Drought and vegetation change in the central Rocky Mountains: Potential climatic mechanisms associated with ~~the mega~~ drought 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)

We would like to thank both reviewers and the Editor for their valuable comments. Below you will find our response to each reviewer, as well as the Editor, and highlight all changes that have been made to the manuscript. Our responses are shown in blue text.

Reviewer 1

The composites are based on only five events. But there is no attempt anywhere in the paper to address the statistical significance or the robustness of the results. The features of the maps may easily in many cases be just results of chance. This should be investigated by calculating and showing the statistical significance. Also, it should be tested if the results are robust and if they depend on one or a few of the five events. It should also be tested if results depend on the threshold (-1.5 standard deviations).

We thank Reviewer 1 for pointing out this specific weakness in the paper. We now include which statistical significance test we used, and justify the use of this particular significance test in the Methods section (please see page 16 lines 7-12 below). Specifically, we used a two-tailed Student's t-test with an alpha of 0.05 to quantify significance at each grid point in the data set by comparing the precipitation that fell during our five composite years to that during the 30-year climate normal (1981-2010). We have demonstrated that spatially, if we look at the most statistically significant case years ($p < 0.05$) (i.e. those that were -1 standard deviations from the mean) from the modern record (e.g. the shared common period between the precipitation data and NARR data between 1979 and present), the significance values are representative of persistent drought conditions which we use as modern climate analogues in our analyses. To illustrate these results, we also included an additional figure (Figure 2b; see below) and associated text. This additional figure depicts the spatial distribution of significant p-values ($p < 0.05$) (i.e. those at the -1 standard deviation threshold) across our study region. The plotted significance values in Figure 2b indicate spatial coherency of anomalous dry conditions rather than spurious individual grid cells that would likely occur from chance, further supporting the use of our selected years as representative of both persistence (in time) and consistence (in space) of anomalous dry conditions.

To test whether the composite-anomaly values were dependent upon one of the constituent within the five events, we reviewed individual seasonal composite values within each of the five case years, and with the exception of DJF in 2012 and 1988, all of the anomalous precipitation values are consistently below normal with regards to precipitation, indicating that our composites dominated by representative persistent anomalously dry conditions. Thus, our composite values are not dependent upon one or a few of the seasons within the five event years. Additionally, it has been demonstrated in the literature (Mock and Brunelle-Daines, 1999; Mock and Shinker, 2013) that the use of a single analogue case year or even month is robust to discuss synoptic processes in the past.

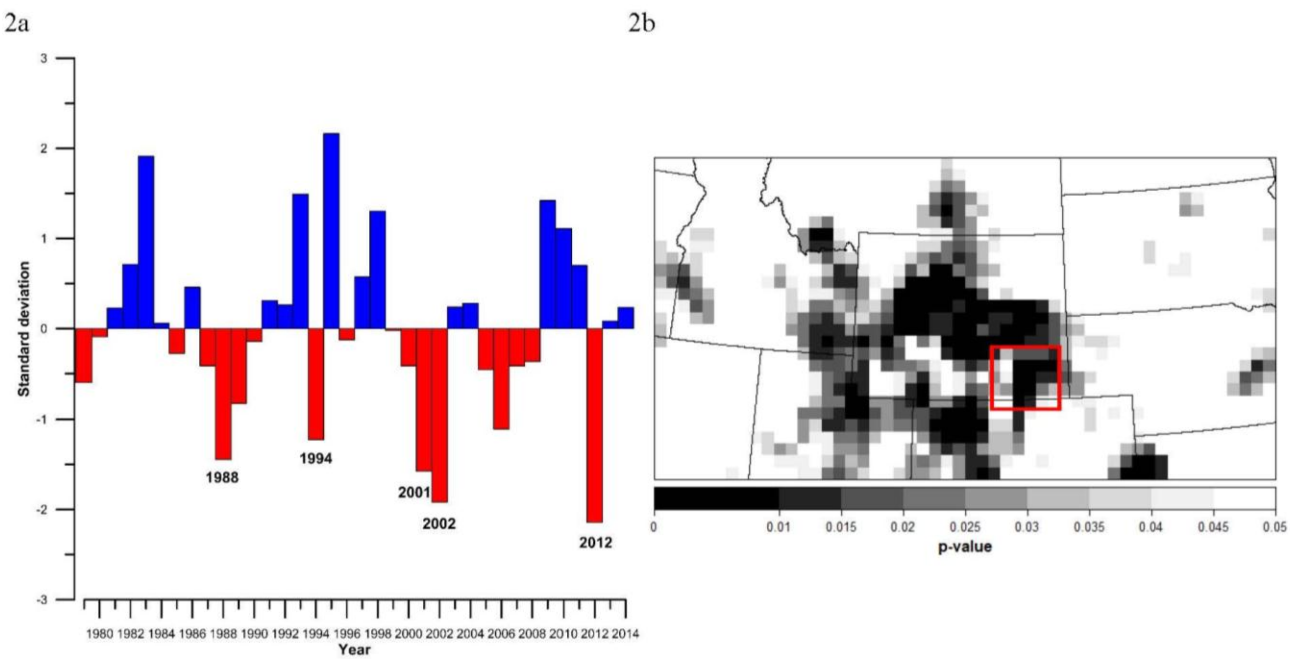


Figure 2. Precipitation anomalies and the spatial distribution of significant p-values across the study region of south-eastern Wyoming. A) A time series of annual precipitation anomalies for 1979-2014 compared to the long-term average (1981-2010) from Wyoming climate division 10, Upper Platte River 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) A 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.

The duration of the modern analogues are around a year, while the duration of the mega drought is more than 100 years. Is there any reason at all to believe that events on such different time-scales have the same or related mechanisms? Long lasting events tend, in general, to also be more spatially extended. See e.g. DOI:10.1002/2016RG000521 for a review of how the number of spatial degrees of freedom depends on the temporal scale considered. The validity of the method of modern analogues should be investigated and discussed in detail. There is a lot of available model experiments (e.g., CMIP5) where this could be investigated.

The underlying assumption in the modern climate analogue approach is in the principle of uniformitarianism (Barry and Perry, 1973), which assumes that the range of modern conditions contains extreme events that likely occurred in the past, and that the processes involved with modern synoptic processes behaved similarly in the past. It has been demonstrated that multi-decadal to centennial-scale droughts were common phenomena in the Great Plains region during the late Holocene (Schmieder et al., 2011). Therefore, we believe that our composite-anomaly approach takes into consideration the overall processes occurring within the five case years, when combined, as representative of persistent conditions, providing an analogue to the long-term drought identified in the paleoecological record. We discuss the principle of uniformitarianism in the Introduction (page 13 lines 8 below) and discussion section 5.3 (page 26 lines 2 below).

Your statement ‘Long lasting events tend, in general, to also be more spatially extended’ is illustrated in the additional figure (Figure 2b) which demonstrates that that our case years were not only anomalously dry in our study region of south-eastern Wyoming, but our case years were anomalously (and statistically significant) dry across the region. Thank you for suggesting the Christiansen and Ljungqvist (2017) reference. While we agree the degrees of freedom should be considered in temperature reconstructions, our paper is not attempting to reconstruct temperature, which does have a normal distribution because of the influence of seasonal insolation – rather the goal of the modern climate analogue approach is to understand atmospheric processes involved with prolonged drought associated with precipitation, which is not normally distributed because of the variability of uplift mechanisms and moisture availability, which we use in our approach to analyze and explain the climatic controls of ecological responses to persistent drought conditions.

We have included a new paragraph in the Introduction section that discusses the validity of the modern analogue method. In this new paragraph, we provide a brief literature review on previous research that used the modern climate analogue technique as a way to explain past atmospheric processes associated with a variety of environmental change. This new paragraph can be found on page 13 line 20.

Our analysis is a first-step approach to understanding the relationship between vegetation change and drought-related disturbance at a local and regional scale. Since the NARR data are initiated with climate station data, our study can be used for data-model comparisons utilizing climate models (e.g. CMIP5), as well as sensitivity tests of the described processes in future analyses. While we did not include model simulations in this study, we have included a new discussion section, 5.3, titled ‘Model simulations and implications for drought in the central Rocky Mountains and central Great Plains’ where we briefly discuss previous research that have used GCMs and RegCMs to investigate and model drivers of drought in the region. Our results agree with existing model simulations that anomalous high-pressure ridges and anti-cyclonic flow are prominent features involved with drought in the region at multiple timescales (e.g. mid-Holocene, historical Dust Bowl, recent modern drought within the timeframe of our study). Section 5.3 begins on page 25 line 12.

Reviewer 1 Minor comments

p6, l13: Why are these years "suitable analogues". Are other conditions than the drought index used?

We apologize if this text was vague. What we meant by 'suitable analogues' is that the five case years identified represent the driest years (i.e. -1 standard deviations below the mean) in the modern record. However, using the results from the Student's t-test, we are able to say that our case years are statically robust analogues, rather than just stating they are 'suitable.' The sentence has been edited to read: "Five case years (2012, 2002, 2001, 1988, and 1994) that were at least -1 standard deviations below the long-term average were chosen because they were found to be the most statistically significant ($p < 0.05$) analogues for dry conditions in the Upper Platte River Basin (Figure 2b). These five case years are representative of persistently low annual precipitation conditions and are therefore used to as analogues to explain the climatic mechanisms responsible for dry conditions identified in the paleoclimate record." This can be found on page 17 line 5.

Figure 2: What is the value of the standard deviation?

