan Holocene-late Wisconsinan isotope record: tropical Pacific-Yukon connections. Holocene 18, 667-677, doi: 10.1177/0959683608092236, 2008.

~~Forman, S., Oglesby, R., and Webb, R.S.: Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links, Glob. Planet. Chang., 11, 35-55, doi:10.1016/S0921-8181(00)00092-8, 2001.~~

Garfin, G., Jardine, A., Merideth, R., Black, M., LeRoy, S.: Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment (A report by the Southwest Climate Alliance). Island Press, Washington, DC, 2013.

Goble, R.J., Mason, J.A., Loope, D.B., Swinehart, J.B.: Optical and radiocarbon age of stacked paleosolos and dune sands in the Nebraska Sand Hillss, USA. Quat. Sci. Rev. 23, 1173-1182, doi: 10.1016/j.quascirev.2003.09.009, 2004.

Grimm, E.C., Donovan, J.J., Brown, K.J.: A high-resolution record of climate variability and landscape response from Kettle Lake, northern Great Plains, North America. Quat. Sci. Rev. 30, 2626-2650, doi: 10.1016/j.quascirev.2011.05.015, 2011.

Halfen, A.F., Fredlund, G.G., and Mahen, S.A.: Holocene stratigraphy and chronology of the Casper Dune Field, Casper, Wyoming, USA, Holocene, 20, 773-783, doi:10.1177/0959683610362812, 2010~~09~~.

Halfen, A.F., and Johnson, W.C.: A review of Great Plains dune field chronologies. Aeolian Res. 10, 135-160, doi: 10.1016/j.aeolia.2013.03.001, 2013.

Hanna, P. and Kulakowski, D.: The influences of climate on aspen dieback, Forest Ecol. Manag., 274, 91-98, doi:10.1016/j.foreco.2012.02.009, 2012.

Herweijer, C., Seager, R., Cook, E.R.: North American droughts of the mid to late nineteenth century: a history, simulation and implication for Mediaeval drought. Holocene 16, 159-171, doi: 10.1191/0959683606hl917rp, 2006.

Heyer, J.P., Brewer, S., and Shinker, J.J.: Using high-resolution reanalysis data to explore localized western North America hydroclimate relationships with ENSO. J. Climate, 30, 1395-5417, doi:10.1175/JCLI-D-16-0476.1, 2017.

~~Higuera, P.E., Briles, C.E., Whitlock, C.: Fire-regime complacency and sensitivity to centennial- through millennial-scale climate change in Rocky Mountain subalpine forests, Colorado, USA. J. Ecol. 102, 1-13, doi:10.1111/1365-2745.12296, 2014.~~

~~Hoerling, M. and Kumar, A.: A perfect ocean for drought, Science, 299, 691-694, doi:10.1126/science.1079053, 2003.~~

Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., Schubert, S., Seager, R.: Causes and predictability of the 2012 Great Plains drought. Bull. Am. Meteorol. Soc., 95, 269-282, doi:10.1175/BAMS-D-13-00055.1, 2014.

Hogg, E.H., Brandt, J.P., and Michaelin, M.: Impacts of regional drought on the productivity, dieback, and biomass of Canadian aspen forests, Can. J. For. Res., 38, 1373-1384, doi:10.1139/X08-001, 2008.

IPCC Climate Change 2014: Synthesis Report (Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change) [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland: IPCC, 2014.

~~Karl, T.R.: Some spatial characteristics of drought duration in the United States, J. Appl. Meteorol., 22, 1356 – 1366, doi:10.1175/1520-0450(1983)022<1356:SSCODD>2.0.CO;2, 1983.~~

~~Karl, T.R. and Koscielny, A.J., Drought in the United States: 1895-1981, Int. J. Climatol., 2, 313-329, doi: 10.1002/joc.3370020402, 1982.~~

Kalnay, E., Kanamitsu, M., Baker, W.E.: Global numerical weather prediction at the National Meteorological Center, Bull. Am. Meteorol. Soc., 71, 1410-1428, doi: 10.1175/1520-0477(1990)071<1410:GNWPAT>2.0.CO;2, 1990.

~~Kay, C.E.: Is aspen doomed?, J. Forest., 95, 4-11, 1997.~~

Kashian, D.M., Romme, R.H., and Regan, C.M.: Reconciling divergent interpretations of quaking aspen decline on the Northern Colorado Front Range, Ecol. Appl., 17. 1296-1311, doi:10.1890/06-1431.1, 2007.

Leathers, D.J., Yarnal, B., Palecki, M.A.: The Pacific/North American teleconnection pattern and United States climate. Part I: regional temperature and precipitation associations. J. Clim., 4, 517–528, doi:10.1175/1520-0442(1991)004<0517:TPATPA>2.0.CO;2, 1991.

Liu, Z., Yoshimura, K., Bowen, G.J., Buenning, N.H., Risi, C., Welker, J.M., Yuan, F.: Paired oxygen isotope record reveal modern North American atmospheric dynamics during the Holocene. Nat. Commun. 5, 1 – 7, doi: 10.1038/ncomms4701, 2014.

~~Little, E.L.: Atlas of United States Trees, vol. 1. Conifers and Important Hardwoods, Miscellaneous Publication 1146, US Department of Agriculture, Digitized 1999 by US Geological Survey, http://esp.cr.usgs.gov/data/little/, 1971.~~

Loope, D.B., Swinehart, J.B., Mason, J.P.: Dune-dammed wetlands and buried paleovalleys of the Nebraska Sand Hills: intrinsic vs. climatic controls on the accumulation of lake and marsh sediments. Geol. Soc. Am. Bull. 107, 396-406, doi: 10.1130/0016-7606(1995)107<0396:DDPOTN>2.3.CO;2, 1995.

Lundeen, Z., Brunelle, A., Burns, S.J. Polyak, V., Asmerom, Y.: A speleothem record of Holocene paleoclimate from the northern Wasatch Mountains, southeast Idaho, USA, Quat. Int., 310, 83-95, doi:10.1016/j.quaint.2013.03.018, 2013.

Madole, R.F.: Spatial and temporal patterns of late Quaternary eolian deposition, eastern Colorado, USA. Quat. Sci. Rev. 14, 155-177, doi: 10.1016/0277-3791(95)00005-A, 1995.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256-1260, doi:10.1126/science.1177303, 2009.Mason, J.A., Swinehart, J.B., Goble, R.J., Loope, D.B.: Late-Holocene dune activity linked to hydrological drought, Nebraska Sand Hills, USA. Holocene, 14, 209-217, doi: 10.1191/0959683604hl677rp, 2004.

Maurer, M.K., Menounos, B., Luckman, B.H., Osborn, G., Clague, J.J., Beedle, M.J., Smith, R., Atkinson, N.: Late Holocene glacier expansion in the Cariboo and northern Rocky Mountains, British Columbia, Canada. Quat. Sci. Rev., 51, 71-80, doi: 10.1016/j.quascirev.2012.07.023, 2012.

Mayer, J.H. and Mahan, S.A.: Late Quaternary stratigraphy and geo- chronology of the western Killpecker Dunes, Wyoming, USA, Quat. Res. 61, 72–84, doi:10.1016/j.yqres.2003.10.003, 2004.

Menking, K.M. and Anderson, R.V.: Contributions of La Nina and El Nino to middle Holocene drought and late Holocene moisture in the American Southwest, Geology, 31, 937-940, doi:10.1130/G19807.1, 2003. \

Menounos, B., Clague, J.J., Osborn, G., Luckman, B.H., Lakeman, T.R., Minkus, R.: Western Canadian glaciers advance in concert with climate change circa 4.2ka. Geophys. Res. Lett. 35, L07501, doi: 10.1029/2008GL033172, 2008.

Mensing, S.A., Sharpe, S.E., Tunno, I., Sada, D.W., Thomas, J.M., Starratt, S., Smith, J.: The Late Holocene Dry Period: Multiproxy evidence for an extended drought between 2800 and 1850 cal yr BP across the central Great Basin, USA, Quat. Sci. Rev., 78, 266–282, doi:10.1016/j.quascirev.2013.08.010, 2013.

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P.C., Ebisuzaki, W., Jović, D., Woollen, J., Rogers, E., Berbery, E.H., Ek, M.B., Fan, Y., Grumbine, R., Higgins, W., Li, H., Lin, Y., Manikin, G., Parrish, D., Shi, W.: North American regional analysis, Bul. Am. Meteorol. So., 87, 343-360, doi:10.1175/BAMS-87-3-343, 2006.

