A REANALYSIS OF THE RELATIONSHIP BETWEEN STRONG WESTERLIES AND PRECIPITATION IN THE GREAT PLAINS AND MIDWEST REGIONS OF NORTH AMERICA

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Abstract. A conceptual model relating expanded or strengthened mid-latitude summer westerlies with summer precipitation patterns has been used to explain past drought events in the Great Plains and Midwest of North America, including drought between 1200 and 1400 AD. However, this relationship was originally described using 20 years of instrumental data from the mid 20th century, and has not been verified with modern datasets. We reinvestigated the relationship between July westerlies and precipitation in the United States using instrumental records of the last 55 years. We also investigated whether changes in summer zonal flow patterns associated with precipitation anomalies represent a shift in the latitude of peak westerly winds or an increase in wind speed, or a combination of both. Finally, we briefly compare the pattern of precipitation anomalies to paleoclimatic records of drought between 1200 and 1400 AD. Results confirm that strong westerlies are associated with a band of decreased precipitation extending from the northern Rockies into the Midwest. Changes in summer westerlies associated with these patterns are characterized by a strengthening of mean westerly winds, with only a slight southward shift of peak winds over the Atlantic. Changes in the strength of the westerlies over both the Pacific and Atlantic appear to be important to precipitation deficits in the Midwest. Proxy-climate records from 1200 to 1400 AD indicate widespread drought in the Great Plains and Midwest, consistent with the hypothesis of stronger westerlies at this time. However, drought conditions also extended to other regions of North America, indicating a more detailed understanding of the potential causes and synoptic climatology is needed.

1. Introduction

The relationship between circulation patterns and precipitation has long been a topic of interest (e.g., Namais, 1955). Spatial and temporal patterns of precipitation deficits in portions of the Midwest and Great Plains regions of North America have often been explained by the increased influence of airmasses originating from the Pacific basin (e.g., Bryson, 1966; Bryson and Baerreis, 1968; Woodhouse and Overpeck, 1998). These dry airmasses of Pacific origin, in association with strong westerly flow patterns, may also block moisture penetration into the continental interior from the Gulf of Mexico. The domain of dominant Pacific airmass influence corresponds well to the border of the prairie peninsula (Borchert, 1950; Bryson, 1966; Bryson et al., 1970), and past changes in the position of the prairie-forest border also may have been related to changes in the westerlies (Webb et al., 1983). Stronger or expanded (i.e., latitudinally displaced) westerly circulation has been

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used to explain droughts in paleoclimate and instrumental records from the region, including the 1930s drought of the Great Plains (Borchert, 1971), drought on the Great Plains between 1200 and 1400 AD (Bryson and Baerreis, 1968; Bryson et al., 1970), late Holocene droughts of the Colorado front range (Muhs, 1985), and early to mid-Holocene aridity of the Upper Midwest (Bartlein et al., 1984; Dean et al., 1996).

Although changes in the westerlies have been suggested as a potential cause of past precipitation anomalies in the Great Plains and Midwest, quantitative documentation of this relationship was based on the analysis of only 20 years of instrumental climate data (Bryson and Baerreis, 1968). In their classic study, Bryson and Baerreis (1968) compared July precipitation in years with strong/expanded versus weak/contracted westerlies, and showed that strong or expanded westerlies were associated with a belt of reduced precipitation stretching from the northern Rockies across the plains to the Midwest (Bryson and Murray, 1977). Also, by examining the limited amount of paleoecological and archeological evidence available in the 1960s, they concluded that a dry period occurred on the Plains between about 1200 and 1400 AD. The spatial patterning of moisture anomalies between 1200 and 1400 AD was consistent with drought associated with expanded or strong westerlies, leading to the conclusion that this period may have been a period of stronger or expanded westerlies.

In this paper, we use data sets that have accumulated since the work of Bryson and Baerreis (1968) to reevaluate the link between strong or expanded westerly circulation and summer precipitation in the Midwest and Great Plains regions of the United States. We also examine the index traditionally used to describe the mid-latitude westerlies, to assess whether changes in the westerlies involve strengthening or a shift in the latitude of peak winds (i.e., expansion or contraction), or a combination of both. Finally, we briefly examine whether broad-scale drought occurred during the period 1200–1400 AD, and if so, whether the spatial patterning of drought at this time was consistent with expanded or stronger westerlies.