We apologize we did not include this information. One standard deviation is equivalent to 58.89 mm per year. This information has been included in both the Methods section (page 16 line 7 below), and in the new Figure 2b figure caption (see above).

Reviewer 2

Incomplete discussion of the regional extent of a so-called '_150 year long' '4200 Cal BP mega drought' and implications for the utility of seasonal synoptic analogues. More close attention to precisely what regions this study is meant to be useful for is needed. The Long Lake record, within the Medicine Bow Range, is described here as reflecting the Rocky Mountain region, according to another recently published paper by this author; Carter et al. (2017). However, the citation for the 4.2 ka 'mega' drought is Booth et al. (2005), who focus on the Northern Great Plains. It is not mentioned here that Booth et al.'s hypothesis was not further verified by additional high resolution multi-proxy data (e.g., Grimm et al., 2011). The other records mentioned in support of the drought are Wyoming dune activity and speleothem isotopes from northeastern Utah. However, the dune data is not well-enough dated (OSL and 14C) and conflicting interpretations are possible for the carbon and oxygen speleothem isotopes from Minnetonka Cave.

Therefore, it is puzzling why the synoptic analyses are focused on the central Rocky mountain region of Wyoming (rather than the Northern Great Plains), and that there is no mention of other paleohydroclimatic data from Wyoming and northern Colorado that are numerous and nearby. Perhaps these regional selections were discussed and justified by Carter et al. (2017) but then this would need to be explained in more detail here. As it is, readers of this study cannot actually evaluate the spatial regional patterns of the modern analogues in relation to any proxy data because it is not shown on the maps. Unfortunately, there are

nearby records that do not indicate a 4.2 ka ‘mega’ drought and which are not mentioned in this study. Through this omission, the study overlooks important implications that likely limit the utility of the modern analogue approach.
Thank you for your suggestion. We have expanded our discussion to reflect the regional complexities of climate variability both spatially and temporally. Due to the proximity of our study region in south-eastern Wyoming to the central Great Plains, our composite anomaly maps illustrate that the broad-scale synoptic processes that impact the central Great Plains also influence our study region. Therefore, we focus on proxy evidence closest to our study region. Because Booth et al. (2005) included sites in both the central and northern Great Plains, and the additional text we have included supports the climatic connections between the Great Plains region and the eastern portion of the central Rocky Mountains.

We now include a new discussion section, section 5.1 ‘Proxy evidence for regional climate variability at 4200 cal yr BP’ (please see page 19 line 10 below) which includes additional sites in the central Rocky Mountains and central Great Plains region that also experienced ecological change in response to drought conditions around 4200 cal yr BP. We also discuss sites near our study region that do not record drought conditions at this time. The conflicting climate interpretations from the region (i.e. cool and wet versus warm and dry) is to be expected because our single site cannot reconstruct similar conditions found in the northern Great Plains and interior intermountain west which have different precipitation regimes and synoptic controls, and are topographically more complex and lacking proximity to Great Plains climatic influences. Additionally, contrasting evidence in the region can be explained by differences in site and proxy sensitivities, seasonal biases in proxy, as well as temporal resolution of each individual site.

Incomplete discussion of the temporal uncertainty of drought timing and length and how to understand the relationship between seasonal analogues and lower frequency climate mean states (i.e., multi-decadal to century time-scales). There is currently no helpful discussion of time-scales in the paper. The range of uncertainty associated with timing of the so called ‘_150 year’ ‘mega drought at 4200 Cal BP’ is necessary to know in order to contemplate how seasonal anomalies could be translated by radiocarbon dated proxy records. At the very least some discussion of the age control, and uncertainties, for the timing of the quaking aspen rise at Long Lake is needed. The analogues provide seasonal-scale drought mechanisms but discussion about how seasonal synoptic scale mechanisms inform our understanding of drought mechanisms on century time-scales is not here.
Thank you for pointing out the discrepancy in temporal uncertainty. We discuss the length and timing of the drought in the Introduction section on page 12 line 26. We expand upon the temporal certainty regarding the timing of the drought at Long Lake in the Study Area section on page 15 line 14 below.

The underlying assumption of using the modern climate analogue approach is in the principle of uniformitarianism (Barry and Perry, 1973), which assumes that the range of modern conditions contains extreme events that may have been more frequent in the past, and that the processes involved with modern synoptic controls behaved similarly in the past. Our composite-anomaly analyses use statistically significant dry years which represent persistent (in time) dry conditions as analogues for climate mechanisms and processes associated with drought conditions in the past. While Carter et al. (2017a) were unable to confirm whether the drought between 4300 and 4100 cal yr BP was indeed ~150-years long because of low temporal resolution involved with slow sediment accumulation rates, it is more plausible that this drought occurred on multi-decadal time-scales. However, both multi-decadal- and 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 modern climate analogues are representative of persistent drought conditions and thus could be reflective of droughts on both multi-decadal and centennial- time-scales given the consistency in synoptic controls (persistent anomalous high pressure supporting subsidence, and block moisture flow into the region). Our modern climate analogue results include synoptic patterns that are consistent with other reconstructed droughts in the Great Plains region during a variety of times (e.g. mid-Holocene, historical Dust Bowl, and recent modern droughts).

Incomplete discussion of changing boundary conditions across the 5000 to 4000 Cal BP time window and the potential role of the North American Monsoon (NAM) and El Nino Southern Oscillation (ENSO) that could have potentially affected this study region during that time.

There is no discussion of previous studies based on nearby proxy records that indicate potentially significant changes in the mean state of the NAM and ENSO before and after _4 to 3 ka (see Reference list below). Modern day ENSO effects are discounted based on an argument that the region is currently unaffected. The same assumption for the mid-Holocene is likely incorrect. Even if a thorough evaluation of Holocene changes in mean state of NAM and ENSO is beyond the scope of this study, a discussion explaining their potential significance still needs to acknowledged. Changing boundary conditions present major challenges for understanding how to apply modern analogues and should be acknowledged.

Thank you for your suggestion. We have rewritten section 5.1 which as previously mentioned, discusses the regional climate variability between 5000 and 4000 cal yr BP as evidenced from regional proxy data. Also included in this new discussion section are discussions regarding changing boundary conditions that may have caused the different spatial patterns in climate. The new 5.1 discussion section begins on page 19 line 10 below. We provide additional context and additional references for the role, or lack thereof, of changes and impacts of ENSO and the NAM on our region, and the relationship to synoptic patterns associated with our modern climate analogue processes.

Sampling of missing relevant references, and references therein: (in no particular order and by no means complete)

Thank you for the suggested references. We have included the suggested references, and references therein in our new discussion sections.

Reviewer 2 Minor comments

Technical Corrections (typing errors, grammar etc.) -As previous reviewer suggested, avoid emotive language and delete “Unfortunately” on lines 5 and 13. -p.5 Line 24, spelling of “analyse” -p.9 Line 24, “of flow of cold”?

Thank you for your suggestions. We deleted 'unfortunately' from page 12 line 1 and line 12, as well as on page 29 line 12. We corrected the spelling of 'analyse' on page 16 line 27 below.

Editor's comments

Dear Carter et al, Thank you very much for submitting your manuscript to the YSM special issue of Climate of the Past and for your responses to the reviewer's comments. We would like to submit your paper for major revisions and a second round of review. We agree with the reviewer's comments and look forward to your planned edits of the manuscript in line with their suggestions.

We would like to thank the Handling Editor and Co-Editor for the opportunity to revise and resubmit our manuscript, cp-2017-107: "Drought and vegetation change in the central Rocky Mountains: Potential climatic mechanisms associated with mega drought conditions at 4200 cal yr BP." We are appreciative of the comments from the two anonymous reviewers. Their comments have greatly improved the discussion and applicability of the modern climate analogue technique in regards to the drought at 4200 cal yr BP.

We have slightly changed the title of our manuscript in this submission: ' Drought and vegetation change in the central Rocky Mountains: Potential climatic mechanisms associated with ~~themega~~ drought conditions at 4200 cal yr BP' because of Reviewer 2 comments. Carter et al. (2017a) were able to reconstruct a drought between 4300 and 4100 cal yr BP, but because of temporal resolution reasons, the authors were unable to determine whether the drought was indeed a 'megadrought.' We therefore have removed 'mega' from our title.

We have included a new co-author, Jonathon Preece. His affiliation has been included in the revised manuscript.

Per the major revision recommendation, we have completely rewritten the discussion section; section 5.1 'Proxy evidence for regional climate variability at 4200 cal yr BP' addresses Reviewer 2 Comment 1 and 3; section 5.2 'Regional climate variability based on modern climate analogues of drought at 4200 cal yr BP' uses the modern climate analogue approach to explain the ecological response in our study region of south-eastern Wyoming, as well as within the central Great Plains; finally, section 5.3 'Model simulations and implications for drought in the central Rocky Mountains and central Great Plains' addresses Reviewer 1 Comment 2 regarding the use of model simulations. While we did not include simulations in this paper (this will be included in a follow-up paper), we did compare the results of our modern climate analogue approach to existing literature that have used GCMs and RegCMs to investigate drivers of drought in the region. Our results are supportive of existing models and simulations that suggest persistent high-pressure ridges and anti-cyclonic winds are prominent features in droughts from the region.

As additional editorial advice, we also request that in response to Reviewer 1 Comment 1 the method of testing for statistical significance should be included in the Data and Methods section of the paper. This section should include a response to the question of whether your results are sensitive to exclusion of any of the five composite members and to the choice of -1 standard deviation threshold. To address Reviewer 1 Comment 2, the addition of an introductory paragraph on the climate analogue approach is welcomed.