Metcalfe, S.E., Barron, J.A., Davies, S.J.: The Holocene history of the North American Monsoon: ‘known knowns’ and ‘known unknowns’ in understanding its spatial and temporal complexity. Quat. Sci. Rev., 120, 1-27, doi: 10.1016/j.quascirev.2015.04.004, 2015.

Miao, X., Mason, J.A., Swinehart, J.B., Loope, D.B., Hanson, P.R., Goble, R.J., Liu, X.: A 10,000 year record of dune activity, dust storms, and severe drought in the central Great Plains. Geology, 35, 119-122, doi: 10.1130/G23133A.1, 2007.

Mock, C.J. and Bartlein, P.J.: Spatial variability of late-Quaternary paleoclimates in the western United States, Quat. Res., 44, 425-433, doi:10.1006/qres.1995.1087, 1995.

Mock, C.J.: Climatic controls and spatial variations of precipitation in the western United States, J. Climate, 9, 1111-1124, doi:10.1175/1520-0442(1996)009<1111:CCASVO>2.0.CO;2, 1996.

Mock, C.J., and Anderson, P.M.: Some perspectives on the late Quaternary paleoclimate of Beringia. In Isaacs, C.M. and Tharp, V., editors, Proceedings of the Thirteenth Annual Pacific Climate (PACLIM) Workshop, Technical Report 53 of the Interagency Ecological Program, California Department of Water Resources, 193–200, 1997.

Mock, C.J. and Brunelle-Daines, A.R.: A modern analogue of western United States summer paleoclimate at 6,000 years Before Present, Holocene, 9, 541-545, doi:10.1191/095968399668724603, 1999.

Mock, C.J. and Shinker, J.J.: Modern analogue approaches in paleoclimatology. In: Elias SA (ed) The Encyclopedia of Quaternary Science. Elsevier, Amsterdam, The Netherlands, pp. 102-112, 2013.

Morris, J.L., Brunelle, A., Munson, A.S., Spencer, J., Power, M.J.: Holocene vegetation and fire reconstructions from the Aquarius Plateau, Utah, USA. Quat. Int., 310, 111-123, doi: 10.1016/j.quaint.2012.10.055, 2013.

~~Moser, K.A., and Kimball, J.P.,: A 19,000-year record of hydrologic and climatic change inferred from diatoms from Bear Lake, Utah and Idaho. Geological Society of America Special Papers, 450, 229–246, doi.org/10.1130/2009.2450(10), 2009.~~

Müller, W.A., and Roeckner, E.: ENSO impact on midlatitude circulation patterns in future climate change projections. Geophys. Res. Lett., 33, 1–4, doi:10.1029/2005GL025032, 2006. Namias, J.: Spring and Summer 1988 Drought over the Contiguous United States – Causes and Prediction, Journal of Climate, 4, 54-65, doi:10.1175/1520-0442(1991)004<0054:SASDOT>2.0.CO;2, 1991.

NOAA. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml. Accessed July 15, 2015.

Notaro, M., Wang, W-C., Gong, W.: Model and observational analysis of the Northeast U.S. regional climate and its relationship to the PNA and NAO patterns during early winter. Mon. Weather. Rev., 134, 3479–3505, doi:10.1175/MWR3234.1, 2006.

NRCS, unpublished data. https://www.wcc.nrcs.usda.gov.

Overpeck, J.T., Webb, T., III, Prentice, I.C.: Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogs. Quat. Res., 23, 87–108, doi: 10.1016/0033-5894(85)90074-2, 1985.

Palmer, T.N. and Branković, Č: The 1988 US drought linked to anomalous sea surface temperature, Nature, 338, 54-57, doi: 10.1038/338054a0, 1989.

~~Perala, D.A.: Populus tremuloides Michx. Silvics of North America, Vol. 2, Hardwoods. Agriculture Handbook 654 (ed. By R.M. Burns and B.H. Honkala), United States Department of Agriculture, Washington DC, pp. 555-569, 1990.~~

Rawling, III, J.E., Fredlund, G.G., Mahan, S.A.: Aeolian cliff-top deposits and buried soils in the White River Badlands, South Dakota, USA. Holocene, 13, 129-129, doi: 10.1191/0959683603hl601rr, 2003.

Rehfeldt, G.E., Ferguson, D.E., and Crookston, N.L.: Aspen, climate, and sudden aspen decline in western USA. Forest Ecol. Manag., 258, 2352-2364, doi:10.1016/j.foreco.2009.06.005, 2009.

Salzer, M.W., Bunn, A.G., Graham, N.E., Hughes, M.K.: Five millennia of paleotemperature from tree-rings in the Great Basin, USA. Clim. Dyn. 42, 1517-1526, doi:10.1007/s00382-013-1911-9, 2014.

Schmieder, J: The Nebraska Sand Hills – Mid- to Late-Holocene Drought Variation and Landscape Stability Based on High-Resolution Lake Sediment Records, PhD dissertation, Earth and Atmospheric Sciences, University of Nebraska – Lincoln, 2009.

Schmieder, J., Fritz, S.C., Swinehart, J.B., Shinneman, A.L.C., Wolfe, A.P., Miller, G., Daniels, N., Jacobs, K.C., Grimm, E.C.: A regional-scale climate reconstruction of the last 4000 years from lakes in the Nebraska Sand Hills, USA. Quat. Sci. Rev., 30, 1797-1812, doi: 10.1016/j.quascirev.2011.04.011, 2011.

Schmeisser, R.L., Loope, D.B., and Mason, J.A.: Modern and late Holocene wind regimes over the Great Plains (central U.S.A.), Quat. Sci. Rev., 29, 554-566, doi:10.1016/j.quascirev.2009.11.003, 2010.

Schubert, S.D., Suarez, M.J., Pegion, P.J., : Causes of long-term drought in the U.S. Great Plains, J. Climate, 17, 485-503, doi: 10.1175/1520-0442(2004)017<0485:COLDIT>2.0.CO;*2*, 2004.

~~Seager, R., Tzanova, A., and Nakamura, J.: Drought in the Southeastern United States: Causes, Variability over the Last Millennium, and the Potential for Future Hydroclimate Change, J. Climate, 22, 5021-5044, doi:0.1175/2009JCLI2683.1, 2007.~~

Shabber, A., and~~&~~ Khandekar, M.: The impact of el Nino-Southern oscillation on the temperature field over Canada: Research note. Atmos. Ocean., 34(2), 401-416, doi: 10.1080/07055900.1996.9649570, 1996.

Shinker, J.J., Bartlein, P.J., and Shuman, B.: Synoptic and dynamic climate controls of North American mid-continental aridity, Quat. Sci. Rev., 25, 1401-1417, doi:10.1016/j.quascirev.2005.12.012 , 2006.

Shinker ,J.J.: Visualizing spatial heterogeneity of Western United States climate variability. Earth Interact., 14, 1-15, doi: 10.1175/2010EI323.1, 2010.

Shinker, J.J.: Climatic controls of hydrologic extremes in south-interior intermountain west of Colorado, U.S.A. Rocky Mount. Geology., 49, 51-60, 2014.

Shulmeister, J., and Lees, B.G.: Australasian evidence for mid-Holocene climate change implies precessional control of Walker Circulation in the Pacific. Quat. Int., 57/58, 81-91, doi:10.1016/S1040-6182(98)00052-4, 1995.

Shuman, B.N., Henderson, A.K., Colman, S.M., Stone, J.R., Fritz, S.C., Stevens, L.R., Power, M.J., Whitlock, C.; Holocene lake-level trends in the Rocky Mountains, USA. Quat. Sci. Rev., 28, 1861-1879, doi: 10.1016/j.quascirev.2009.03.003, 2009.

Shuman, B.N., Carter, G.E., Hougardy, D.D., Powers, K., Shinker, J.J.: A north-south moisture dipole at multi-century scales in the central and southern Rocky Mountains, USA during the late Holocene. Rocky Mount. Geology, 49, 33-49. doi: 10.2113/grocky.49.1.33, 2014.

Shuman, B.N., Pribyl, P., and Buettner, J.: Hydrologic changes in Colorado during the mid-Holocene and Younger Dryas, Quat. Res., 84, 187-199, doi:10.1016/j.yqres.2015.07.004, 2015.

Shuman, B.N., and Marsicek, J.: The structure of Holocene climate change in mid-latitude North America. Quat. Sci. Rev., 141, 38-51, doi: 10.1016/j.quascirev.2016.03.009, 2016.

