A Comparative Analysis of Surface Winds in the Mid-Continental United States of America During Severe Droughts in the 1950s and 2010s

by

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Abstract

The Mid-Continental United States of America (USA) has experienced several exceptional droughts, which are frequently linked with increased dust storms in response to reduced vegetation and intensified surface wind speeds. This investigation examined surface wind speed behaviour in the Mid-Continental USA between 1954 and 2016 to assess differences in wind speeds between severe drought and wetter periods and determine what climatic conditions may have influenced these changes. Results show that droughts periods had significantly higher extreme surface wind speeds, and the 1950s Southwest drought had significantly higher surface wind speeds compared to the 2010s drought. Composite patterns of sea-level pressure, temperature, precipitation, and Palmer Drought Severity Index suggest that synoptic weather conditions reinforce dry and windy conditions during drought versus wetter years. However, synoptic conditions were largely similar between the two droughts, suggesting that land surface management practices may have been responsible for decreased surface winds during the 2010s drought.

Keywords: drought; wind speed dynamics, Dust Bowl; Southwest drought; Palmer Drought Severity Index; National Centers for Environmental Prediction

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Chapter 1.

Introduction

In the early 2010s, the Mid-Continental United States of America (USA) experienced one of its worst droughts since the 1930s “Dust Bowl” and the 1950s Southwest drought (Wang et al., 2016). Both the 1950s and 2010s droughts were similar in severity, but the 1950s drought was longer. While 39% of the contiguous USA experienced severe to extreme drought in 2012, as much as 50% was affected during the 1950s (Karl, Gleason, & Menne, 2012).

Increased dustiness and dust storms are typically associated with severe drought periods and arise from a combination of increased soil aridity, reduced vegetation, and enhanced wind speeds (Cook, Miller, Seager, & Hansen, 2009). During the 1930s and 1950s, aridity is thought to have increased as a complex response to regional changes in sea-surface temperatures (SST) around North America (Cook, Seager, & Miller, 2010). These arid conditions resulted in reduced vegetation cover and exposed soil surfaces, which led to a higher frequency and severity of dust storms (Cunfer, 2005; Lee & Gill, 2015). Anthropogenic land degradation was also a main contributor to dust storms during the 1930s and 1950s droughts (Cook et al., 2009). Agricultural expansion throughout the Great Plains during the 1920s resulted in the replacement of drought-resistant prairie grasses with extremely drought-sensitive wheat. The ensuing loss of vegetative cover contributed to dust storms and led to widespread ecological and economic losses across the Mid-Continental USA.

Changes in surface wind speed also influence dust production and are likely to change through time in response to climate and land-surface conditions. Changes in the potential sediment transport rate of wind as well as the wind’s “gustiness” influence dust production (Kocurek & Lancaster, 1999; Engelstaedter & Washington, 2007). Beyond a threshold surface wind speed, dust emission increases are roughly proportional to the cube of the wind speed (Gillette, 1978). Wind speeds respond to climate-related, synoptic-scale patterns in surface pressure, which can intensify (or reduce) surface wind responses (e.g., Klink, 1999). Furthermore, the degree of surface roughness, which changes in response to vegetation height and density, has a direct influence on surface wind speed behaviour (Vautard, Cattiaux, Yiou, Thépaut, & Ciais, 2010). During the late 1930s and 1940s, the US Soil Conservation Services and the US Forest Service’s Prairie States Forestry Project were tasked with addressing land management issues through terracing, contour ploughing, and tree planting, as well as purchasing farms to encourage resettlement to less drought-sensitive areas (McLeman et al., 2013). These land management initiatives were put in place not only to minimize sources of dust but also to slow surface winds. Since many of these projects were implemented after the 1930s Dust Bowl, their impact on dust storm frequency and surface wind behaviour would likely be discernable during the 1950s drought and onward.

The extent to which surface winds have changed in the Mid-Continental USA during severe droughts as well as wetter periods remains an open question. Several studies have observed decreasing trends in surface wind speeds across North America. Statistically significant declines have been observed in 50th and 90th percentile wind speeds between 1973 and 2005 (Pryor et al., 2009), as well as in annual mean surface wind speeds between 1979 and 2008 (Vautard et al., 2010). In addition to trends, inter-annual variability in mean monthly surface wind speeds between 1962 and 1990 have been related to seasonal variability in synoptic-scale features (Klink, 1999). These investigations focused on long-term trends over large areas but have not addressed wind speed behaviour during drought conditions or its influence on dust production.