We used a Student's t test to address Reviewer 1 Comment 1, which we now discuss in the Methods section on page 16 line 7 below. Using this statistical analysis, we were able to confirm that -1 standard deviations is a statistically significant, representing persistent drought conditions through time. We plotted the resulting significance values to illustrate their spatial coherence to illustrate the valid threshold used in our study. This can be found in the Methods section on page 16.

The netcdf files used for the statistical analyses, as well as for creating the composite anomaly maps, will be uploaded to PANGAEA.

Additionally, it has been demonstrated in the literature (Mock and Brunelle-Daines, 1999; Mock and Shinker, 2013) that the use of a single analogue case year is robust to discuss synoptic processes in the past. We did investigate whether our composite-anomaly values were dependent upon one of a few of the seasons within the five case years selected by reviewing individual seasonal composite values within each of the five selected case years. With the exception of DJF in 2012 and 1988, all of the anomalous precipitation values are consistently below normal with regards to precipitation, indicating that our composites are representative of persistent anomalously dry conditions (also evident in the significance values form the time series). We included this information in the discussion section on page 22 lines 20.

Lastly, we have also included an introductory paragraph regarding the climate analogue approach. This new paragraph can be found on page 13.

We further request that the assumptions underlying the climate analogue approach should also be discussed in the Discussion section and inform the Conclusions.

We now discuss the underlying assumption involved with the modern climate analogue technique in the new 5.3 discussion section (see page 25 line 12). The underlying assumption was used to inform the Conclusion section which begins on page 27.

We would also request that you address the suggestion to use CMIP5 simulations to test the assumptions in the MAT.

We believe climate simulations like CMIP5 and other GCMs and RCMs are beneficial for understanding climate variability and teleconnection impacts in areas sensitive to drought. Currently, there are several leading hypotheses regarding the mechanism behind the 4.2 ka event, but no climate simulations exist for this time period. The goal of using an environment-to-circulation approach using the modern climate analogue technique was to investigate synoptic processes that may be used to explain the ecological changes we see in south-eastern Wyoming at 4200 cal yr BP. The results of this study are meant to inform future climate simulations regarding this climatic event, not reconstruct and model climate processes involved with initial cause of the event. Future work will involve data-model comparisons to test whether the results presented, while consistent with past regional drought reconstructions (e.g. mid-Holocene, historical Dust Bowl, and modern droughts) are useful for reconstructing boundary conditions to improve our understanding of the 4.2ka event.

To help address Reviewer 2 Comment 2, we suggest removing Section 3.1 from the paper and expanding on the length and timing of the dry spell in the Introduction instead.

Thank you for the suggestion. We have removed section 3.1, but have used some of the relevant information in the end of the study area section (see page 15). There, we expanded upon Reviewer 2 Comment 2 regarding the temporal constraint of the drought identified in our sedimentary record. Additionally, we briefly expand on the length and timing of the drought in the Introduction section (see page 12 line 26).

For Reviewer 2 Comment 3, we advise using the suggested references to develop your discussion further in light of other studies conducted in the area, and particularly in the context of your revised Figure 2b.

We thank Reviewer 2 for the suggested references and used these papers in our new discussion section, 5.1 which begins on page 19. We have provided context for the differences in proxy and site sensitivities within the region, which is to be expected given the topographic diversity of the interior intermountain west, as well as variability with synoptic processes (e.g. variations in the influence of the polar jet stream). In other words, topographically complex regions such as the Rocky Mountains and intermountain west region experiences different precipitation regimes (seasonally and spatially) that can impact the ecological signals recorded in proxy data at a variety of sites. We discuss this further in section 5.1.

References cited in author response

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

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.

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.

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, 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.

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.

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.

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.

Drought and vegetation change in the central Rocky Mountains: Potential climatic mechanisms associated with ~~the mega~~ drought 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 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 ~~lake sediments from~~ Long Lake, south-eastern Wyoming. However, pollen evidence does not record the climate mechanisms that caused the drought; they only provide evidence that the drought occurred. A modern climate analogue technique using North American Regional Reanalysis data was applied to the sedimentary pollen data to provide a conceptual framework for exploring possible mechanisms responsible for the observed ecological changes. ~~in order to identify possible synoptic and dynamic patterns that may have caused the mega drought at 4200 cal yr BP.~~ The ~~Our~~ ~~results~~ modern climate analogues illustrate ~~demonstrate~~ ~~the~~ that persistent warm and dry conditions throughout the growing season were a result of anomalously higher-than-normal geopotential heights ~~that were~~ centred over the Great Plains, which ~~beginning in spring and persisting until the fall. Drought conditions during the growing seasons was the result of the anomalous high-pressure ridge, which~~ suppressed moisture transport via the low level jet from the Gulf of Mexico, as well as brought in dry continental air from ~~in~~ the interior region of North America. 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 c~~C~~onditions provide insight as to the mechanisms that facilitated abrupt changes in ~~associated with the mega drought likely led to the changes in~~ vegetation composition in the past in our study region of south-eastern Wyoming. ~~as evidenced by the pollen record.~~

1. Introduction

Throughout the 20th century, droughts have caused both economic and societal losses throughout the Great Plains and the western United States (US) (Diaz, 1983; Karl and Koscielny, 1982; Karl, 1983; Woodhouse and Overpeck, 1998). However, these most recent droughts were both shorter in duration, and less severe than mega droughts that have plagued the region in the past (Woodhouse and Overpeck, 1998). ~~Unfortunately,~~ 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). ~~because of the rise in globally averaged land and ocean temperatures, changes in the hydrological cycle and moisture availability have occurred in these regions (IPCC, 2014).~~ Subsequently, drought vulnerability has increased in both the Great Plains and western US (Garfin et al., 2013). In the Upper~~North~~ Platte River drainage basin (~~our~~ the region ~~area~~ of interest in ~~for~~ 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 ~~and/~~or intensity of drought (Breshears et al., 2005; Cayan et al., 2010; Seager et al., 2007; Sterl et al., 2008). Such changes in the hydrological cycle have the potential to influence hydrologic systems, ecosystem processes, and vegetation distribution in the future.

~~Unfortunately,~~ Since 1970, widespread forest mortality on a global-scale has occurred as a result of water or heat stress (Allen et al., 2010). ~~changes in vegetation distribution are already occurring. Allen et al. (2010) documented widespread global forest mortality since 1970 as a result of water and/or heat stress.~~ Drought and increased temperatures have resulted in widespread mortality among certain ~~In~~ western North American , ~~mortality has increased among certain~~ quaking aspen (*Populus tremuloides* Michx.) communities ~~as a result of drought and increased temperatures~~ (Anderegg et al., 2013a; 2013b; Hanna and Kulakowski, 2012; Hogg et al., 2008; Kashian et al., 2007; Rehfeldt et al., 2009; Worrall et al., 2008; 2010; 2013). Quaking aspen is the most widely distributed deciduous tree species in North American, and is considered a keystone species in the Intermountain West region (Kay, 1997; Little, 1971; Perala, 1990). While the recent decline of quaking aspen appears to be influenced by increased temperatures, the relationship between climate variability and quaking aspen mortality remains poorly understood prior to the 20th century (Anderegg et al., 2013b; Hanna and Kulakowski, 2012; Worrall et al., 2010). ~~However,~~ Carter et al. (2013) documented a unique change in vegetation composition ~4000 cal yr BP from sedimentary proxy evidence from Long Lake, south-eastern Wyoming in the Upper ~~North~~ 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 ~~forest,~~ 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 ~~mega~~ drought between 4300 and 4100 cal yr BP ~~centred on 4200 cal yr BP (Booth et al., 2005)~~ likely influenced the upslope migration of quaking aspen stands in the Medicine Bow Range of south-eastern Wyoming, while 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 such as fires or drought, ~~mega-droughts,~~ 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). Improving our understanding of the climate processes associated with modern drought will provide better insight about past drought variability, and the mechanisms that caused mega droughts evident in paleoecological records. A better understanding about drought and ecological responses, especially in regions with high topographic and climatic variability is important information that can be applied to land managers (Shinker et al., 2006). One tool we use can use to understand the climate processes associated with 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 ~~The modern climate analogue technique is~~ an effective way to identify climate mechanisms associated with past environmental changes (e.g. as seen in reconstructed sedimentary pollen analyses) (Edwards et al., 2001; Mock and Brunelle-Daines, 1999; Shinker et al., 2006; Shinker, 2014; Carter et al., 2017b). A modern climate analogue is ~~simply~~ a conceptual model that uses modern extremes (e.g. drought) as analogues ~~analogs~~ of past events (e.g. vegetation disturbance associated with drought in the ~~palaeo~~ sedimentary record) as a means to understand palaeoclimate patterns that may have caused extremes in the past (Diaz and Andrews, 1982; Ely, 1997; Edwards et al., 2001; Shinker, 2014). Such conceptual models of dynamic processes can provide examples of modern climatic mechanisms in order to explain historic palaeoclimate variability (Mock and Bartlein, 1995; Mock and Brunelle-Daines, 1999; Mock and Shinker, 2013; Shinker et al. 2006; 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). 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). Shinker (2014) 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). Finally, Carter et al. (2017b) used modern climate analogues to describe how atmospheric conditions created unique spatial patterns of wildfire activity over the 1200 years in the northern and southern Rocky Mountains, as seen in 37 sedimentary charcoal records.