Sridhar, V., Loope, D.B., Swinehart, J.B., Mason, J.A., Oglesby, R.J., Rowe, C.M.: Large wind shift on the Great Plains during the Medieval Warm Period, Science, 313, 345-347, doi:10.1126/science.1128941, 2006.

~~Sterl, A., Severijns, C., Dijkstra, H., Hazeleger, W., van Oldenborgh, G.J., van den Broeke, M., Burgers, G., van den Hurk, B., van Leeuwen, P.J., van Velthoven, P.: When can we expect extremely high surface temperatures?, Geophys. Res. Lett., 35, L14703, doi:10.1029/2008GL034071, 2008.~~

Steinman, B.A., Pompeani, D.P., Abbott, M.B., Ortiz, J.D., Stansell, N.D., Finkenbinder, M.S., Mihindukulasooriya, L.N., Hillman, A.L.: Oxygen isotope records of Holocene climate variability in the Pacific Northwest. Quat. Sci. Rev. 142, 40-60, doi: 10.1016/j.quascirev.2016.04.012, 2016.

Stokes, S. and Gaylord, D.R.: Optical dating of Holocene dune sands in the Ferris Dune Field, Wyoming, Quat. Res., 39, 274–281, doi:0.1006/qres.1993.1034, 1993.

Stokes, S., and Swinehart, J.B.: Middle- and late-Holocene dune reactivation in the Nebraska Sand Hills, USA. Holocene 7, 263-272, doi: 10.1177/095968369700700302, 1997.

Taschetto, A. S., and& England, M. H.: El Niño Modoki impacts on Australian rainfall. J. Clim. 22, 3167-3174, doi: 10.1175/2008JCLI2589.1, 2009.

Trenberth, K.E., Branstator, G.W., Arkin, P.A.: Origins of the 1988 North American Drought. Science, 242, 1640-1645, doi: 10.1126/science.242.4886.1640, 1998.

Walker, M.J.C., Berkelhammer, M., Björck, S., Cwynar, C., Fisher, D.A., Long, A.J., Lowe, J.J., Newnham, R.M., Rasmussen, S.O., Weiss, H.: Formal subdivision of the Holocene Series/Epoch: a discussion paper by a Working Group of INTIMATE (Integration of ice-core, marine, and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). J. Quat. Sci., 27, 649-659, doi: 101.1002/jqs.2565, 2012.

Wallace, J.M., and Gutzler, D.S.: Teleconnections in the geopotential height field during the Northern Hemisphere winter. Mon. Weather. Rev., 109, 784–812, doi:10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2, 1981.

Wanner, H., Mercolli, L., Grosjean, M., Ritz, S.P: Holocene climate variability and change; a data-based review. J. Geol. Soc., 172, 254-263, doi:10.1144/jgs2013-101, 20154.

Weiss, H.: Global megadrought, societal collapse and resilience at 4.2-3.9 ka BP across the Mediterranean and west Asia. PAGES Magazine, 24, 62-63, doi: 10.22498/pages.24.2.62, 2016.

Weiss, H.: 4.2 ka BP Megadrought and the Akkadian Collapse. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. University Press, Oxford, UK, pp. 93-160, 2017a.

Weiss, H,: Megadrought, Collapse, and Causality. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. University Press, Oxford, UK, pp. 1-31, 2017b.

Wise, E.K.: Spatiotemporal variability of the precipitation dipole transition zone in the western United States, Geophys. Res. Lett., 37, L07706, doi:10.1029/2009GL042193, 2010.

Wise, E.K.: Five centuries of U.S. West Coast drought: Occurrence, spatial distribution, and associated atmospheric circulation patterns, Geophys. Res. Lett., 43, 4539–4546, doi:10.1002/2016GL068487, 2016.

Woodhouse, C.A. and Overpeck, J.T.: 2000 years of drought variability in the Central United States, Bull. Am. Meteorol. So., 79, 2693-2714, doi:10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2, 1998.

Worrall, J.J., Egeland, L., Eager, T., Mask, R.A., Johnson, E.W., Kemp, P.A., Sheppard, W.D.: Rapid mortality of *Populus tremuloides* in southwestern Colorado, USA, Forest Ecol. Manag., 255, 686-696, doi:10.1016/j.foreco.2007.09.071, 2008.

Worrall, J.J., Marchetti, S.B., Egeland, L., Mask, R.A., Eager, T., Howell, B.: Effects and etiology of sudden aspen decline in southwestern Colorado, USA, Forest Ecol. Manag., 260, 638-648, doi:10.1016/j.foreco.2010.05.020, 2010.

Worrall, J.J., Rehfeldt, G.E., Hamann, A., Hogg, E.H., Marchetti, S.B., Michaelian, M., Gray, L.K.: Recent declines of *Populus tremuloides* in North America linked to climate. Forest Ecol. Manag., 299, 35-51, doi:10.1016/j.foreco.2012.12.033, 2013.

Yarnal, B.: Synoptic climatology in environmental analysis: A primer. Belhaven Press, London, England, 1993.

Yarnal, B., Comrie, A.C., Frakes, B., Brown, D.P.: Developments and prospects in synoptic climatology, Int. J. Climatol., 21, 1923–1950, doi:10.1002/joc.675, 2001.