2. Datasets and Analytical Methods

Bryson and Baerris (1968) used a surface zonal westerly index for their analyses, an index used since the mid 20th century to describe the strength of the westerly winds at mid-latitudes (e.g., Namias, 1950). For the western hemisphere, this index is often defined as the sea level pressure difference between 35 °N and 55 °N, averaged from 0 ° to 180 °W. High (low) values of the index correspond to strong/expanded (weak/contracted) westerlies at mid-latitudes. Bryson and Baerreis (1968) analyzed the July surface zonal index and associated July precipitation from the time period 1944 to 1963.

For our analyses, we used 1000-mb geopotential height and 1000-mb wind data from the NCEP/NCAR Reanalysis project (Kalnay et al., 1996) and precipitation data for the 344 climate divisions in the conterminous United States. NCEP Reanalysis data and climate division data were obtained from the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, via the internet (http://www.cdc.noaa.gov). Climate division data are monthly averages of instrumental data from regions within states that are thought to be climatically uniform. All analyses were performed on July monthly means for the time period 1948-2003 AD, therefore the overlap between our data sets and the earlier study of Bryson and Baerreis (1968) is less than 30%. We calculated a surface zonal index for July by taking the difference between July 1000-mb geopotential heights at 35 °N and 55 °N, averaged from 0 ° to 180 °W (hereafter referred to as "hemispheric zonal index"). This definition was used for consistency with earlier studies; an index based upon a slightly higher atmospheric level, perhaps between 950–850 mb, would also have been appropriate. We also calculated similar indices separately for 0 °–90 °W and 90 °–180 °W, to assess the relationship between drought patterns and zonal flow in the Atlantic and Pacific sectors of the hemisphere (hereafter referred to as "Atlantic" and "Pacific" zonal indices). We compared the indices to July precipitation data by linear correlation (Pearson) and composite analysis. We assessed the significance of correlations between precipitation and the hemispheric zonal index using two-tailed t-tests (Panofsky and Brier, 1963) after first adjusting the degrees of freedom based upon the lag one autocorrelation of the data (Brooks and Carruthers, 1953). In most cases, we found that the lag one autocorrelation (year to year correlation) was small. Lag one autocorrelations of order 0.1 led to a downward revision of degrees of freedom of about 20%. We also examined zonally averaged u-component wind profiles for years with high and low hemispheric zonal index values. All composite analyses were performed by averaging the climatology of years with zonal index values ±0.5 sigma from the long-term mean (Figure 1).

3. Results and Discussion

3.1. PATTERNS OF DROUGHT AND CIRCULATION

From 1948 to 2003 the surface zonal index (the north-south slope of the 1000 mb geopotential height surface) for the hemisphere ranged from 42 to 85 m in July. Using the geostrophic wind speed equation, this range of slopes corresponds to zonal wind speeds between about 2–4 m/s. Zonal indices calculated separately for the Atlantic and Pacific portions of the hemisphere varied from 40 to 112 m in the Atlantic sector and 28 to 83 m in the Pacific sector. Correlations were strong between the hemispheric index and indices calculated for the two sectors, although no correlation was found between zonal indices of the Atlantic and Pacific sectors (Figure 1).

Our results confirm the association between the strength of the westerlies and precipitation deficits in portions of the central United States (Figure 2). During

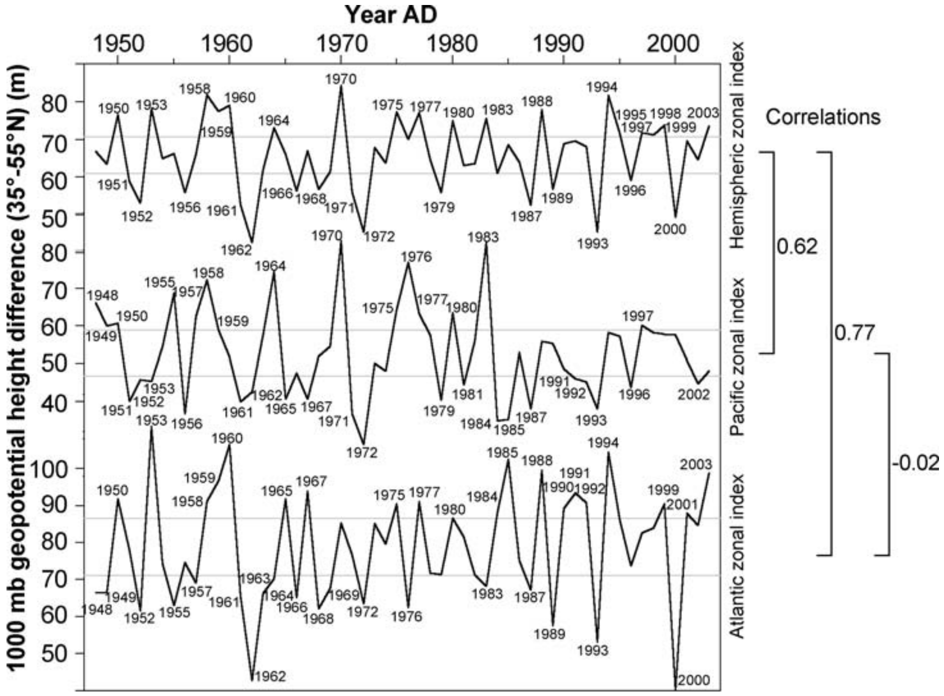


Figure 1. Time series of zonal indices from 1948–2003 showing correlations and years used for composite analyses.