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 ~~The purpose of this study was to apply a modern climate analogy technique to a palaeoecological reconstruction from Long Lake, Wyoming using~~ an environment-to-circulation approach (Barry and Carleton, 2001; Mock and Shinker, 2013; Shinker, 2014; Yarnal, 1993; Yarnal et al., 2001).~~,~~ An environment-to-circulation approach ~~which~~ 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 ~~(i.e. anomalously dry)~~ 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. ~~help identify dominant synoptic processes that may have created the persistent mega drought centred on 4200 cal yr BP.~~ This paper focuses on the relationship between atmospheric synoptic processes and surface climate mechanisms~~, and synoptic processes,~~ and their influence on the ecological changes recorded during the *Populus* period identified by Carter et al., (2013; 2017a).

1. Study Area

Long Lake (41° 30.099′ N, 106° 22.087′ W; 2700 m a.s.l.) is located within the Upper ~~North~~ Platte River watershed in the Medicine Bow Range of south-eastern Wyoming (Figure 1). The lake lies within a closed drainage basin behind a Pinedale-aged terminal moraine with no inlets or outlets (Atwood, 1937). The study site experiences a snow-dominated winter precipitation with a ~~spring~~ precipitation maximum in May (Mock, 1996; Shinker, 2010), albeit that 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 -9.7°C and 11°C, respectively (NRCS, unpublished data). Using the modern pollen analogue technique (~~;~~Overpeck et al., 1985), ~~-~~Carter et al. (2017a) reconstructed ~~both~~ the mean temperature of the coldest month (MTCO; i.e. January) ~~(i.e, January)~~, ~~and~~ mean temperature of the warmest month (MTWA; i.e. July) ~~(i.e., July)~~, and annual precipitation which have ~~which~~ averaged -9°C, ~~and~~ 15°C, 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 -8°C , 16°C, and 394 ± 58 mm (Carter et al., 2017a) ~~Carter et al., (2017) also reconstructed annual precipitation, which averages ~443 ± 39 mm over the past 2000 years.~~ Both the modern and reconstructed climate from the area highlights that the Medicine Bow Range has ~~receives~~ 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 ~~. Additionally, the Medicine Bow~~

~~Range are located within the region that currently does~~ not experience seasonal precipitation patterns associated with ENSO phases (Wise, 2010; Heyer et al., 2017).

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

Carter et al. (2013; 2017a) describe the sedimentary collection that took place at ~~from~~ Long Lake in 2007., while ~~Additionally,~~ Carter et al. (2017a) describe age-depth relations, charcoal and pollen analysis, and the modern pollen analogue technique 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, as well as temporally constraint the drought at 4200 cal yr BP (see Table 1, Carter et al., 2017a).

2. Methods

~~2.1 Sedimentological analysis~~

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

Modern climate analogues and calculation of composite-anomaly values

In order to identify potential climate~~ic~~ mechanisms associated with the 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 ~~Platter~~ basin using data from the National Climate Data Centre (NCDC) (Figure 2). The Upper Platte River basin was chosen because it encompasses the Medicine Bow Range~~,~~ where ~~our study site~~ Long Lake and sedimentological analyses were collected from (Carter et al., 2013; 2017a)~~is located~~. Annual average precipitation values from 1979-2014 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 ~~The times series was calculated for 1979-2014, which is the common period for the~~ North American Regional Reanalysis (NARR) dataset. From the time series, potential analogues (e.g.~~i.e., selected~~ dry case years) that were identified to be the most statistically dry years were selected to ~~chosen that best~~ represent similar conditions (e.g. anomalously dry) that would have potentially caused the ecological response identified ~~found~~ in the sedimentary analyses conducted by Carter et al. (2013; 2017a) ~~(Mock and Brunelle-Daines, 1999)~~. In this study, c~~C~~ase years ~~were selected~~ that were ~~greater than or equal to~~ -1~~.5~~ standard deviations below ~~from~~ the long-term average (one standard deviation being equivalent to 58.89 mm per year) were selected as modern analogues~~.~~ Statistical significant of each case year were evaluated at each grid point in our study region using a two-tailed Student's t-test which 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 2b).

~~Once the modern climate analogue case years were selected, anomalies were calculated by subtracting the five case years that were less than or equal to -1.5 standard de~~n~~viations from the long-term average (1979-2014).~~ For the purpose of understanding modern synoptic processes that may have influenced vegetation change, a variety of surface and atmospheric climate variables ~~were used~~ from the NARR dataset (Mesinger et al., 2006) were used to calculate and map anomalous patterns (Table 1). ~~Use of the~~ The NARR dataset is advantageous for two reasons; 1) it provides a variety of climate variables that represent atmospheric synoptic processes (e.g. atmospheric pressure, wind direction and speed, moisture availability, and vertical motion), as well as surface conditions (e.g. precipitation rate and temperature); and 2) The spatial resolution (32-km grids) of the NARR 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). The 32-km resolution is therefore valuable for capturing the topographic and climate diversity of the geographic study region.~~of the NARR is valuable for our area of geographic study because it captures topographic and climatic diversity of the central Rocky Mountains~~. The seasonal values (e.g. winter = December, January, and February; or DJF) of the selected modern analogue case years were averaged together (composited) and compared to the long-term mean (1981-2010) to create composite-anomaly values for each season. These composite-anomaly values were mapped in order to analyze ~~analyse~~ and assess the spatial and temporal variability of both the surface and atmospheric variables ~~our selected modern climate analogues~~ to identify ~~surface and atmospheric~~ 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 ~~(e.g. atmospheric pressure and wind vectors)~~ were mapped at a continental scale to illustrate the large spatial scales in which such variables operate. ~~Similarly, the surface variables (e.g. precipitation rate) were mapped at the local or regional level to illustrate the spatial heterogeneity of such processes.~~ Composite-anomaly values were calculated using the NAAR Monthly/Seasonal Climate Composites plotting and analysis page (https://www.esrl.noaa.gov/psd/cgi-bin/data/narr/plotmonth.pl). The resultant netCDF (Network Common Data Form) files were 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.

3. Results

Five case years (2012, 2002, 2001, 1988, and 1994) that were -1~~.5~~ standard deviations below the long-term average were chosen because they were found to be the most statically significant ($p < 0.05$) ~~suitable~~ analogues for dry conditions in the Upper ~~North~~ Platte River b~~B~~asin. These five case years are representative of persistently low annual precipitation conditions and are therefore used as analogues to explain the climate mechanisms responsible for dry conditions identified in the paleoclimate record (Carter et al., 2013; 2017a).~~offer potential synoptic and dynamic processes that led to the ecological responses from the central Rocky Mountains.~~ The composite-anomaly values provide context regarding the spatial patterns associated with the anomalously dry conditions.

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

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

4.1.2 Atmospheric modern climate analogues

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

The 500mb vector wind composite anomaly maps provide information on the anomalous component of flow (Figure 6), which is associated with the 500mb geopotential height composite-anomaly maps. For winter (DJF), the anomalous component of flow is northerly into the study region (Figure 6a). During the spring (MAM), the anomalous component of flow is from the south- to south-east (Figure 6b) associated with the clockwise flow of air around the anomalous ridge seen in Figure 5b. During the summer (JJA), the anomalous component of flow is from the east (Figure 6c) associated with the clockwise flow of air around the anomalous ridge seen in Figure 5c. For fall (SON), the anomalous component of flow is northerly into the study region (Figure 6d).

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, ~~the variable,~~ 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 ~~indicate~~ anomalous sinking motions, indicating ~~(motions that~~ ~~suppress~~ suppression of precipitation~~,)~~ and negative 500mb Omega composite-~~-~~anomaly values indicating~~e~~ anomalous rising motions that ~~(motions that~~ enhance precipitation (Figure 7)~~)~~. ~~Therefore, seasonal maps of 500mb Omega composite-anomaly values illustrate local-scale sinking and rising motions (Figure 6).~~ Winter (DJF) composite-anomaly maps for 500mb Omega indicate weak anomalous rising motions in the study region (Figure 7~~6~~a). Spring (MAM) and Fall (SON) composite-anomaly maps indicate strong anomalous sinking motions in the study region (Figure 7~~6~~b and 7~~6~~d). Summer (JJA) composite-anomaly maps show a mixture of anomalous weak rising and sinking motions in the study region (Figure 7~~6~~c).

The 850mb specific humidity composite anomaly values were plotted on a continental scale to provide context on the spatial extent of ~~available~~ atmospheric moisture available for uplift by Omega during each season (Figure 8~~B~~). Winter (DJF) 850mb specific humidity composite anomaly-values are slightly below normal in the study region (Figure 8~~7~~a). Spring (MAM) 850mb specific humidity composite-~~-~~anomaly values indicate below normal moisture availability (Figure 8~~7~~b), which persisted into the summer (JJA) and fall (SON) (Figure 8~~7~~c, d ~~and 7d~~).