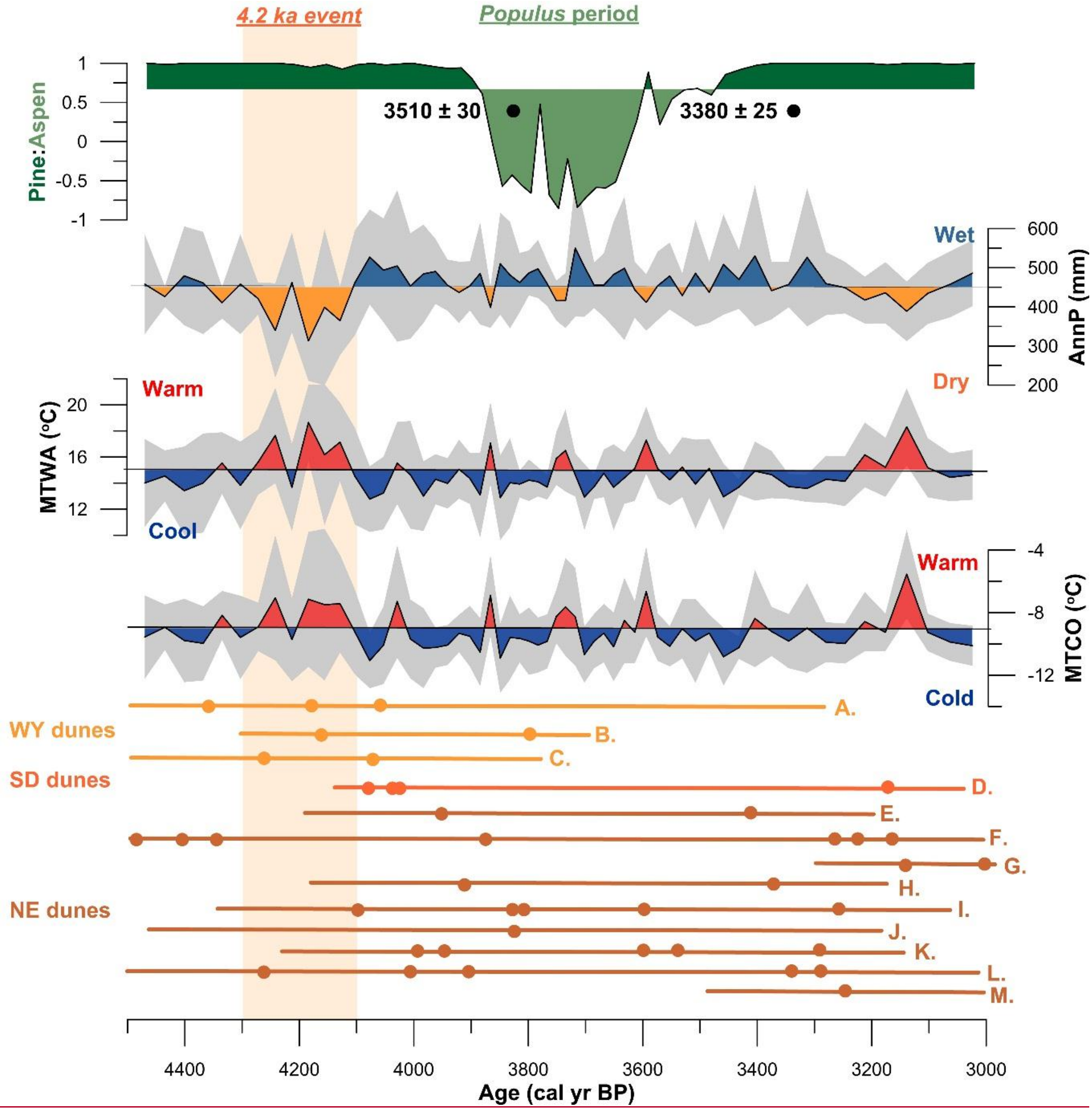
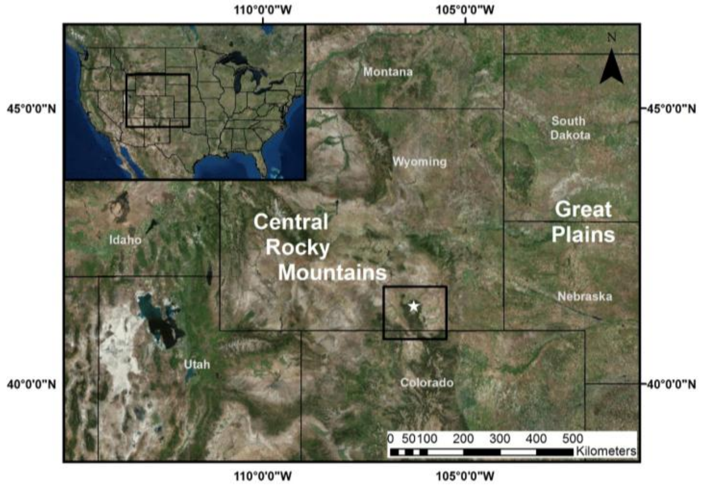
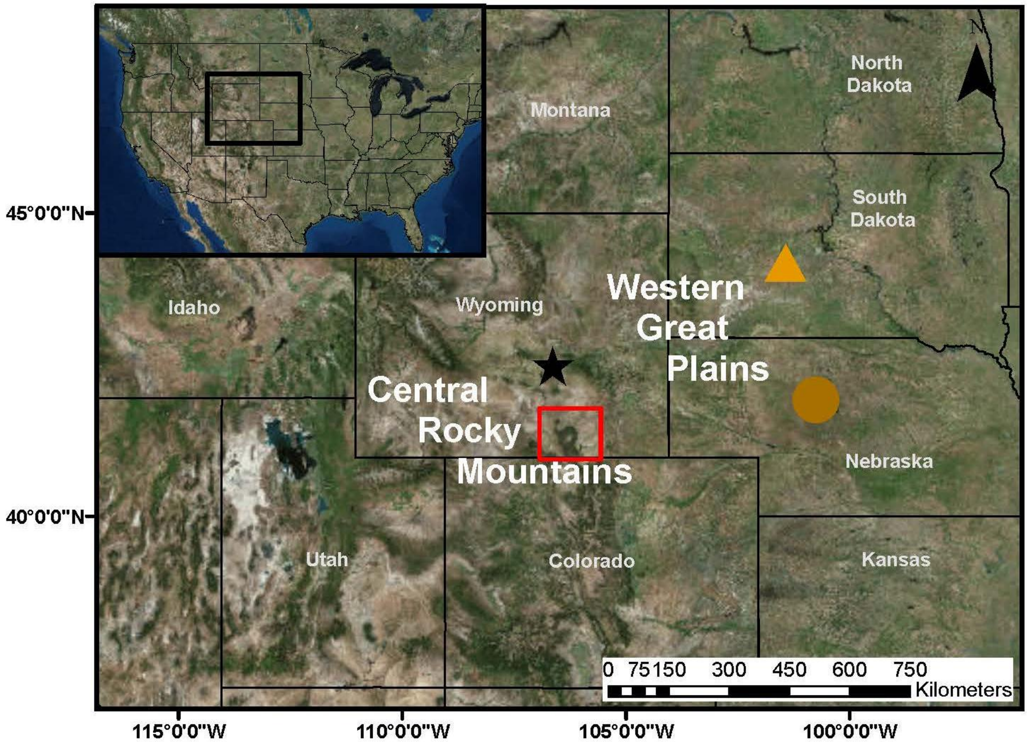


Figure 1. Regional paleo-proxy evidence supporting drought conditions ~4200 and ~4000 cal yr BP. From Long Lake, south-eastern Wyoming, Carter et al. (2013) identified a brief change in vegetation composition from a lodgepole pine dominated forest to a mixed forest of lodgepole pine-quaking aspen, known as the *Populus* period (top), likely in response to the 4.2 ka drought (orange shading). Using the modern climate analogue technique, Carter et al. (2017a) reconstructed persistently dry (reduced annual precipitation (AnnP)), and warm (increased Mean Temperature of the Warmest Month (MTWA); Mean Temperature of the Coldest Month (MTCO)) conditions between 4300 – 4100 cal yr BP. These drought conditions temporally correspond to the 4.2 ka event. Regionally, several dune fields reactivated around this same time period, as demonstrated by clusters of radiocarbon and luminescence dates; Age data error bars reflect those reported by the original authors—typically 1 to 2r; A-C represent dunes located in Wyoming near

Long Lake, Wyoming; A. Ferris dunes (Stokes and Gaylord, 1993); B-C. Casper dunes (Halfen et al., 2010); D represents South Dakota dune fields relatively near Long Lake, Wyoming; D. White River Badlands dunes (Rawling et al., 2003); E-M represent dunes located in Nebraska near Long Lake, Wyoming; E. Nebraska Hills dunes (Schmeider et al., 2011); F. Nebraska Hills dunes (Miao et al., 2007); G-H. Nebraska Hills dunes (Mason et al., 2004); I. Nebraska Hills dunes (Goble et al., 2004); J. Nebraska Hills dunes (Stokes and Swinehart, 1997); K. Nebraska Hills dunes (Loope et al., 1995); L. Nebraska Hills dunes (Ahlbrandt et al., 1983); M. Nebraska Hills dunes (Madole, 1995). Data was modified from Carter et al. (2013; 2017a), and Halfen and Johnson (2013).





~~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. 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).

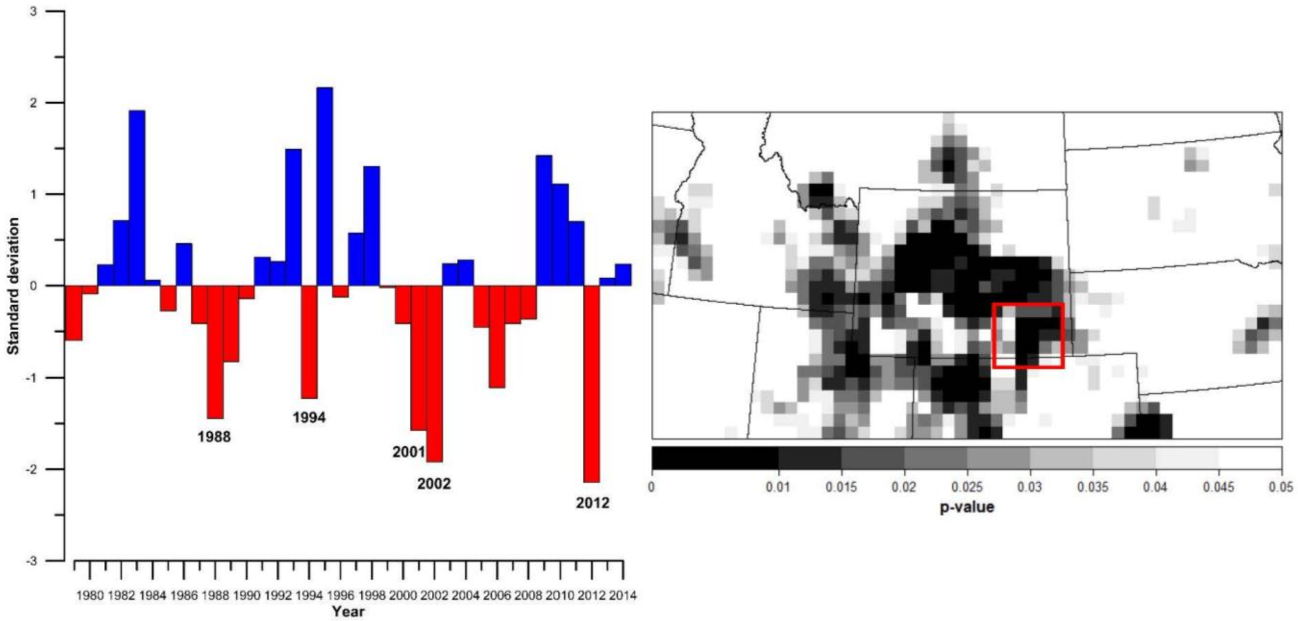


Figure 2. Precipitation anomalies and the spatial distribution of significant p-values across the study region of south-eastern Wyoming. A) Time series of annual precipitation anomalies for 1979-2014 compared to the long-term average (1981-2010) from Wyoming climate division 10, Upper Platte River Basin. The first five years with -1 or more standard deviations below the long-term average include 2012, 2002, 2001, 1998, and 1994. One standard deviation equates to 58.89 mm. Climate division data were collected from http://www.esrl.noaa.gov/psd/cgi-bin/timeseries/timeseries1.pl. B) Map showing the spatial distribution of significant p-values ($p < 0.05$) across the study region (outlined in red box) identified during the five driest years. P-values were evaluated using a two-tailed Student's t-test with an alpha of 0.05.Climate division data were collected from http://www.esrl.noaa.gov/psd/cgi-bin/timeseries/timeseries1.pl.