years with high hemispheric zonal index (Figure 2c), decreased July precipitation tends to occur in a region extending from the northern Rockies and northern Great Plains to the central Midwest. Increased precipitation tends to occur in portions of the southeast. During years with low hemispheric zonal index values (Figure 2d), increased precipitation is observed in the Great Plains and Midwest. The difference between July precipitation in groups of years with high and low hemispheric zonal index values highlights these patterns (Figure 2e), and compares favorably with similar differences calculated by Bryson and Baerreis (Figure 2f). Differences between years of high and low hemispheric zonal index (Figure 2e) also closely resemble the correlation map between zonal index and July precipitation in the central U.S. and southeast (Figure 2a). However, correlation and composite patterns (Figure 2) differ somewhat in regions outside of the Great Plains, Midwest, and Southeast, suggesting that there is not a strong linear correlation between zonal index and precipitation in other regions. Also, significant correlations between the hemispheric zonal index and precipitation only occurred in the mid-continent and southeastern United States (Figure 2b).

The pattern of precipitation anomalies associated with the hemispheric zonal index led us to investigate whether changes in the July westerlies were primarily related to a strengthening or a shift in the latitude of peak winds. North-south profiles

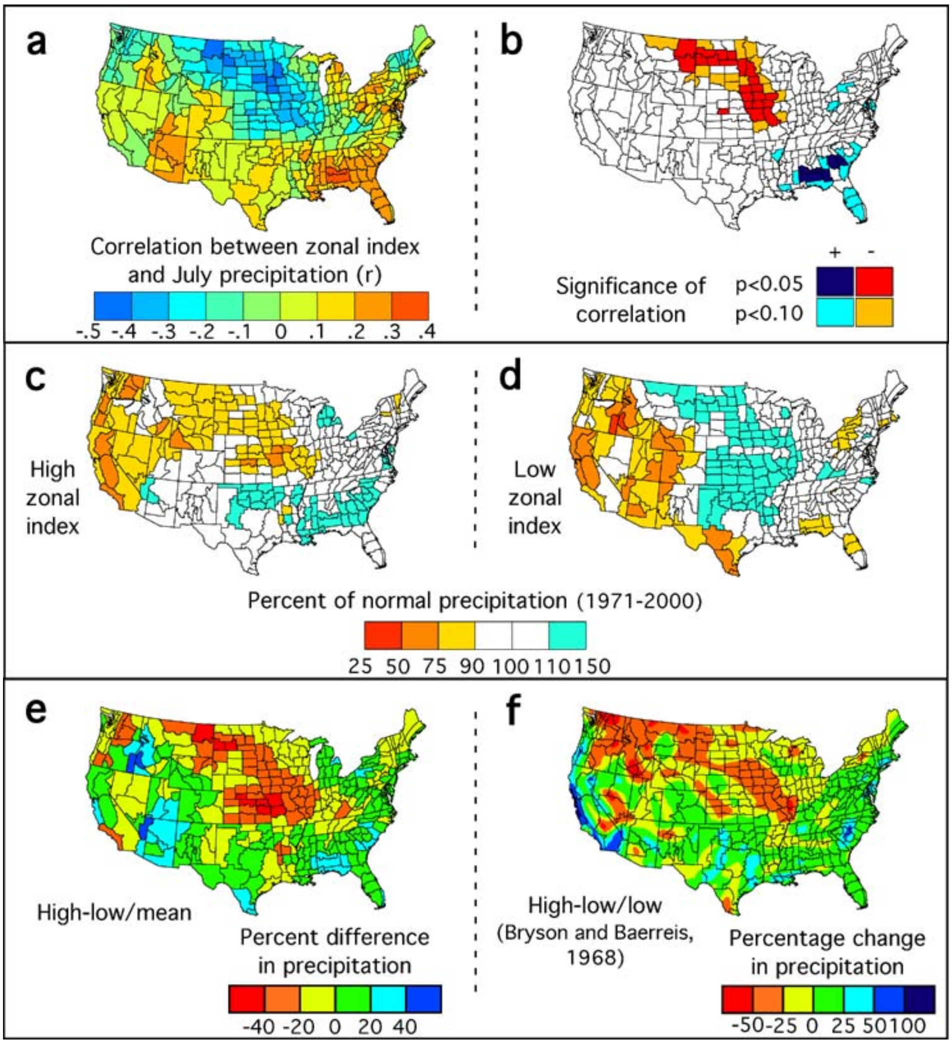
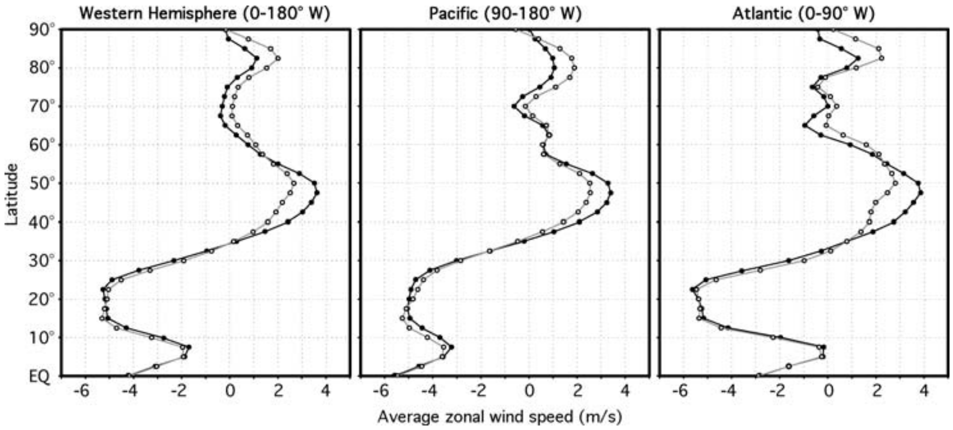