This investigation compares historic and modern surface wind speeds to determine how surface wind conditions may have changed during the strongest drought and wetter periods between 1954 and 2016. I then examine composite maps of sea-surface pressure, temperature, precipitation, and drought during five years of highest and lowest wind speeds, to assess what regional climatic conditions may have influenced changes in surface winds. Understanding how land surface conditions, synoptic weather systems, and/or climate change influence surface winds will help improve our understanding of the links between wind speed, drought, and dust production.

Chapter 2.

Methods

2.1. Study area

This study focuses on US states that have historically experienced severe droughts, high rates of soil erosion, and dust storm activity (Cook, Seager, Cane, & Stahle, 2007; McVicar et al., 2012; Cook, Ault, & Smerdon, 2015). The study region is mainly composed of the Great Plains, North American Desert, and Southern Semi-arid Highlands, and includes Texas, New Mexico, Oklahoma, Kansas, Colorado, Nebraska, South Dakota, North Dakota, Montana, Utah, and Wyoming (25° to 49°N, 116° to 93°W) (Figure 2.1.Figure 2.1). This dryland region has a highly variable continental climate characterized by hot, dry summers and cold winters (McLeman et al., 2013).

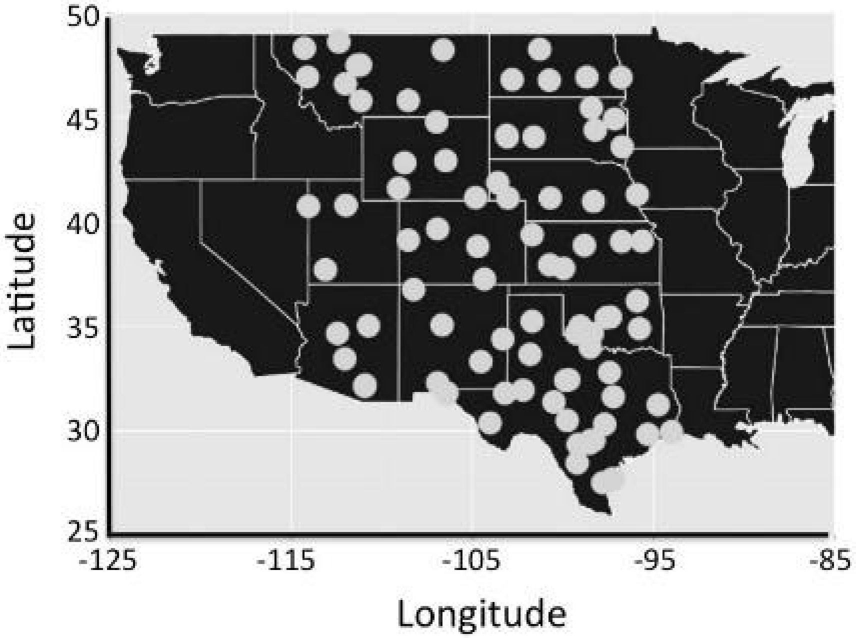

Figure 2.1. **Study area and 87 meteorological stations from the Integrated Surface Hourly Database that met the completeness criteria**

2.2. Meteorological station data

Wind speed data acquisition and all analyses in this investigation were completed in R (version 3.1.3) (R Core Team, 2013). An overview of all completed steps is shown in Figure 2.2. Observational data from 1600 meteorological stations were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Integrated Surface Hourly Database (Smith, Lott, & Vose, 2011) to determine spatial and temporal variations in surface wind speed behaviour. Hourly wind speed data between 1945 and 2016 were compiled from the Integrated Surface Database archived at the US National Climatic Data Center (NOAA, 2016).

The compiled meteorological station data were filtered to meet specific completeness criteria to reduce sampling bias. A station's data were required to meet all four of the following criteria:

- Day: 90% or at least 22 hourly measurements in a day
- Month: 90% or at least 27 valid days in month
- Year: at least three years that meet the day and month criteria
- Contains data that meet the three previous criteria for at least two years between 1954 and 1956 and two years between 2011 and 2013

The time periods of 1954–1956 and 2011–2013 represent the most severe drought periods in the Mid-Continental United States following the 1930s Dust Bowl (Burnette *&* Stahle, 2012). The 1930s Dust Bowl was not included in this investigation due to the scarcity of observational data. Of the original 1600 stations, 87 met these criteria (Figure 2.1., Table A-1).