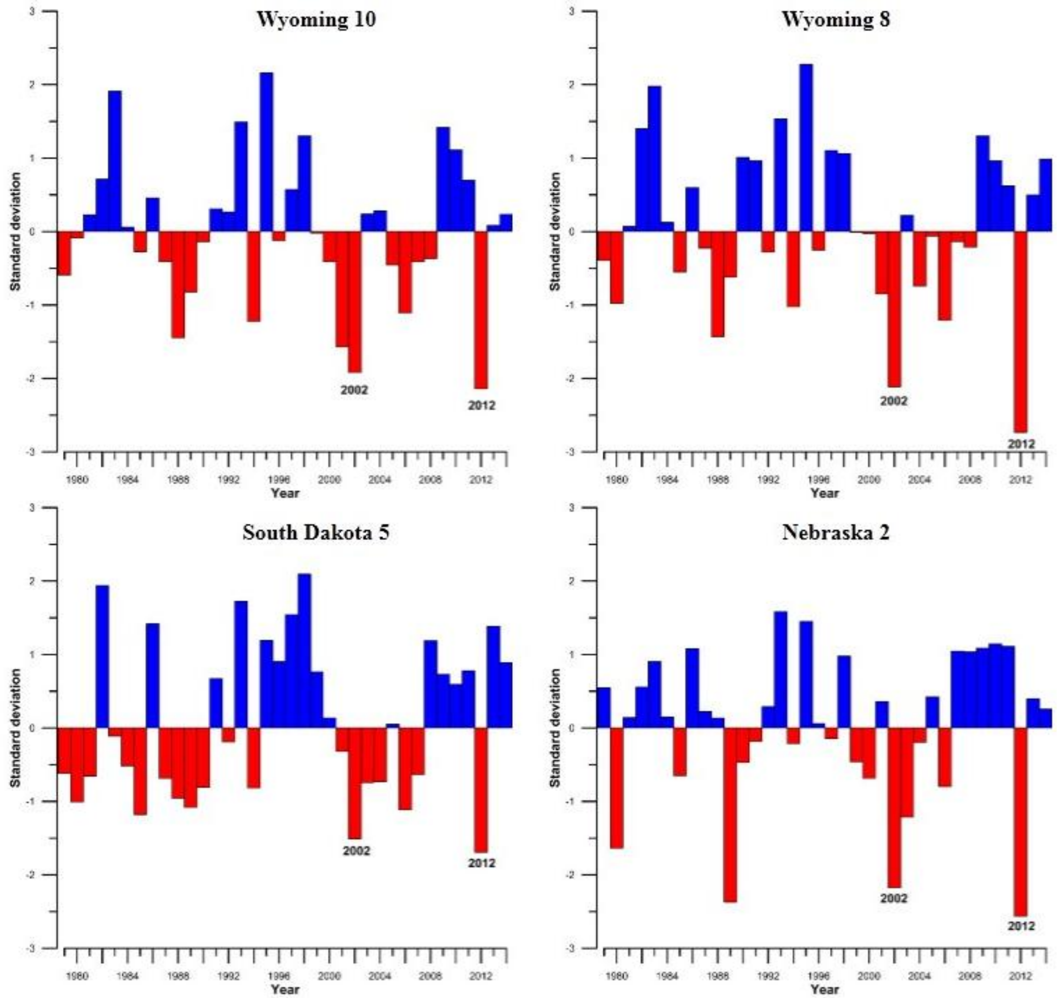


Figure 3. Time series of precipitation anomalies from Wyoming Climate Divisions 10 (top left) and 8 (top right), South Dakota Climate Division 5 (bottom left), and Nebraska Climate Division 2 (bottom right). Annual precipitation anomalies for 1979-2014 were compared to the long-term average (1981-2010) 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.

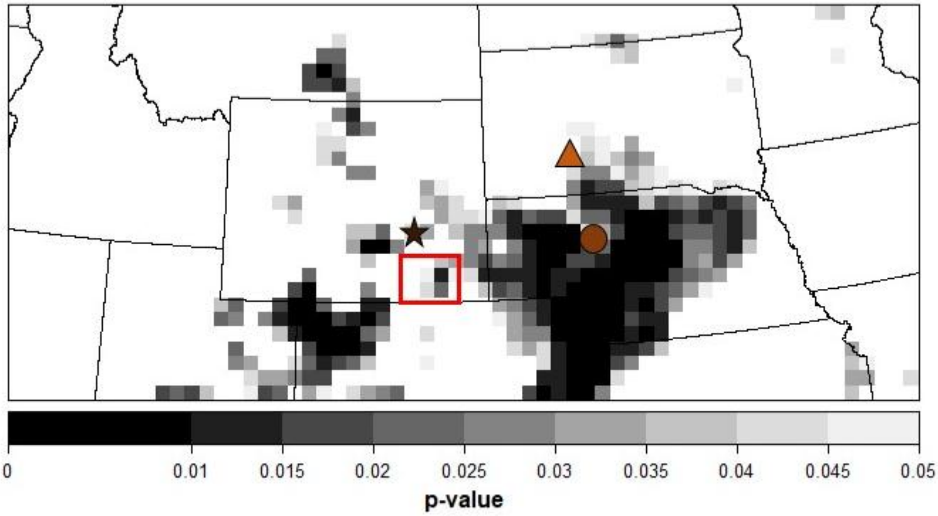
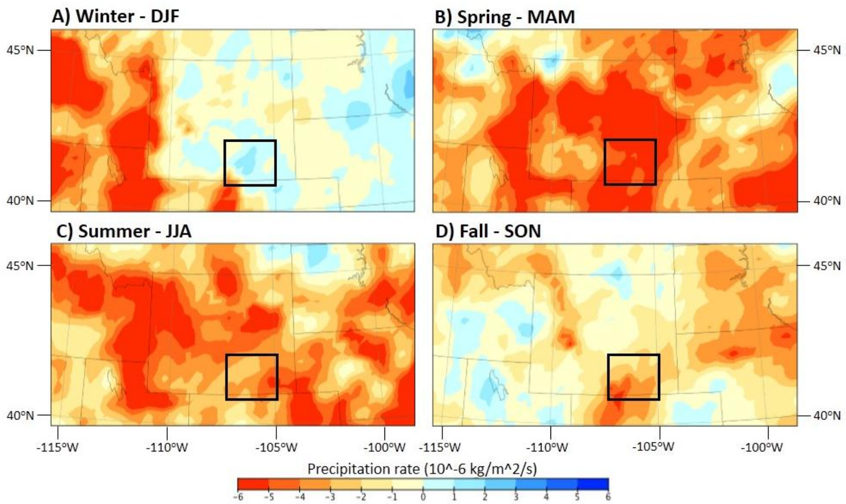


Figure 4. Map showing the spatial distribution of significant p-values ($p < 0.05$) during the two case years (2002 and 2012) across the central Rocky Mountains and western Great Plains, USA. P-values were evaluated using a two-tailed Student's t-test with an alpha of 0.05. Sedimentary proxy data from 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).