Figure 2. July precipitation patterns associated with high and low hemispheric zonal index values from the (f) original 20-year study of Bryson and Baerreis (1968), where the scale represents precipitation change from weak westerlies to strong westerlies expressed as a percentage change of the weak westerly mean precipitation, and the (a–e) reanalysis based on 55 years of data. Correlations between hemispheric zonal idex and July precipitation are shown in a, and statistically significant correlations (two-tailed t-test) at the 90% and 95% levels shown in (b). Composite maps associated with high and low hemispheric zonal index values are shown in (c) and (d). The percentage difference between July precipitation in years with high and low index values is shown in (e), and is a close approximation of the method used in Bryson and Baerreis (1968) and shown in (f).

of average westerly winds for composite years of high and low hemispheric zonal index values shows that during high hemispheric zonal index years the average peak westerly winds during July are more than 3.5 m/s and during low zonal index years they are less than 3.0 m/s (Figure 3). Peak westerly winds occur between



(a) (b) (c)

Figure 3. Composites of average u-component wind speed for high and low hemispheric zonal index years in the (a) Western hemisphere, (b) Pacific sector, and (c) Atlantic sector. Composite profiles of years with high hemispheric index are shown with black line and closed circles, and years with low hemispheric index are shown with gray lines and open circles.

50 ° and 45 °N in both the Pacific and Atlantic sectors. There is slight southward displacement of the peak westerly winds during years of high hemispheric index (~2.5 degrees or about a grid cell), and this small southward displacement occurs primarily in the Atlantic sector (Figure 3c). However, the hemispheric zonal index values appear to be primarily related to a strengthening or weakening of the westerlies. Strong mid-latitude westerlies are also associated with weaker westerly winds (or enhanced easterlies) at high latitudes poleward of about 60 °N, and slightly stronger easterly winds between 20 ° and 30 °N (Figure 3). The observed strengthening or weakening of the mid-latitude westerlies in July, associated with very little change in the latitude of maximum winds, contrasts with studies of the westerlies during winter that have shown southward extension of the maximum winter westerlies during periods of low zonal index (weaker westerlies) (Namais, 1950).