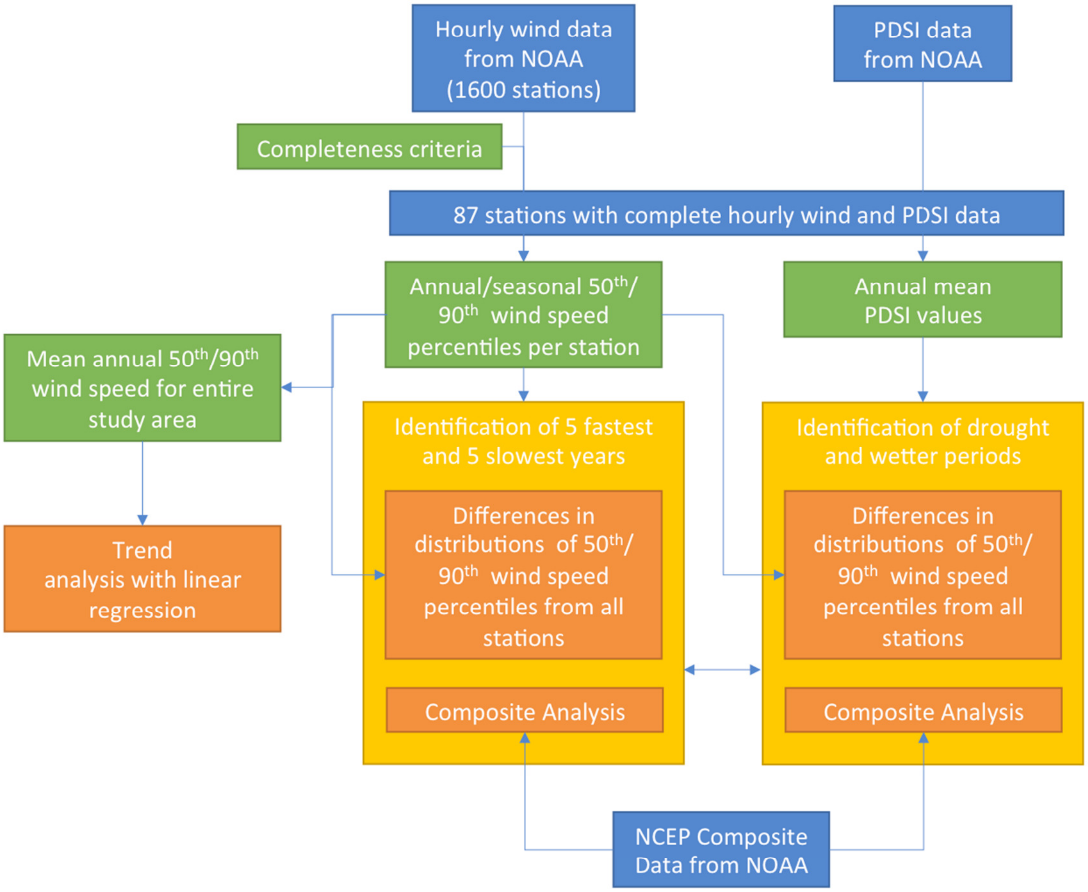

Figure 2.2. **Flowchart depicting data acquisition (blue boxes), analysis (green boxes), and results (orange boxes)**

2.3. Identification of “wetter” and “dry” periods between 1950 and 2016

One goal of this work was to examine potential differences in surface wind speed behaviour during the strongest drought and wetter periods between 1954 and 2016. Wetter periods were identified using estimates of the Palmer Drought Severity Index (PDSI) extracted at each of the 87 meteorological stations (Palmer, 1965; Alley, 1984; Hein, 2002). The PDSI is a comprehensive drought indicator that uses regional temperature and precipitation data to estimate soil moisture and determine the presence of long-term droughts. Monthly PDSI values for each station were downloaded (NOAA, 2016), and annual means for the study region were calculated by averaging all the stations’ monthly values for each year between 1935 and 2016 (Figure 2.3.). Moderate to extreme drought levels (PDSI ≤ -2.00)(Heim, 2002) were observed during the periods of 1954–1956 and 2011–2013 and were the lowest since the 1930s Dust Bowl. Two other time periods, 1983–1987 and 1992–1998, were identified as prolonged wetter periods. These wetter periods have been identified using independent methodologies by several other researchers (Seager, Kushnir, Herweijer, & Naik, 2005; Hua, Ming, & Qi, 2010; Burnette & Stahle, 2012). Surface wind speed distributions from these two defined wetter periods were then compared to wind speed distributions from the drought periods.