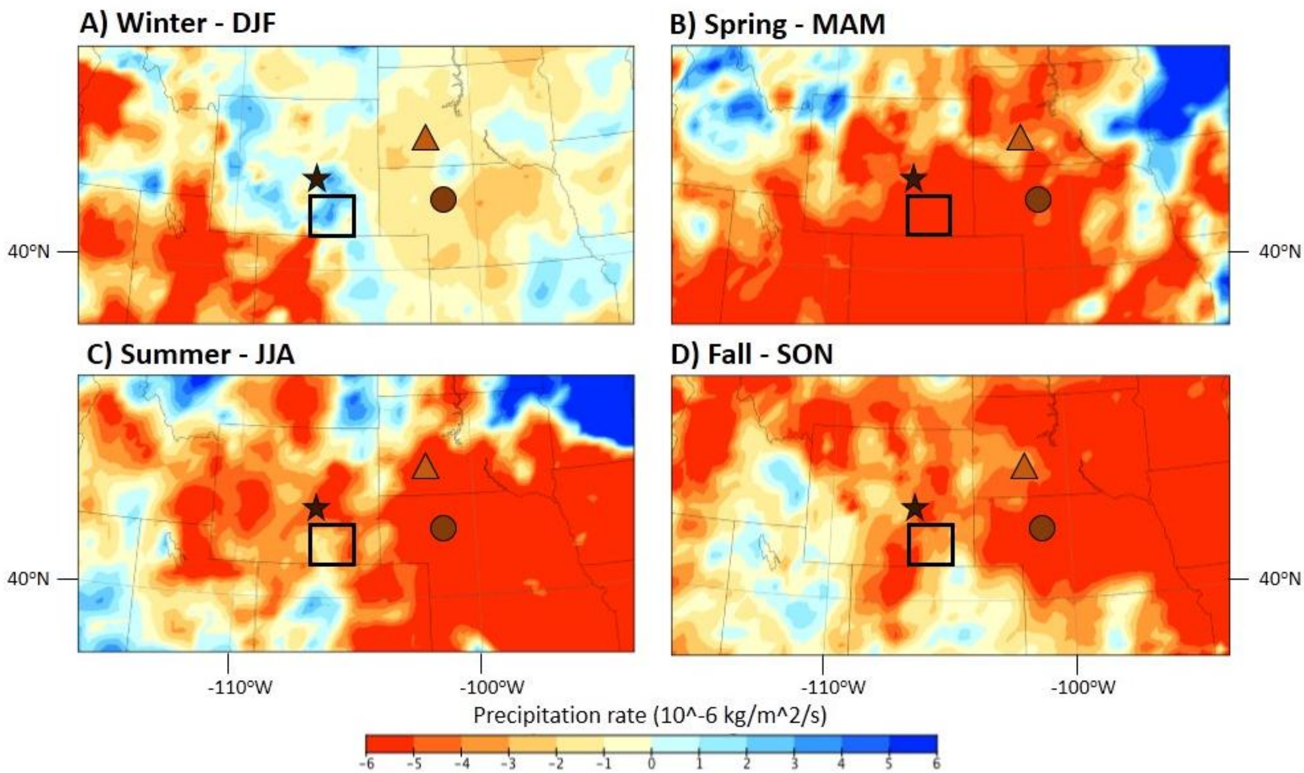
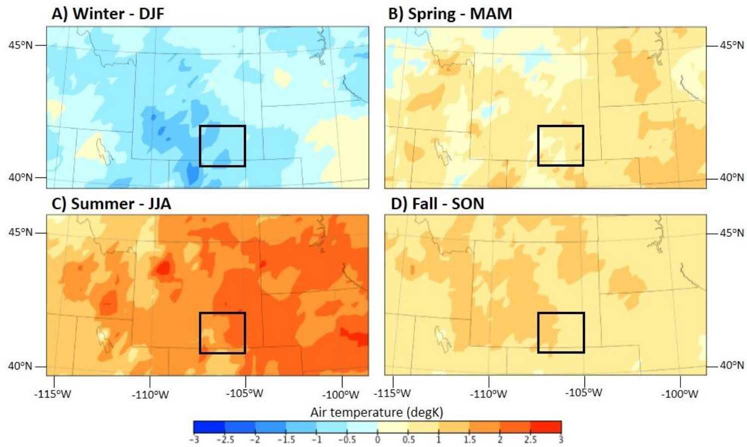


Figure 53. Composite anomaly maps for precipitation rate at the surface. A) Precipitation rate at the surface for winter (DJF); B) Spring (MAM); C) Summer (JJA); D) Fall (SON). Positive values (cool colours) for precipitation rate indicate wetter-than-normal conditions. Negative values (warm colours) indicate dryer-than-normal conditions. The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. 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.



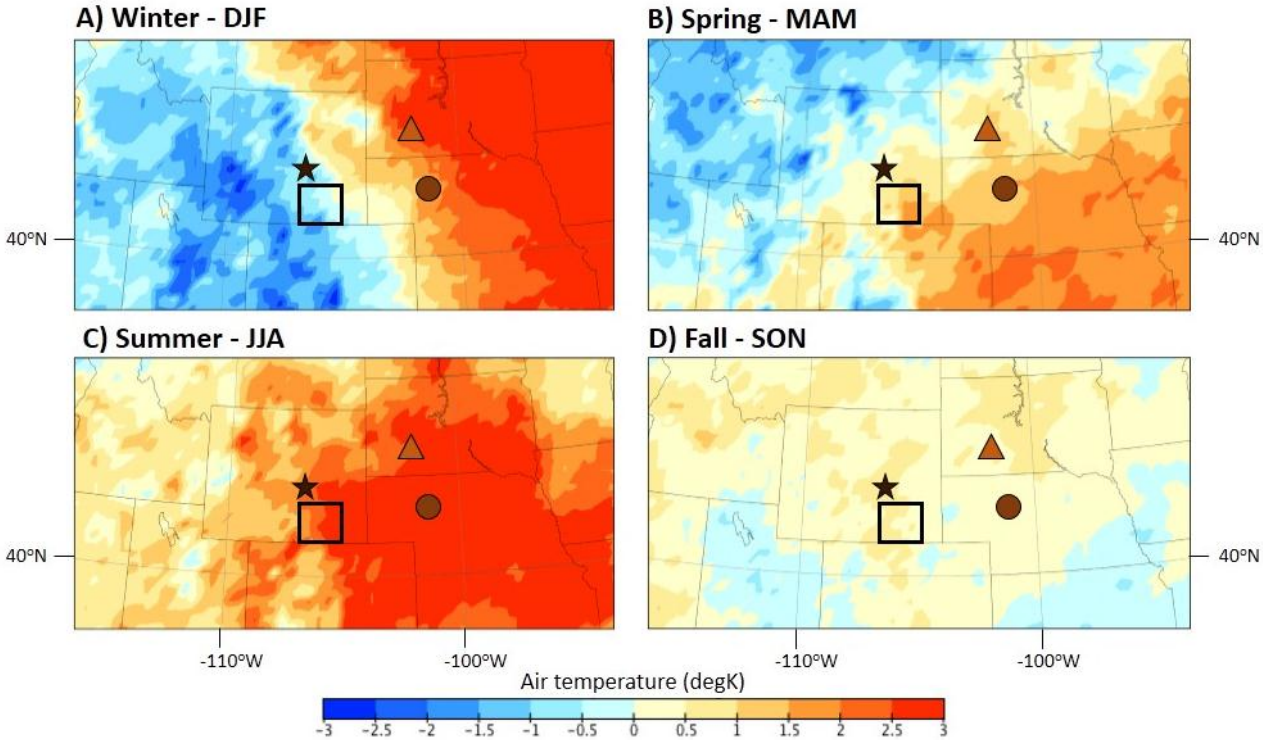
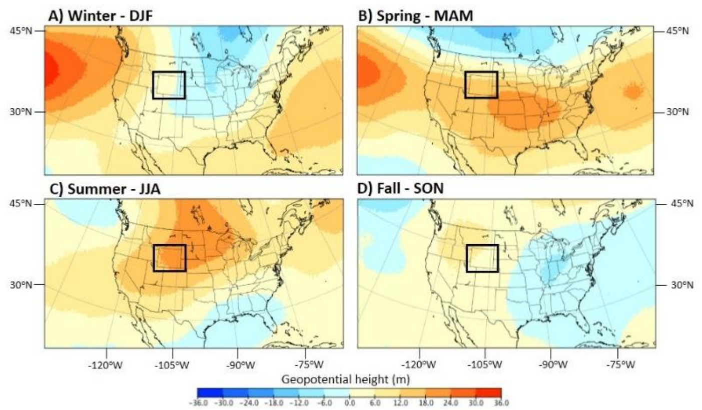


Figure 64. Composite anomaly maps for air temperature at the surface. A) Air temperature during the winter (DJF~~J~~); B) Spring (MAM); C) Summer (JJA); D) Fall (SON). Positive values (warm colours) for air temperature indicate warmer-than-normal conditions. Negative values (cool colours) indicate cooler-than-normal conditions. The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. 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.