Much current research on North American precipitation anomalies and drought is focused on the relative importance of Atlantic and Pacific Ocean influences (Enfield et al., 2001; Gray et al., 2003; Lau et al., 2004; McCabe et al., 2004; Schubert et al., 2004a, b), and July precipitation patterns associated with zonal indices calculated separately for the Pacific and Atlantic portions of the hemisphere reveal some interesting patterns. High index values in both sectors are associated with precipitation deficits in the mid-continent (Figure 4), suggesting that zonal flow patterns in both portions of the hemisphere are important to the pattern of precipitation anomalies in the Midwest. However, overall patterns of moisture anomalies throughout the 48 states are more regionally consistent with the stratification of precipitation based upon the Atlantic zonal index (Figure 4b, d, f). Precipitation

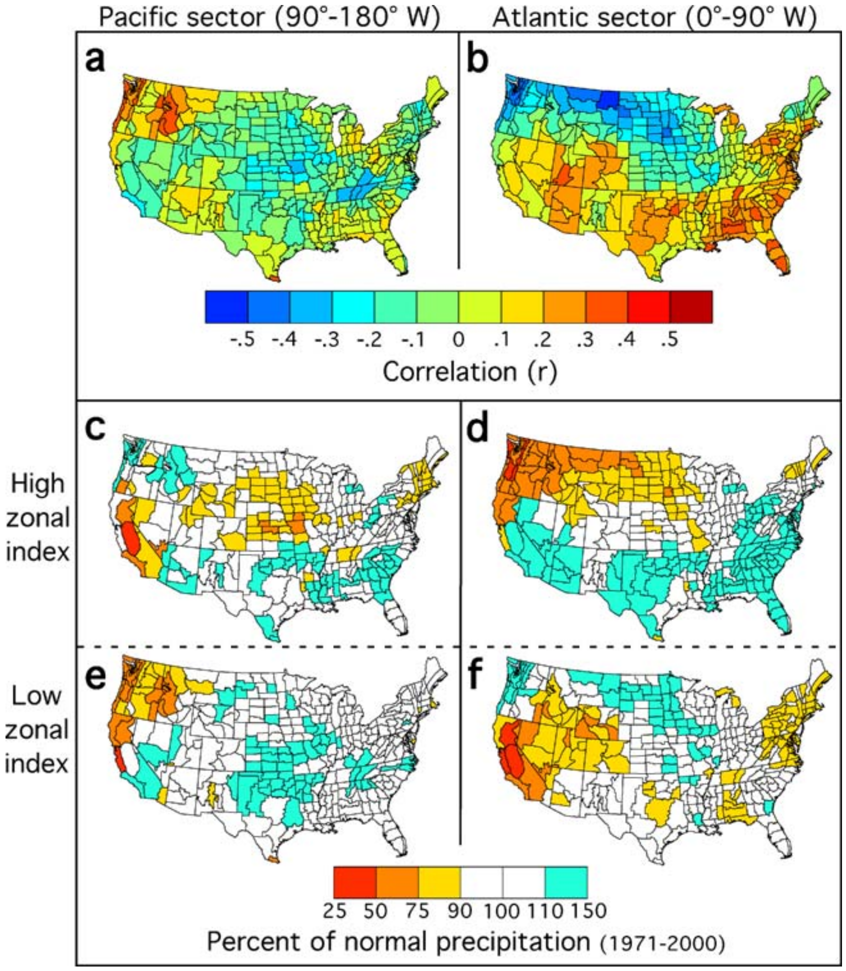


Figure 4. July precipitation patterns associated with high and low zonal index values in the Atlantic and Pacific sectors, with (a) and (b) showing correlations and (c–f) showing composite maps.

deficits associated with high Atlantic zonal index values extend from the Pacific northwest to the Midwest, and increased precipitation tends to occur in the southeast and southwest. These patterns are similar to those associated with the hemispheric zonal index (compare Figure 4b, d, and f with Figure 2a, b, and c), suggesting that while mid-latitude airflow across both ocean basins is associated with July precipitation distribution in the Midwest, the overall precipitation patterns, particularly the increased moisture in the southeast, may depend more on changes in the Atlantic than the Pacific. However, the influence of the Pacific circulation is also apparent, and Lau et al. (2004) have described important links between summertime sea surface temperature (SST) anomalies in the North Pacific and downstream circulation and precipitation changes over North America, including the Midwest.