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

5. Discussion

5.1 Proxy evidence for regional climate variability at 4200 cal yr BP ~~Holocene evidence of mega drought conditions in the central Rocky Mountains and central Great Plains, USA~~

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~~. These changes can be~~ 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 – 3800 cal yr BP also indicates drought conditions in the Sand Hills of Nebraska (Schmieder, 2009); third, lower lake levels were recorded between ~5000 - ~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 – 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 – 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. ~~the increase in temperatures associated with the ~150-yr long (Carter~~

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

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

5.2 Regional climate variability based on modern climate analogues of drought at 4200 cal yr BP~~A seasonal modern climate analogue explanation for the mega drought in the central Rocky Mountains and central Great Plains of North America~~

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

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 40^{o} – 42^{o}N) 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 ~40^{o}N 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 winter precipitation is beneficial for vegetation during the growing season in the form of soil recharge via snowpack accumulation, 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 in the study area. 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. ~~During the spring months, warm and dry conditions prevailed in the region (Figure 3b). The 500mb geopotential height pattern indicates an enhanced high-pressure ridge centred over the Great Plains region, which subsequently brought an anti-cyclonic component of flow from the continental interior of North America, as demonstrated by the 500mb vector winds (Figure 8). However, dry conditions during the spring can be attributed to a~~

~~combination of enhanced atmospheric sinking, and a lack of atmospheric moisture, as illustrated by the 500mb Omega and 850mb specific humidity (Figures 6 & 7).~~

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

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

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~~–~~ Model simulations and implications for drought in the central Rocky Mountains and central Great Plains~~Paleowinds and the application of the modern climate analogue technique during the mega drought at 4200 cal yr BP~~

The current state of research is in agreement that anomalous and persistent high pressure ridges over the Great Plains are the most common contributor of drought (Basara et al., 2013). Persistent high pressure ridges lead to subsidence (e.g. sinking vertical motions) which suppresses precipitation. 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 contribute to summer precipitation in the Great Plains region (Hoerling et al., 2014). 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 and Great Plains drought 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), 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.

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.

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

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

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

6. Conclusion

Paleoecological reconstructions are valuable for understanding how ecosystems and disturbances respond to both gradual and abrupt changes in climate. However, proxies preserved in sedimentary records fail to record mechanisms that caused the ecological responses; the proxies only record that there was a change in vegetation composition or a change in disturbance regimes. Using the modern climate analogue technique and the underlying principle of uniformitarianism, our results offer potential climatic mechanisms that explain how persistent drought conditions in the central Great Plains affected vegetation composition at Long Lake, Wyoming ~4000 cal yr BP. Specifically, the atmospheric modern climate analogues illustrate 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).

~~We applied a modern climate analogue technique to explain potential climatic mechanisms that occurred during the mega drought centred on 4200 cal yr BP, and that led to the ecological changes recorded in the paleoecological reconstruction from Long Lake, Wyoming.~~

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

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 northwestern Mexico region) ~4000 cal yr BP.

~~Mega~~ D~~d~~roughts such as the one centred on 4200 cal yr BP, as well several droughts in the 13^{th} and 16^{th} centuries were more severe and of longer duration than the more recent droughts of the 20^{th} century (Woodhouse and Overpeck, 1998). ~~Unfortunately,~~ Understanding the climate ~~-global climate change is projected to increase the frequency and/or intensity of droughts in the future (Cayan et al., 2010; Sterl et al., 2008). Improving our understanding of the climate~~ processes associated with modern drought ~~will~~ 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 Long Lake in order to better understand the potential climatic mechanisms that impacted ecological changes such as the changes in ~~the~~ quaking aspen populations in the Medicine Bow Range.

7. Data Availability

Modern climate analogue years were selected based on NOAA/NCDC Wyoming Climate Division 10 from the Earth System Research Laboratory Physical Science Division of NOAA (https://www.esrl.noaa.gov/psd/data/timeseries/). Surface and atmospheric variables used in the composite-anomaly analysis are available through the Earth System Research Laboratory Physical Science Division of NOAA (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr). 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. (2017).

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.

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.

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.: 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.

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, 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.

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.

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, 2009.

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.

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.

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.

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.

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 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.

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.

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., & 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.

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.

Taschetto, A. S., & 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., 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, 2014.

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.

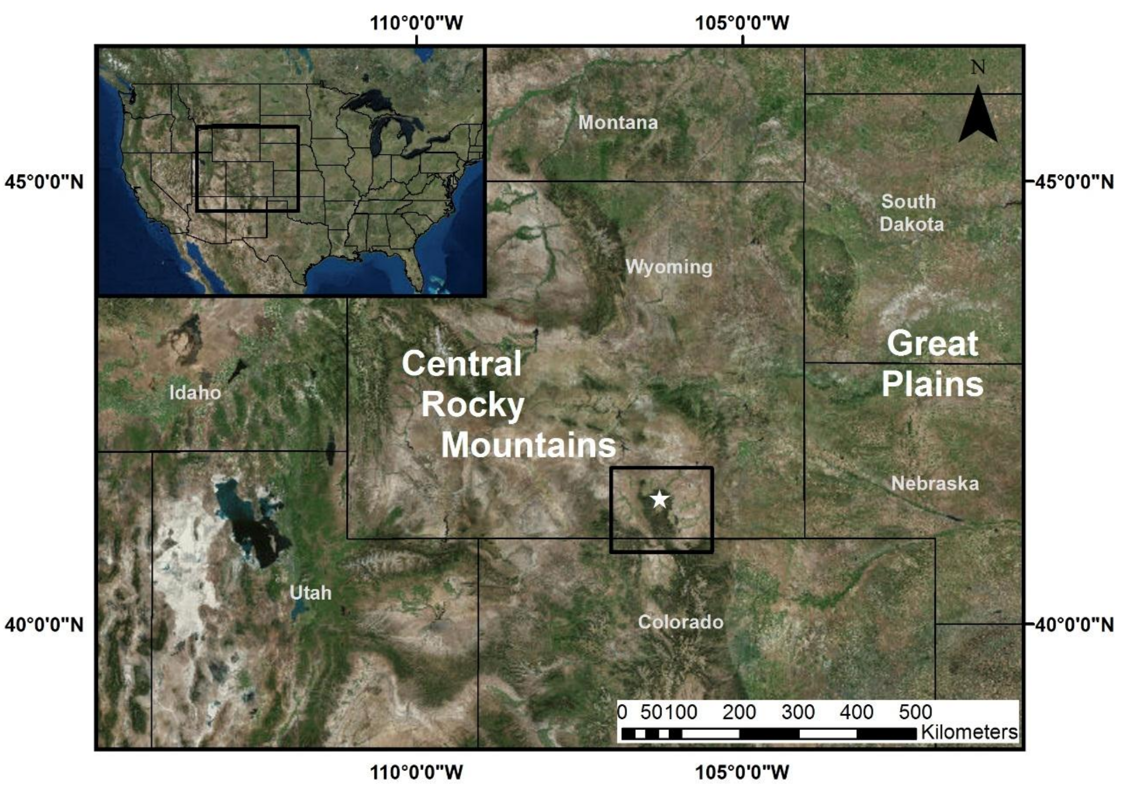


Figure 1. Location map of the study region in the western United States (small panel; black box). Long Lake, Wyoming (white start inside the black box indicating the study area) is located in south-eastern Wyoming within the central Rocky Mountain region on the edge of the Great Plains.