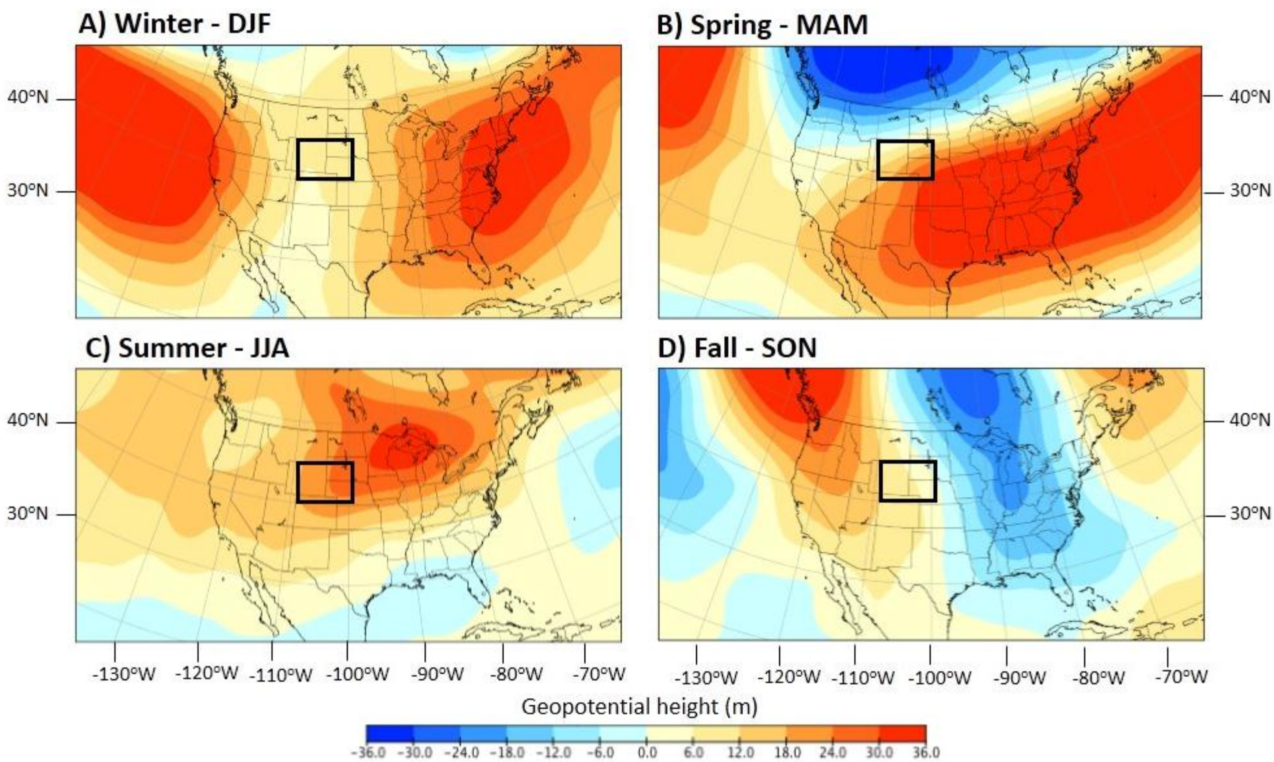
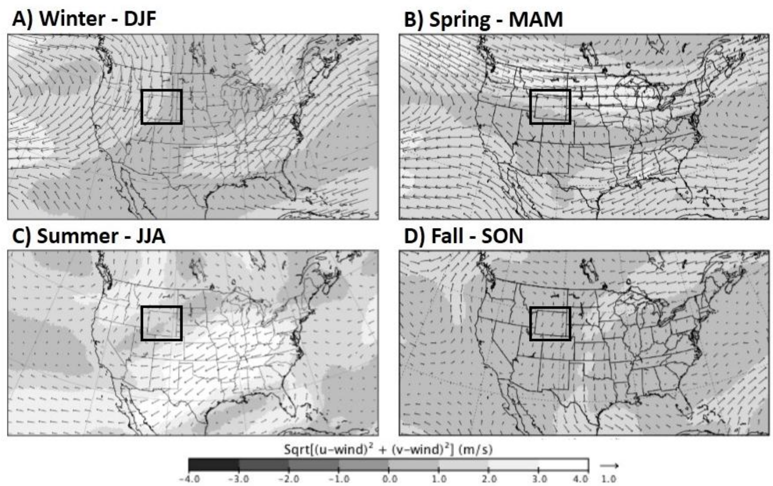


Figure 75. Composite anomaly maps for 500mb geopotential height during A) the winter season (DJFJJA); B) spring (MAM); C) summer (JJA); and D) fall season (SON). Positive values (warm colours) for 500mb geopotential heights indicate a stronger-than-normal ridge. Negative values (cool colours) indicate a strong-than-normal trough. The black box denotes the study region, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. 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.



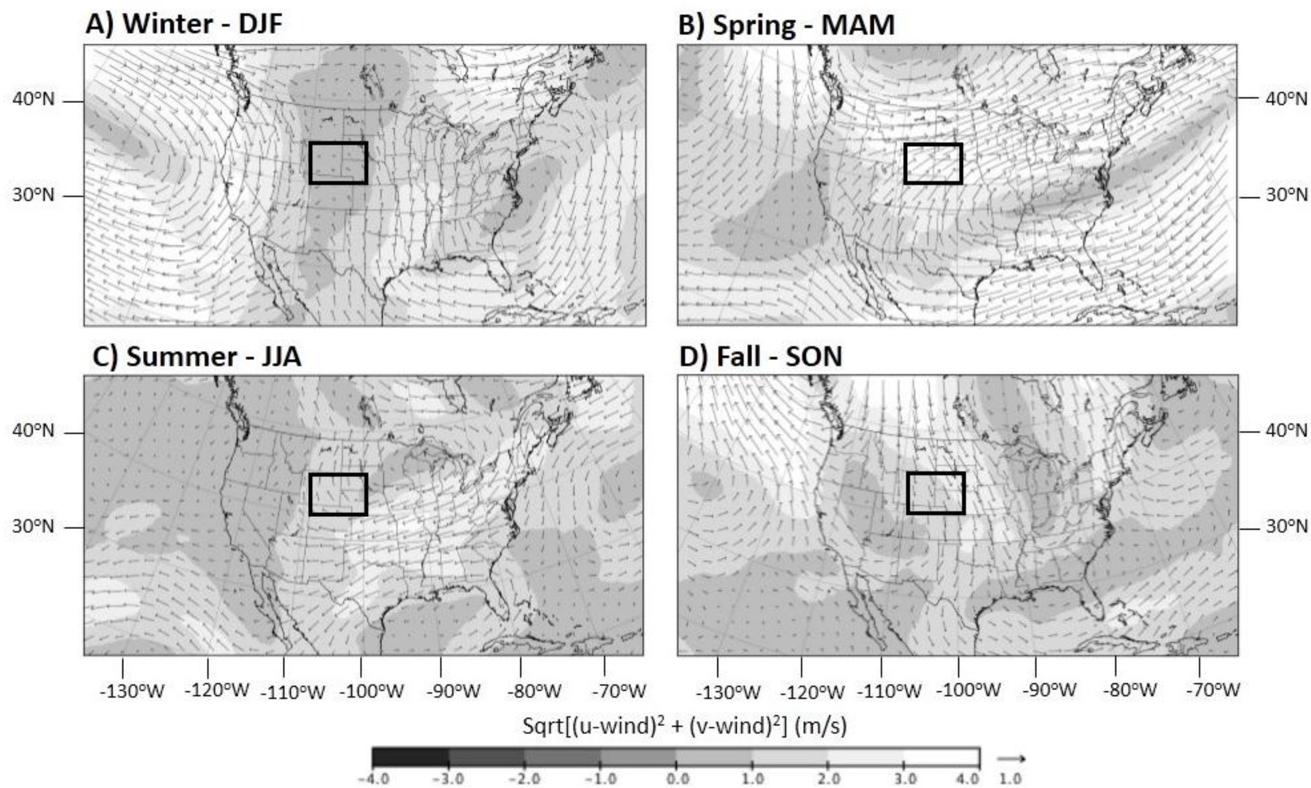
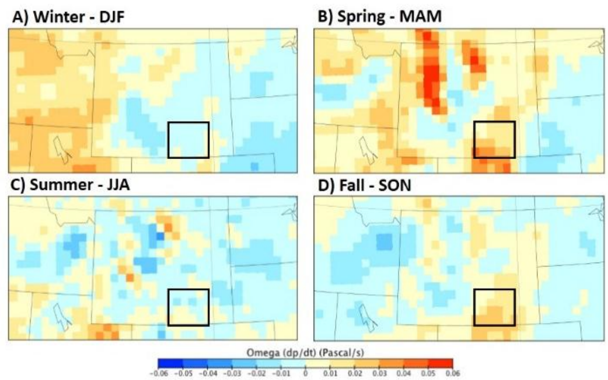


Figure 86. Seasonal composite anomaly maps for 500mb vector winds during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) fall season (SON). The black box denotes the study region, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming. The black star denotes 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.