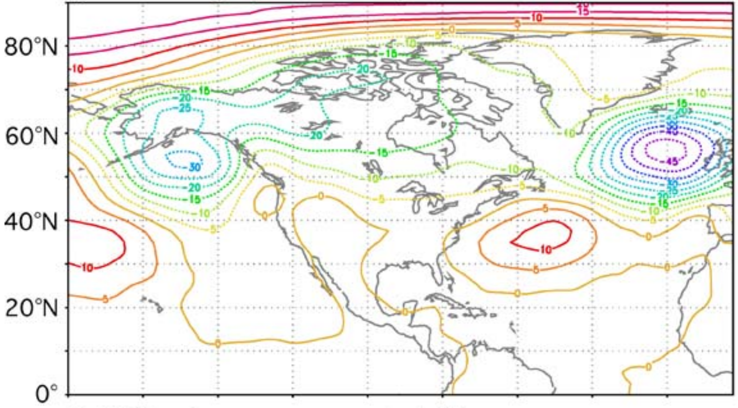
The suggestion of the dependence of the patterns of July precipitation anomalies on large-scale changes in atmospheric circulation patterns over both the Atlantic and the Pacific points to a need for a more detailed examination of the synoptic climatology. For example, changes in zonal circulation indices may be related to changes in the position and/or strength of the Bermuda High, affecting the trade winds and possibly the Great Plains low-level jet, which bring moisture into the continent. Similarly, the location and strength of the Pacific High influences west coast precipitation. Geopotential height maps at the 1000 mb level show that during years of high hemispheric zonal index the Bermuda and West Pacific High are strengthened (Figure 5a). Westerlies are strengthened most over the oceanic regions, although a belt of slightly stronger westerlies joins the two oceanic maxima (Figure 5a and c). Stronger easterlies associated with the Bermuda high (Figure 5c) probably bring more moisture toward the southeast in years of high zonal index. Southerly winds in the southeast are also strengthened during these years (Figure 5b), resulting in increased precipitation in the region. Geopotential height and wind patterns suggest that years with high index are associated with slightly weaker southerly flow in the southern half of the Mississippi Valley (Figure 5a and b). This pattern suggests that the northward advection of Gulf moisture into the upper Midwest is reduced in association with the stronger mid-latitude westerlies.

Like the original study of Bryson and Baerris (1968), our analysis of precipitation anomalies associated with mid-latitude circulation patterns is focused on the movement or blockage of moisture into the mid-continent. However, a more complete understanding of precipitation anomalies needs to also consider mechanisms that suppress or promote precipitation, like vertical motion, and interactions and feedbacks associated with vegetation and soil moisture conditions (e.g., Delworth and Manabe, 1988; Schubert et al., 2004a,b; Manabe et al., 2004).

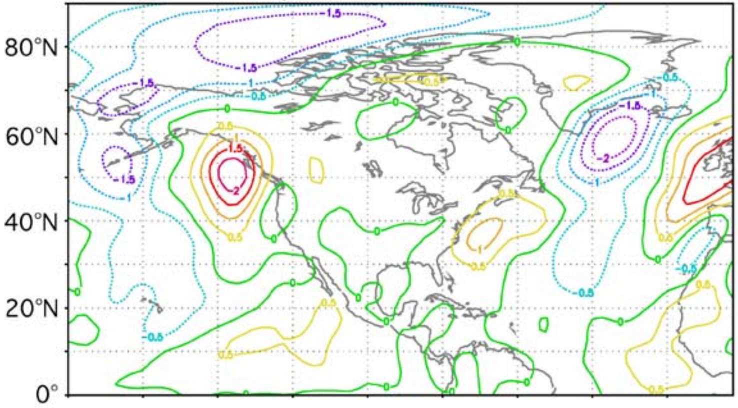
3.2. PALEOCLIMATIC RECORDS OF DROUGHT 1200–1400 AD

Based on the limited amount of data available at the time, Bryson and others hypothesized that a drought occurred on the Great Plains between about 1200 and 1400 AD and was related to an expansion or strengthening of the westerlies (Bryson and Baerreis, 1968; Bryson et al., 1970; Bryson and Murray, 1977). Much paleoclimate data has accumulated since the 1960s, and we attempt to compare the pattern of moisture anomalies indicated by proxy-climate records from this time period with July precipitation changes that might be expected with a strengthening of the westerlies (Figure 6). Our comparison is not meant to be a comprehensive review of climate changes during this time period, as recent reviews and discussions have already synthesized much of the relevant paleoclimatic and archeological records (Woodhouse and Overpeck, 1998; Laird et al., 2003; Mason et al., 2004). Rather, our goal is to briefly compare the distribution of moist/dry conditions as inferred