The 87 stations selected above were examined for their completeness during the four time periods highlighted in the study. Gaps in the data appear during the mid-1960s and early 1970s for 23 of the stations (Figure A-1), but this absence of data does not affect the comparison of wind speed distributions between the drought and wetter periods.

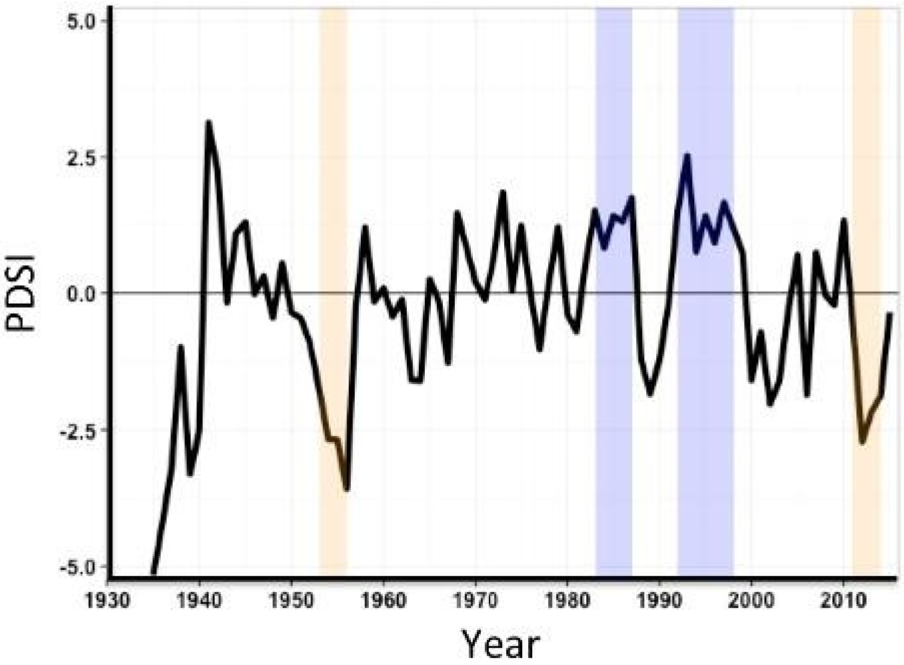

Figure 2.3. **Annual mean PDSI values averaged for the 87 meteorological stations used to identify wetter and dry periods for comparison of surface wind speed distributions during wetter and dry periods. Orange shading denotes dry periods and blue shading denotes wetter periods**

2.4. Comparison of wind speed behaviour for "wetter" and "dry" periods

To analyze annual and seasonal differences in wind speed behaviour between drought (drier) and wetter periods, monthly 50th and 90th percentile values were first calculated from the hourly wind speed data for each station. I then compared the seasonal and annual 50th and 90th percentile wind speed distributions between the two dry (1954–1956 and 2011–2013) and two wetter time periods (1983–1987 and 1992–1998). Seasonal and annual means of the monthly 50th and 90th percentile wind speeds were also calculated. Following McVicar et al. (2012), seasons were defined as:

- Spring (March, April, May)
- Summer (June, July, August)
- Fall (September, October, November)
- Winter (December, January, February)

Independent samples from t-tests were then used to identify whether the mean 50th and 90th percentile wind speeds were statistically distinct between the two severe drought periods as well as between drought and wetter periods. Eleven stations in southeastern Texas were identified as having the potential to be influenced by their proximity to the Gulf of Mexico and consequently greater onshore winds. A sensitivity test was conducted during this analysis that excluded data from 11 coastal stations in Texas from the monthly 50th and 90th percentile calculation. A list of these 11 stations is shown in Table A-1.

2.5. Trend and composite analysis

Average annual 50th and 90th percentile surface wind speeds were calculated from the combined hourly observational wind speed data from all 87 stations between 1950 and 2016 to produce two regional time series, and these data were used in two ways. First, linear trends were estimated between 1948 and 2016 using ordinary linear regression. Ordinary least regression was used to provide an analysis consistent with previous studies that estimated regional wind speed trends (Pryor et al., 2009; Vautard et al., 2010). To assess if 50th and 90th percentile trend estimates were statistically significant, a significance test for linear regression was conducted.