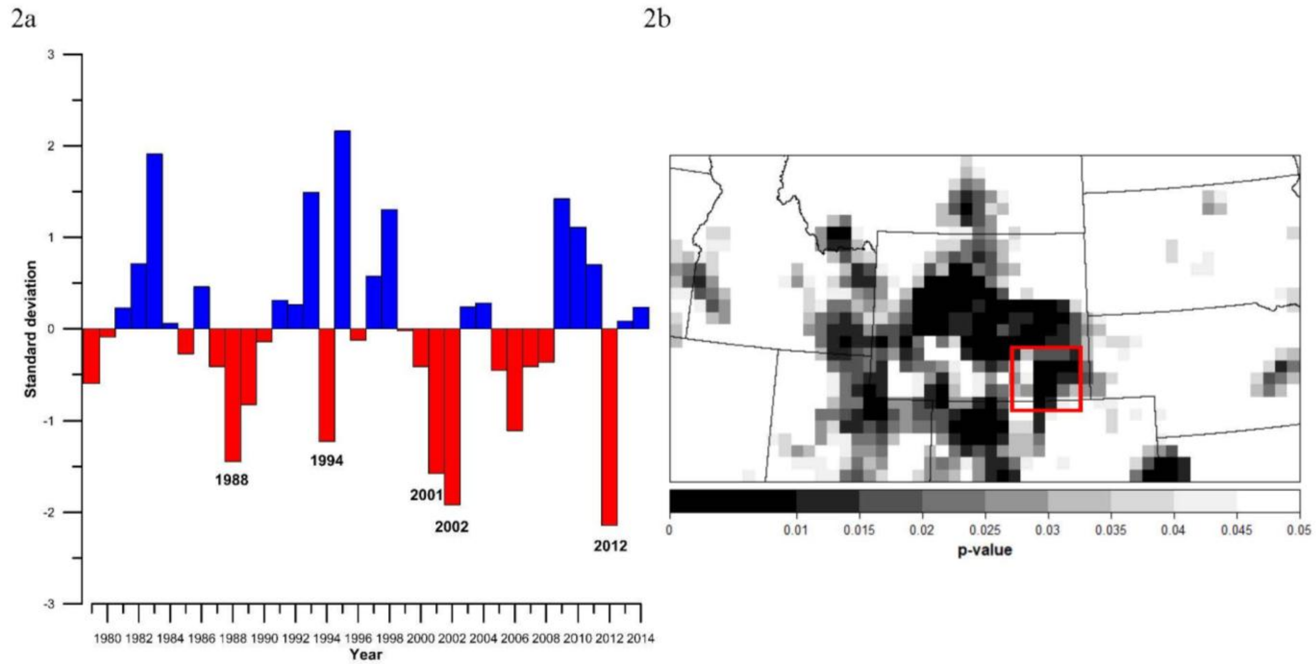
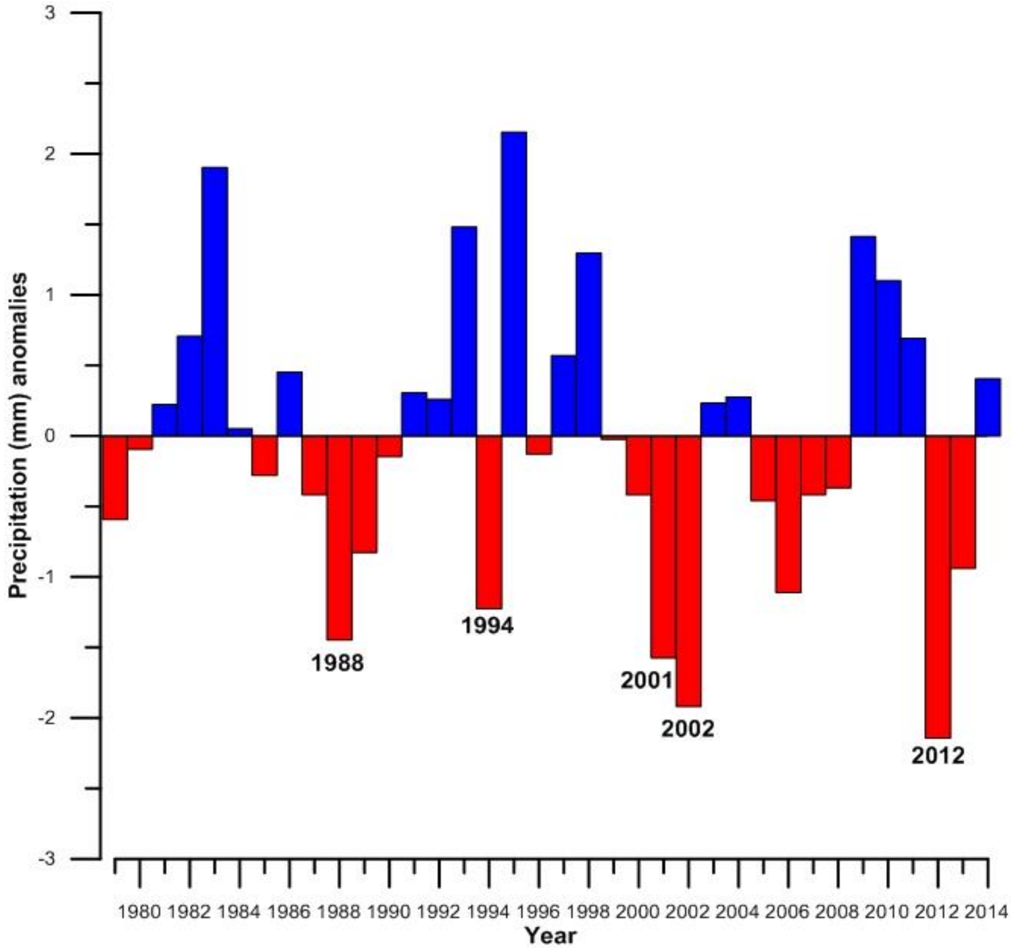


Figure 2. Precipitation anomalies and the spatial distribution of significant p-values across the study region of south-eastern Wyoming. A) Time series of annual precipitation anomalies for 1979-2014 compared to the long-term average (1981-2010) from Wyoming climate division 10, Upper Platte River Basin. 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.



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

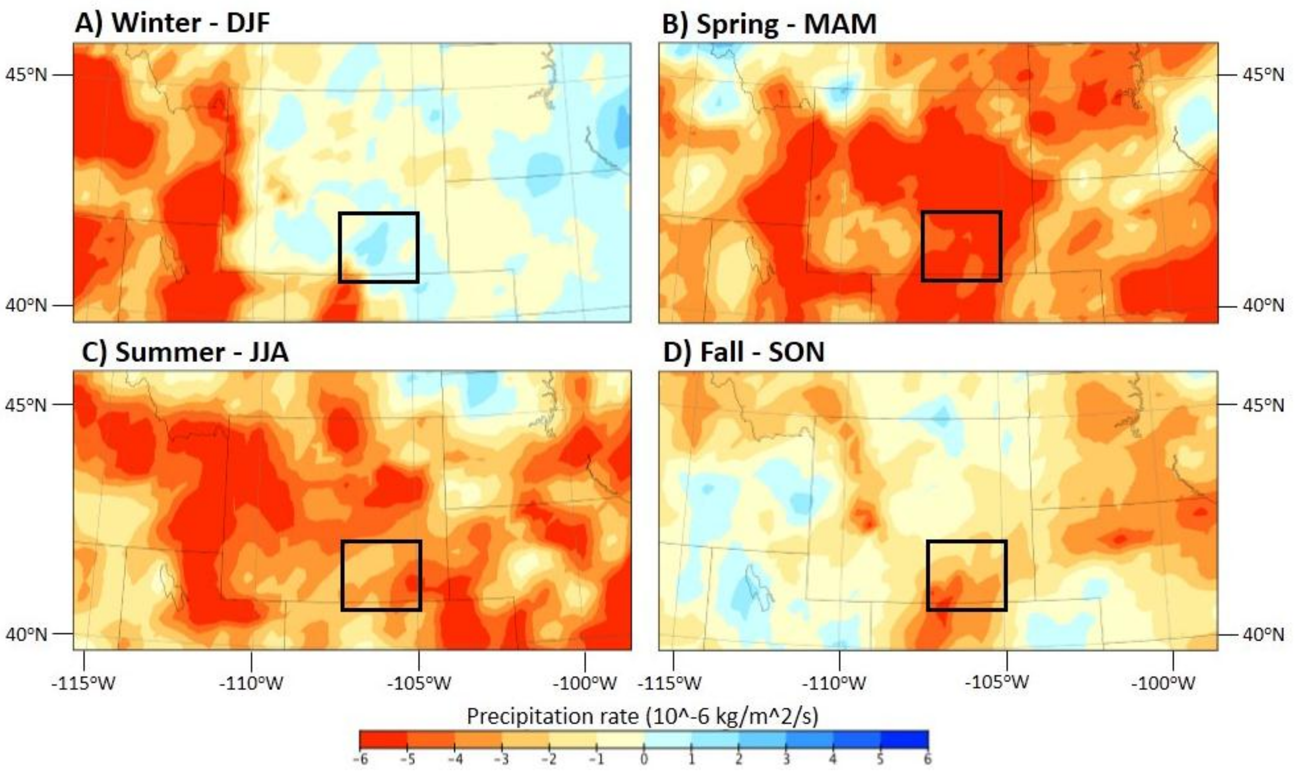


Figure 3. Composite anomaly maps for precipitation rate at the surface. A) Precipitation rate at the surface for winter (DJF); B) Spring (MAM); C) Summer (JJA); D) Fall (SON). Positive values (cool colours) for precipitation rate indicate wetter-than-normal conditions. Negative values (warm colours)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

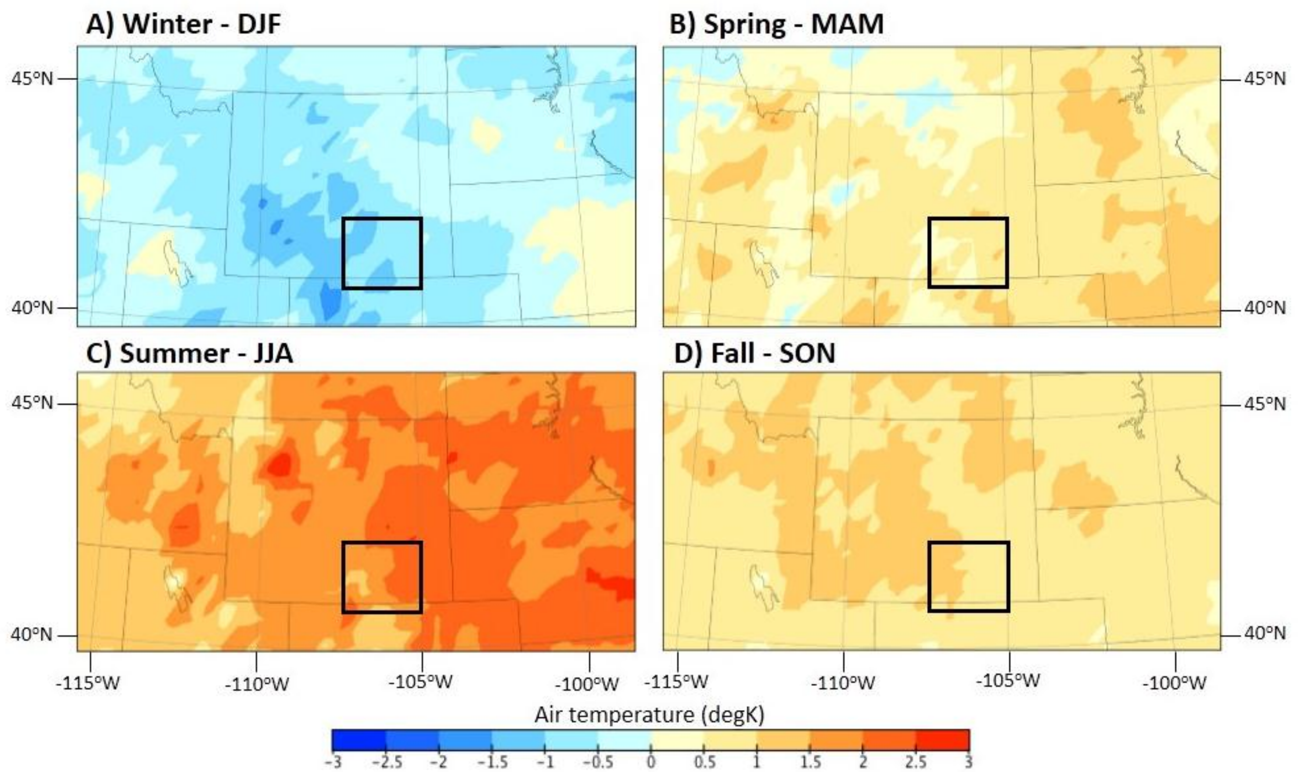


Figure 4. Composite anomaly maps for air temperature at the surface. A) Air temperature during the winter (DFJ); B) Spring (MAM); C) Summer (JJA); D) Fall (SON). Positive values (warm colours) for air temperature indicate warmer-than-normal conditions. Negative values (cool colours) indicate cooler-than-normal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