a) 1000-mb geopotential height difference



b) 1000-mb v-component wind difference



c) 1000-mb u-component wind difference

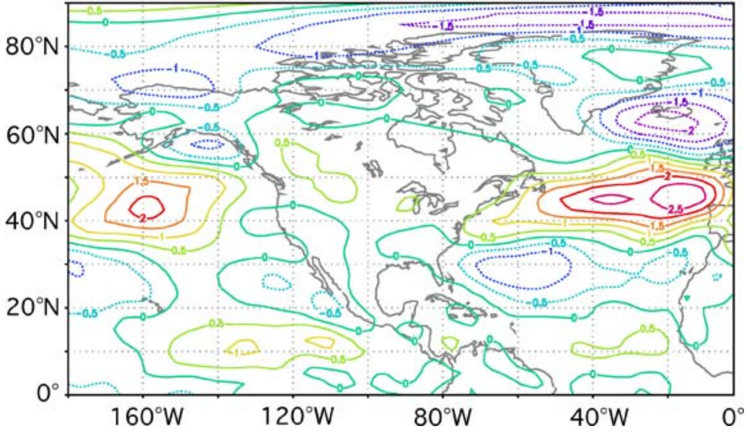


Figure 5. Differences between years of high and low hemispheric zonal index (high-low) for (a) 1000-mb geopotential height, (b) 1000-mb v-component winds, and (c) 1000-mb u-component winds. Positive differences are colored yellow through red and negative differences are colored blue through purple.

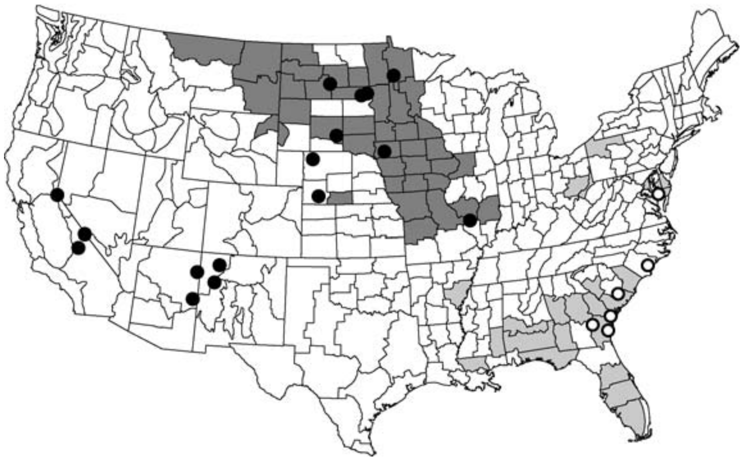


Figure 6. Map showing locations of selected paleoclimatic and archeological records from near or within the regions where July precipitation is strongly correlated with the hemispheric zonal index, where dark gray regions indicate negative correlations and light gray regions indicate positive correlations that are significant at the 90% level (Figure 2b). Filled circles indicate sites that document severe drought between 1100 and 1400 AD, primarily centered in the 13th century. Open circles indicate sites that do not document major climate changes at this time, or are difficult to interpret (see text for discussion). Most data used come from the synthesis of Woodhouse and Overpeck (1998), where full citations and discussion can be found. Additional records from the Midwest and Great Plains and the southeast and mid-Atlantic were compiled from the following sources: Bryson and Murray, 1977; Stahle and Cleaveland, 1992, 1994; Forman et al., 2001; Laird et al., 2003; Mason et al., 2004; Williard et al., 2003.

from the paleoclimate record with the pattern of July precipitation associated with changes in the strength of the westerlies.

A variety of proxy-climate and archeological records suggest that a widespread, multidecadal drought, or series of droughts, occurred between about 1200 and 1400 AD. Some records also suggest that drier conditions began around 1100 AD (Woodhouse and Overpeck, 1998), although it is difficult to assess whether climatic changes during the time period were synchronous in different regions or represent multiple events, because of inadequate temporal resolution and differences among proxies. However, drought was probably most widespread and severe during the 13th century (Woodhouse and Overpeck, 1998). Drought was severe in the region of the Great Plains and Midwest that would be expected to experience drought with strengthened westerlies (Figure 6). For example, widespread activation of the Nebraska Sand Hills occurred between 1000 and 1300 AD (Mason et al., 2004), and extensive dune activity is also recorded at other sites on the Great Plains (Forman et al., 2001). Paleohydrological records from lakes in North Dakota also indicate brief periods of low lake level between 1100 and 1400 AD (Laird et al., 2003) and increased aeolian-derived materials occur in the sediments of Elk Lake in north-central Minnesota (Dean, 1997).

Drought also occurred in other regions of North America between 1100 and 1400 AD, including the southwest and California (Woodhouse and Overpeck, 1998; Cook et al., 2004), regions where decreased July precipitation was not strongly associated with strengthened westerlies during the 55 years of data that we analyzed (Figure 6). However, absence of a strong link between summertime circulation and drought in this region is not particularly surprising given that drought in the southwest has been linked to changes in ENSO variability and associated changes in winter precipitation (Cook et al., 2004). In fact, recent evidence suggests that the 12th and 13th centuries were dominated by La Niña-like conditions in the tropical Pacific (Cobb et al., 2003; Verschuren et al., 2000), and similar conditions have been linked to drought in western North American tree-ring and instrumental records (Hoerling and Kumar, 2003; Cook et al., 2004). Drought in the Great Plains and the Western United States between 1100 and 1400 AD may have been caused by moisture changes in different seasons and different circulation features.