Second, a regional time series generated using monthly 90th percentile surface wind speeds was used to identify the five years with the fastest and slowest monthly wind speeds. Annual and seasonal composite plots (2.5° × 2.5° at monthly intervals) of sea level pressure, precipitation, surface temperature, and PDSI were then created for the five fastest and slowest years using National Centers for Environmental Prediction (NCEP) reanalysis data (NCEP, 2017). Reanalysis datasets were created through the assimilation of observational data (e.g. satellite, radar, and ground stations) and climate models to generate a synthesized approximation of climatological variable. Composite plots of the reanalysis datasets covered the area of 0° to 90°N and 10° to 180°W and were used to visually compare different periods, to determine if synoptic weather system and/or atmospheric general circulation patterns influence surface wind speeds within the study region. Specifically, the five years with the fastest wind speeds were compared with slowest monthly wind speeds; conditions during the drought and wetter periods were compared; and conditions during the droughts of the 1950s and the 2010s were compared. Plots were created by subtracting the amalgamated arrays from each other.

Two sensitivity tests were conducted to address the influence of coastal stations and data gaps on the long-term trend analysis. The first test again involved the exclusion of data from 11 coastal stations in Texas (Figure A-2) described earlier, and the second test involved the removal of 23 stations that exhibited data gaps during the 1960s and 1970s (Figure A-1).

Chapter 3.

Results

3.1. Surface wind behaviour during drought and wetter periods

The distributions of the monthly 50th and 90th percentile surface wind speeds from all 87 stations show that wind speeds were higher during the 1954–1956 (1950s) drought than during the other three periods, with a larger median value and more pronounced upper quartile wind speeds (Figure 3.2.a,b). Although the difference between the 50th percentile wind speeds during the 1950s drought and the 50th percentile wind speeds of the other three time periods is apparent in all four seasons, the difference in distributions is most apparent during the spring season when winds are strongest (Figure 3.2.c,d). Therefore, this analysis will primarily focus on winds during annual and spring periods.

The means of the monthly 50th and 90th percentile spring wind speeds from the combined 1950s and 2011–2013 (2010s) drought periods were 10% and 12% greater than the combined wetter periods, respectively ($p < 0.01$) (Table 3.1.). However, the differences stem primarily from the high wind speeds during the 1950s drought. The monthly 50th and 90th percentile wind speeds from the 1950s drought were statistically greater than both the wetter periods (1983 to 1987 and 1992 to 1998) (Figure 3.2.) (Table 3.2.; p-value < 0.01). Furthermore, annual means of the monthly 50th and 90th percentile wind speeds from the 1950s drought were also 15% and 9% greater than the 2010s drought, respectively (p-value < 0.01) (Tables 3.1., 3.2.). Thus, the largest differences were observed between the 1950s drought and the other three time periods.

Unlike with winds during the 1950s drought, the distributions of annual and spring monthly 50th percentile wind speeds during the 2010s drought were largely similar to the two wetter periods (Figure 3.2.a,c). However, the 90th percentile wind speeds for both annual (Figure 3.2.b) and spring (Figure 3.2.d) during the 2010s drought are 6% and 7% greater than the combined average of the 90th percentile wind speeds for the two wetter periods, respectively.

The average annual and seasonal monthly 50th and 90th percentile wind speeds were recalculated without the 11 coastal stations in Texas (Table A-2, Figure A-2) to test the possible effects of coastal wind speed behaviour on the regional averages. This analysis suggested that removing the 11 coastal stations changed the annually and seasonally averaged monthly 50th and 90th percentile winds speeds by less than 4% (Table A-2).