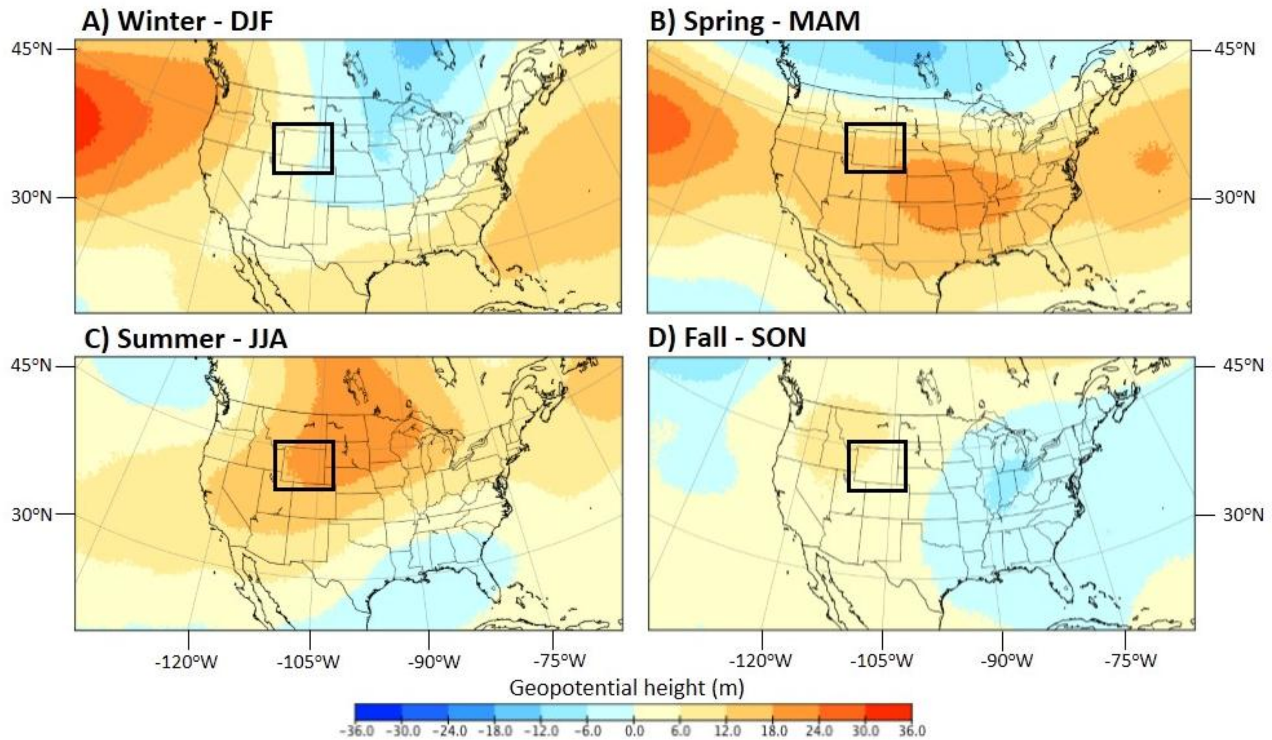


Figure 5. Composite anomaly maps for 500mb geopotential height during A) the winter season (JJA); B) spring (MAM); C) summer (JJA); and D) fall season (SON). Positive values (warm colours) for 500mb geopotential heights indicate a stronger-than-normal ridge. Negative values (cool colours) indicate a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

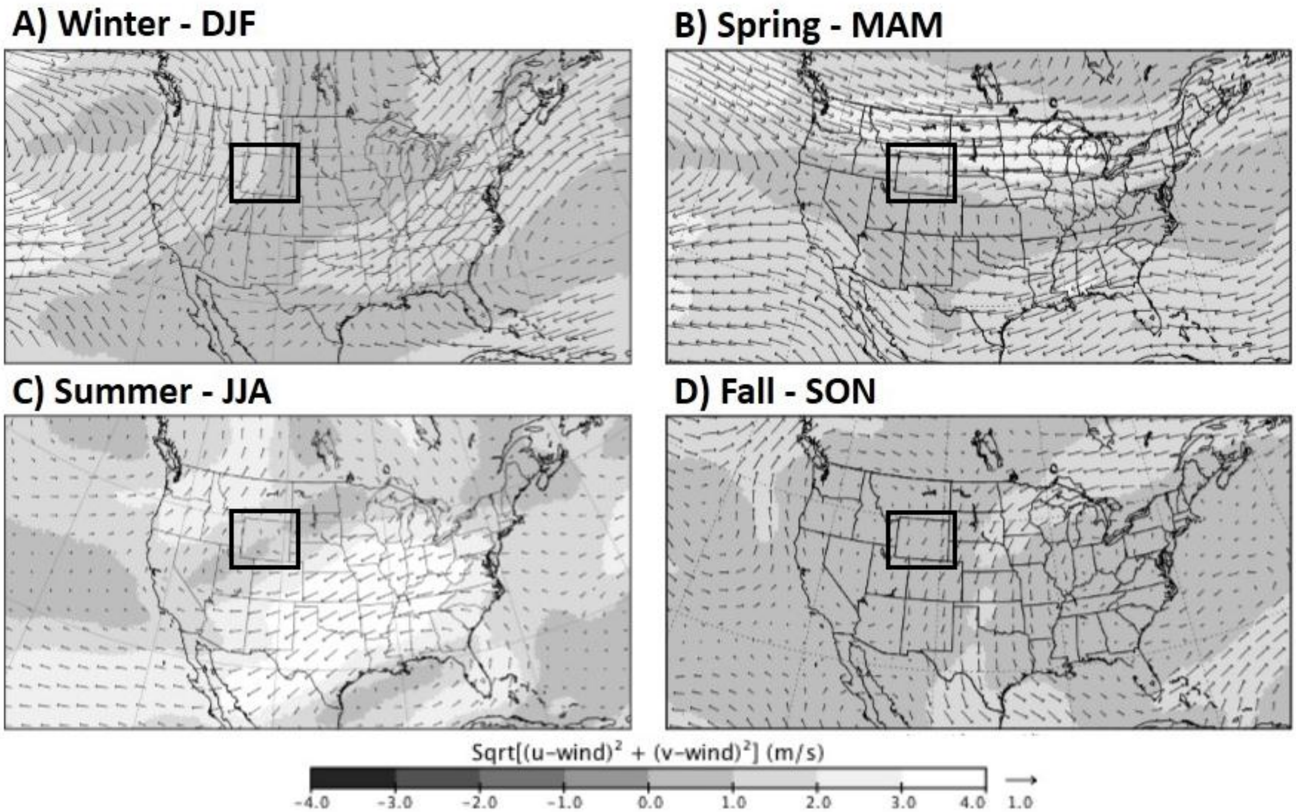


Figure 6. Seasonal composite anomaly maps for 500mb vector winds during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) fall season (SON). The black box denotes the study region, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming.