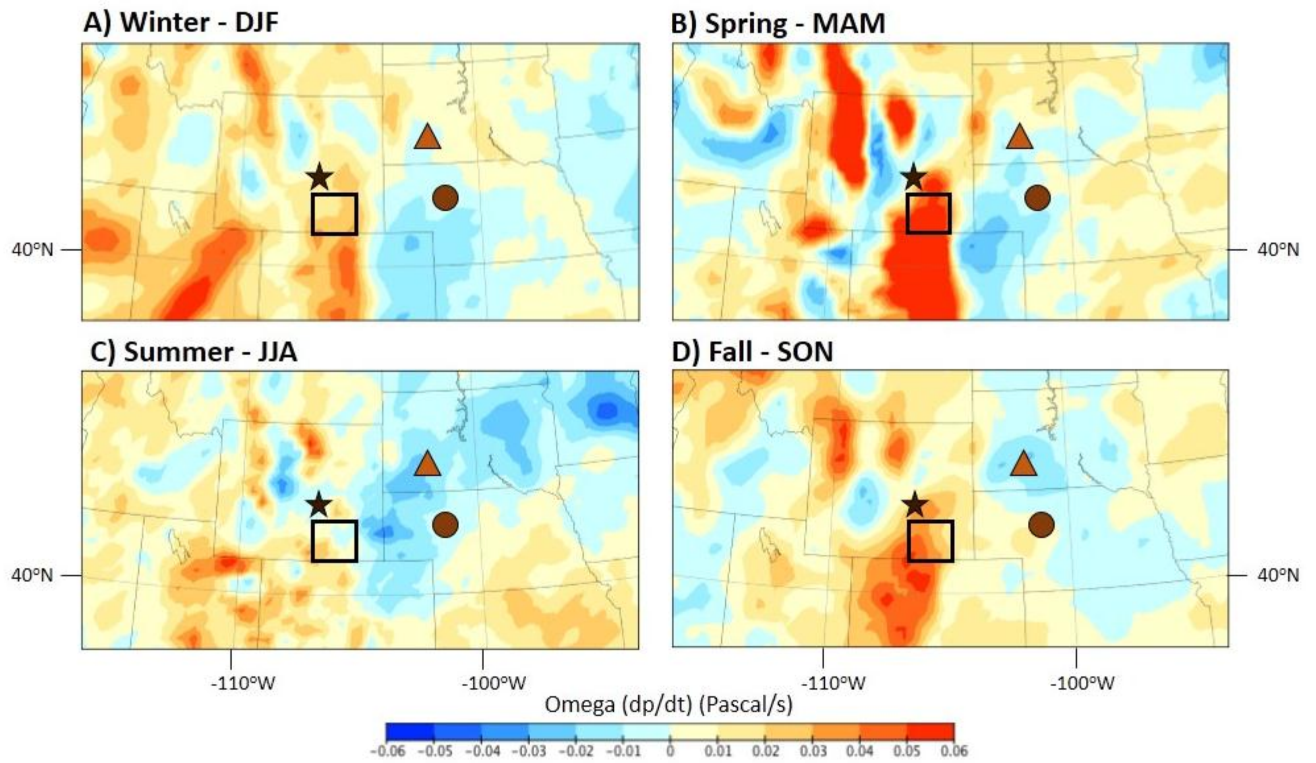
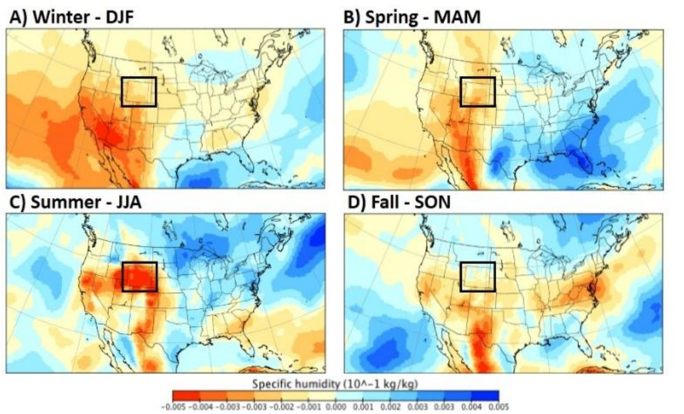


Figure 9~~7~~. Composite anomaly maps for 500-mb Omega (vertical velocity) during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) the fall season (SON). Positive values (warm colours) for omega indicate enhanced sinking motions (suppress precipitation). Negative values (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. 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.



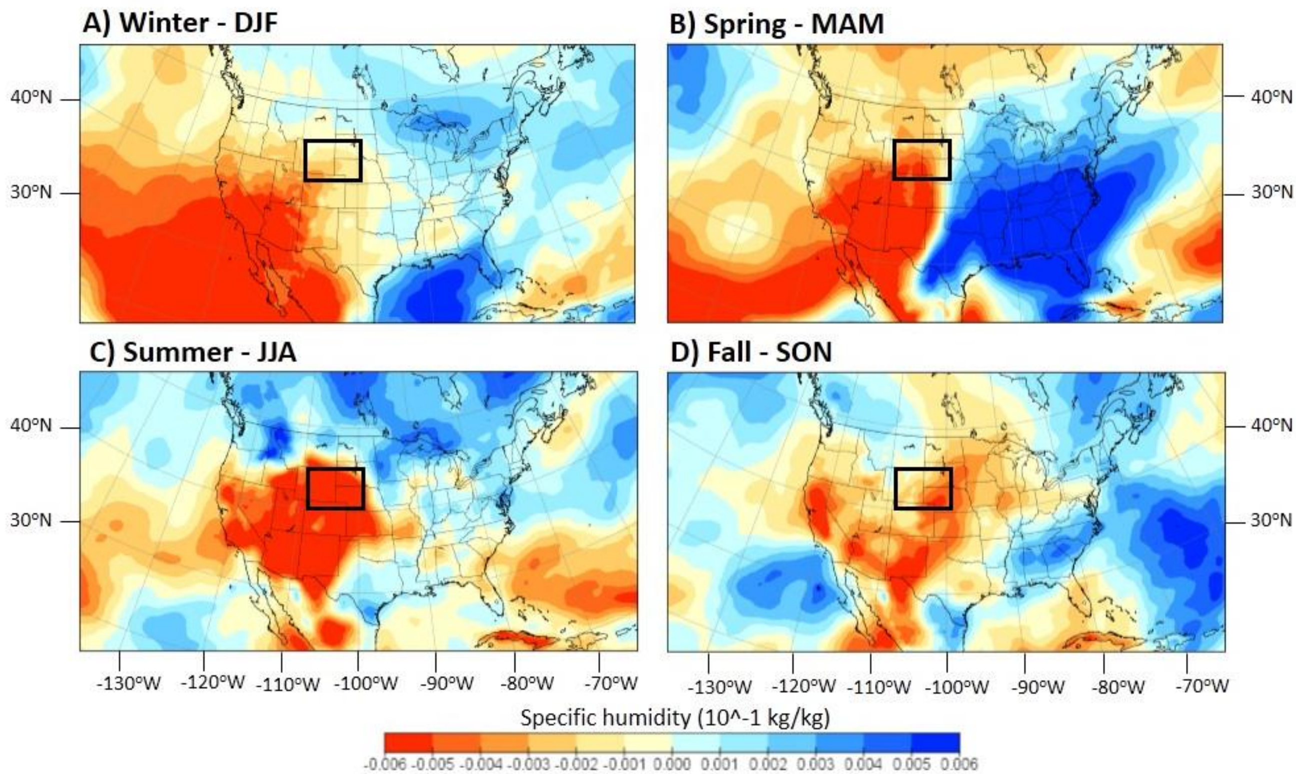


Figure 108. Composite anomaly maps for 850mb specific humidity during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) the fall season (SON). Positive values (cool colours) for 850-mb specific humidity indicate wetter-than-normal conditions in the atmosphere. Negative 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. -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.

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.**~~