If strengthened westerlies and decreased July precipitation were indeed associated with the drought between 1100 and 1400 AD in the Great Plains and Upper Midwest regions, our analysis would further suggest that July precipitation may have increased in portions of the southeast. However, assessing the possibility of increased July precipitation in the southeast is difficult, because there are few high-resolution paleoclimate records from region. Also, the factors controlling spring and summer circulation are often quite different in the region (Stahle and Cleaveland, 1994), and paleoclimate records often integrate seasonal differences. Reconstructions of spring precipitation from 30-yr smoothed tree ring series in North Carolina, South Carolina, and Georgia do show the highest and most spatially coherent amplitudes of the last 1000 years during the period 1000–1300 AD (Stahle and Cleaveland, 1992, 1994), and some of the highest magnitude wet and dry time periods of the last 1000 years occur during this time interval. However, since summer precipitation in the southeast is often inversely correlated with spring precipitation (Stahle and Cleaveland, 1992), comparisons to our analyses, which are based on July, are problematic. Paleoclimate records from sediments in the Chesapeake Bay suggest major drought events centered on 1400 AD and 1000 AD, and the intervening time interval was relatively warm although not particularly unusual in terms of moisture (Cronin et al., 2003; Willard et al., 2003).

In summary, although a severe drought did occur in the Great Plains and Midwest between 1100 and 1400 AD, in the area where July precipitation deficits are correlated with the strength of the westerlies, strong conclusions regarding the synoptic climatology of widespread drought elsewhere in North America at this time are presently not possible. More high-resolution paleoclimate records are needed, particularly records where temperature and precipitation signals can be differentiated, and seasonality of past climate changes can be inferred.

4. Conclusions

Our study confirms that strong July westerlies are associated with a pattern of July precipitation anomalies characterized by decreased precipitation in a belt from the northern Rocky Mountains to the Midwest and increased precipitation in the southeast. These results are based on 55 years of data, and serve to strongly substantiate the earlier results of Bryson and Baerreis (1968), which were based on a much smaller dataset. Changes in the westerlies associated with these patterns are primarily a strengthening or weakening of peak average wind speeds at mid-latitudes, with only a slight southward shift of the wind speed maxima during high zonal index years that occurs primarily in the Atlantic region. Reduced precipitation in the Great Plains and Midwest is probably due to the combined effect of an increased frequency of dry Pacific air and reduced moisture transport up the Mississippi Valley from the Gulf of Mexico. Circulation features responsible for the increased precipitation in the southeast include stronger trade winds and increased southerly flow.

Although stronger westerlies and decreased July precipitation may have been associated with widespread drought between 1200 and 1400 AD in the Midwest and Great Plains of North America, a more complete description of the synoptic climatology and the cause(s) of widespread drought at this time is needed. Recent research suggests that climate variability associated with ocean-atmosphere interactions is an important cause of persistent drought (e.g., Hoerling and Kumar, 2003; Manabe et al., 2004; McCabe et al., 2004; Schubert et al., 2004a, 2004b), and may have played a role in the 13th century drought. Drought in western North America during the 12th and 13th centuries has been linked to SST changes in the Pacific Ocean (Cobb et al., 2003; Cook et al., 2004), and SST anomalies and associated circulation changes may have been important in other large megadroughts observed in the paleoclimate record (Woodhouse and Overpeck, 1998; Gray et al., 2003; Booth et al., 2004). The role of external forcing changes, such as volcanic eruptions or solar variability, including estimates of their magnitude and the potential dynamical response of the climate system, must also be considered (e.g., Bryson, 1988; Cane et al., 1997; Crowley, 2000; Shindell et al., 2001, 2003; Waple et al., 2002; Ammann and Naveau, 2003; Adams et al., 2003; Meehl et al., 2003; Rind et al., 2004). However, the potential role of these changes is outside the scope of this study.

Although more research is needed to delineate past geographic patterns of droughts and their potential causes, particularly widespread and severe events spanning multiple decades like the 13th century drought, this paper serves to validate the important linkages between large-scale summertime circulation and precipitation in the Great Plains and Midwest first described almost 40 years ago. Moreover, the mounting paleoclimatic and paleoecological evidence for the 13th century drought in this region is a strong reminder of the environmental importance of understanding these processes.

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