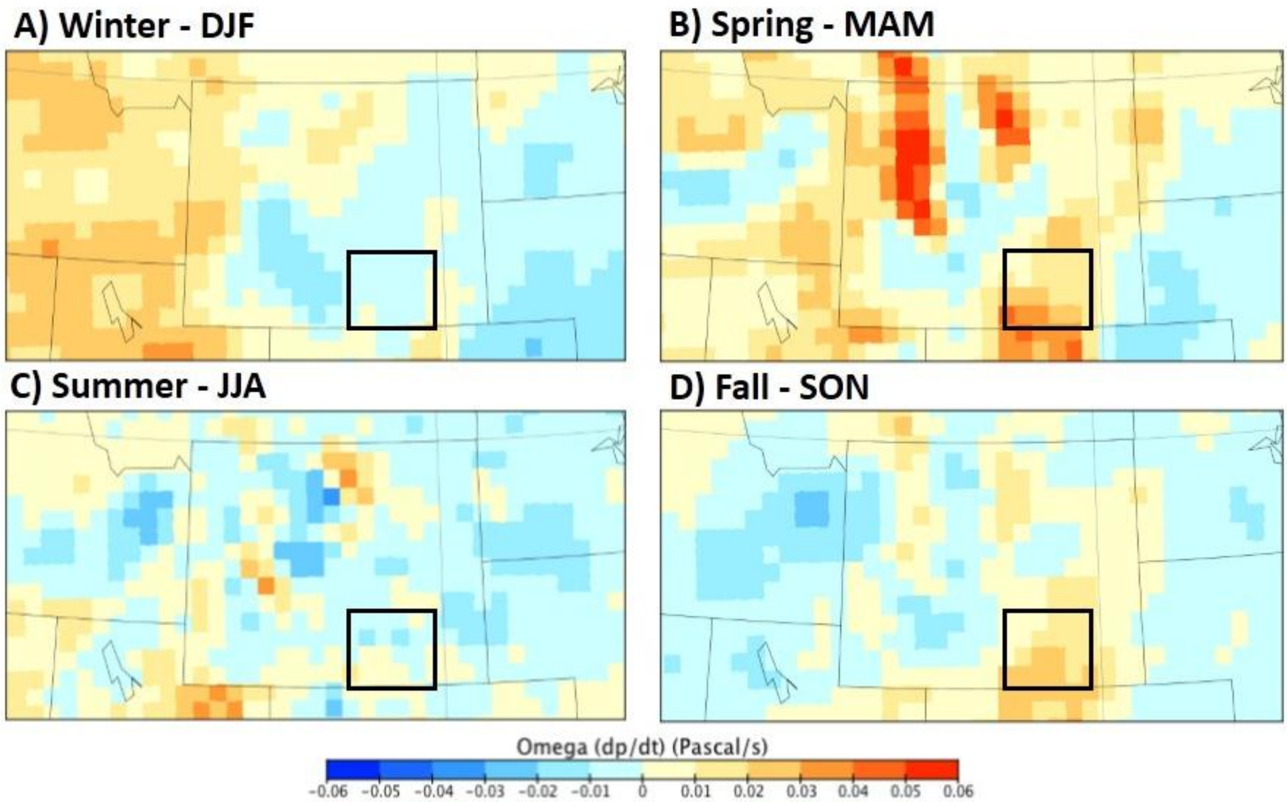


Figure 7~~6~~. Composite anomaly maps for 500-mb Omega (vertical velocity) during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) the fall season (SON). Positive values (warm colours) for omega indicate enhanced sinking motions (suppress precipitation). Negative values (cool colours) indicate enhanced rising motions (enhanced precipitation). The black box denotes the study site, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming.

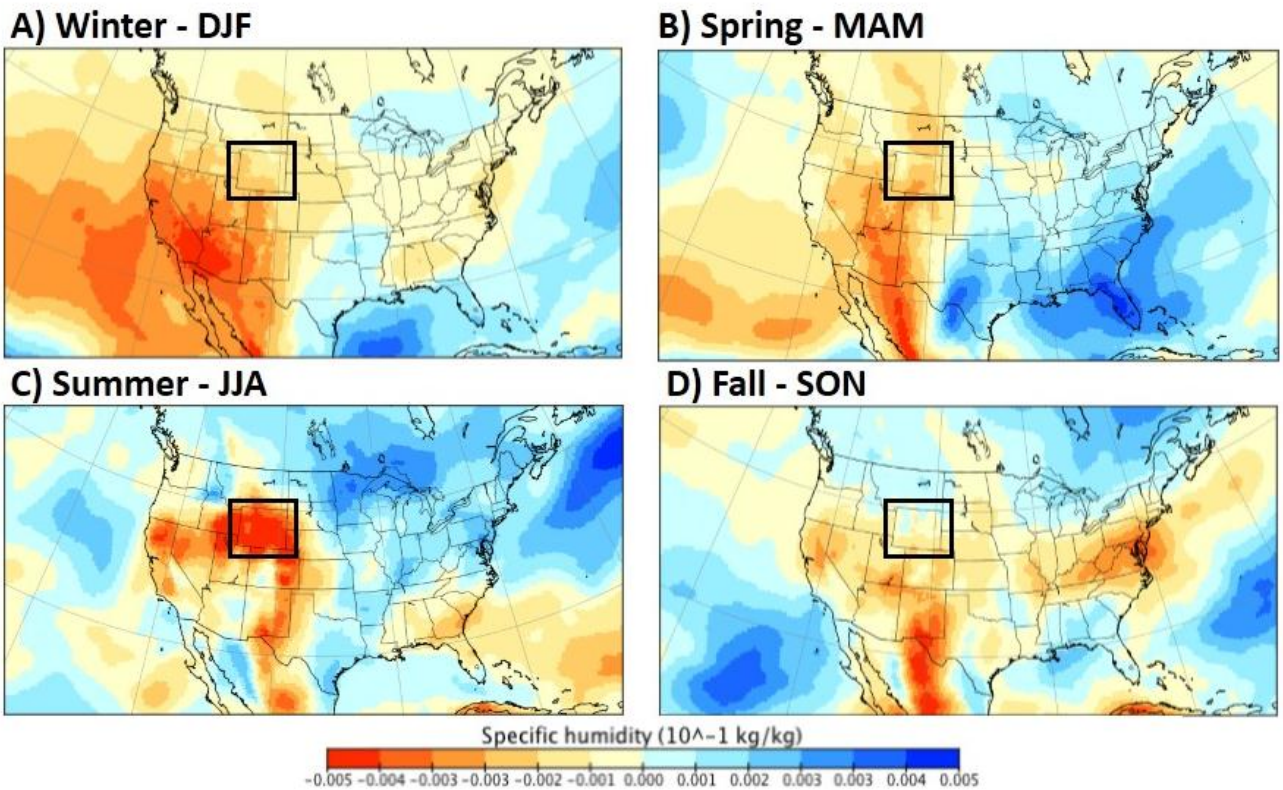
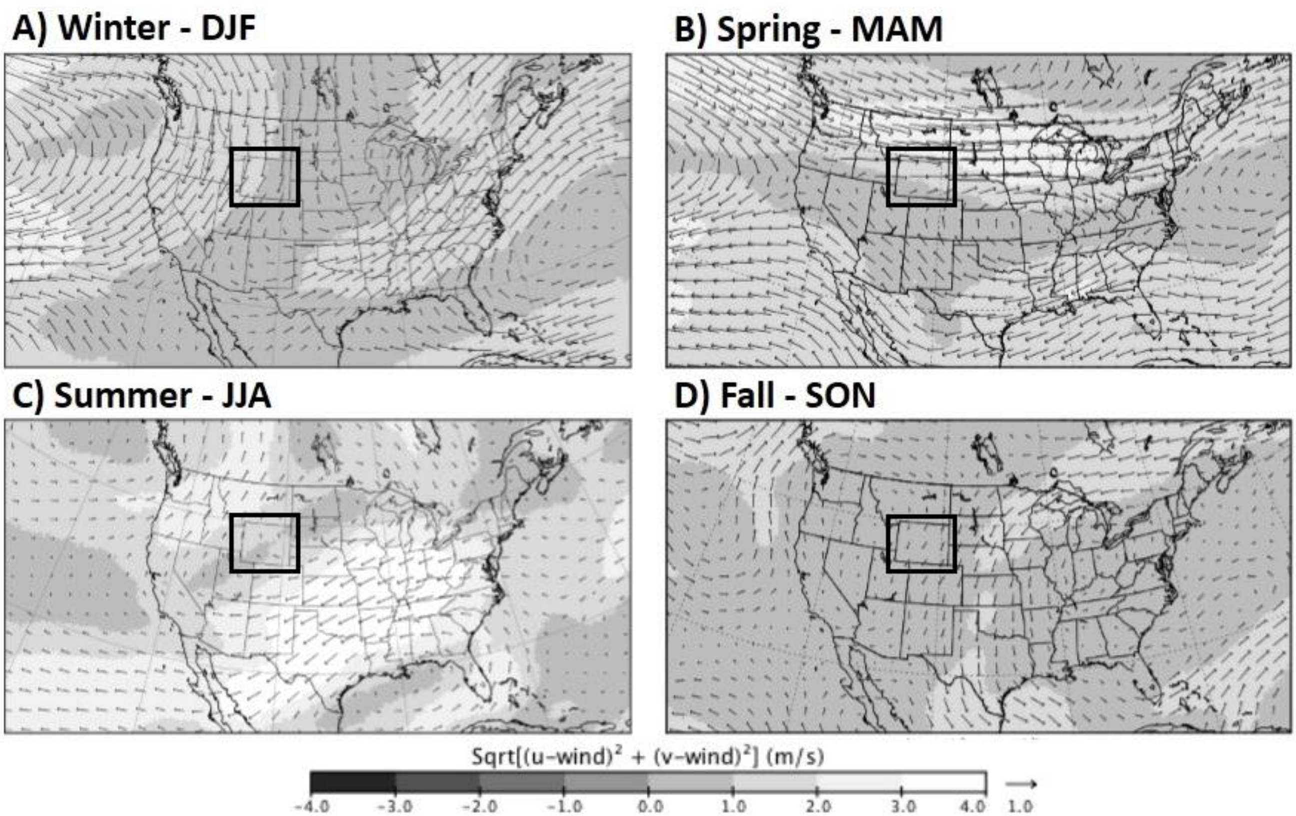


Figure 8~~7~~. Composite anomaly maps for 850mb specific humidity during A) the winter season (DJF); B) spring season (MAM); C) summer season (JJA); and D) the fall season (SON). Positive values (cool colours) for 850-mb specific humidity indicate wetter-than-normal conditions in the atmosphere. Negative values (warm colours) indicate dryer-than-normal conditions. The black box denotes the study region, Long Lake in the Medicine Bow Mountains of south-eastern, Wyoming.



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

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.