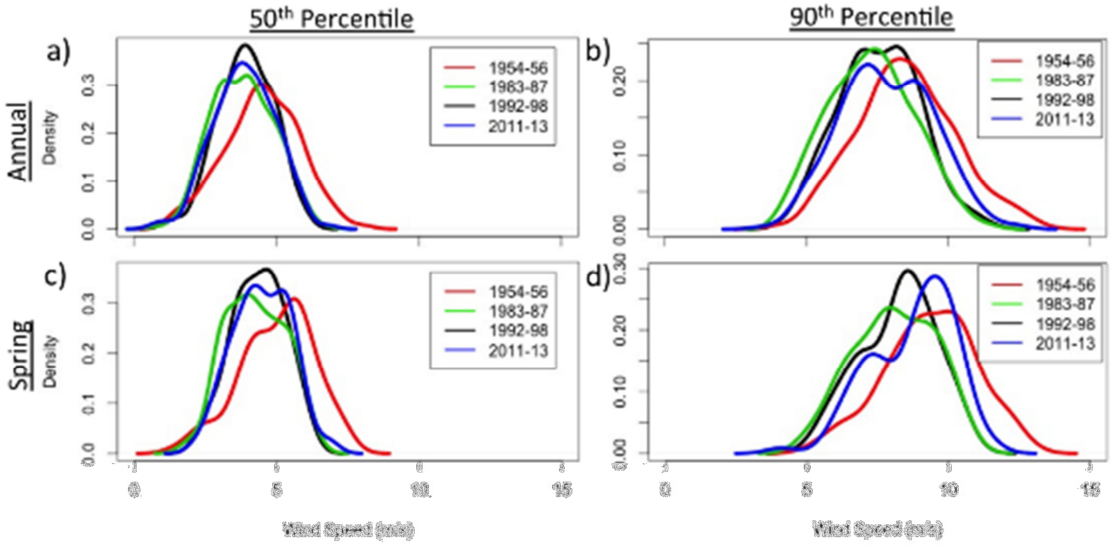

Figure 3.1. **Frequency distributions of the monthly 50th (a, c) and 90th (b, d) percentile wind speeds (m/s) from all 87 meteorological stations in the Mid-Continental USA for the entire time periods (a and b, respectively), and for just the Spring months of March, April, and May (c and d, respectively). Time periods represented are 1954–1956 (red) and 2011–2013 (blue) drought periods, and the 1983–1987 (green) and 1992–1998 (black) wetter periods**

Table 3.1. Average annual and seasonal monthly 50th and 90th percentiles surface wind speeds (m/s), their standard deviations (SD), and the total number of values (n) for select time periods from the 87 stations

		50th percentile		90th percentile		
Season	**Time period**	**Average (m/s)**	**SD (m/s)**	**Average (m/s)**	**SD (m/s)**	**n**
Annual	1954–56	4.48	1.25	8.51	1.61	2306
	1983–87	3.82	1.06	7.28	1.41	5180
	1992–98	3.93	0.95	7.57	1.35	7280
	2011–13	3.88	1.03	7.84	1.54	3120
Spring	1954–56	5.01	1.33	9.36	1.75	577
	1983–87	4.25	1.12	8.07	1.54	1295
	1992–98	4.36	1.04	8.22	1.52	1820
	2011–13	4.48	1.03	8.72	1.5	780
Summer	1954–56	4.4	1.18	7.86	1.72	577
	1983–87	3.68	1.06	6.67	1.39	1295
	1992–98	3.81	0.95	7.02	1.28	1820
	2011–13	3.76	1.02	7.25	1.6	780
Fall	1954–56	4.26	1.18	8.27	1.44	576
	1983–87	3.68	1.07	7.04	1.38	1295
	1992–98	3.76	1.01	7.42	1.29	1820
	2011–13	3.46	0.99	7.34	1.71	780
Winter	1954–56	4.25	1.02	8.54	1.81	576
	1983–87	3.68	1.16	7.34	1.43	1295
	1992–98	3.79	0.99	7.62	1.39	1820
	2011–13	3.77	1.02	7.97	1.56	780

Table 3.2. Annual and spring difference in 50th and 90th percentiles wind speeds (column vs. row) (m/s), percent difference, and p-value for select time periods

	50th percentile			90th percentile		
	Diff (m/s)	% Diff	p-value	Diff (m/s)	% Diff	p-value
			Comparison with annual, 1954–56			
1983–87	−0.66	−17%	$p < 0.01$	−1.23	−17%	$p < 0.01$
1992–98	−0.55	−14%	$p < 0.01$	−0.94	−12%	$p < 0.01$
2011–13	−0.60	−15%	$p < 0.01$	−0.67	−9%	$p < 0.01$
			Comparison with spring, 1954–56			
1983–87	−0.76	−18%	$p <0.01$	−1.23	−15%	$p < 0.01$
1992–98	−0.65	−15%	$p < 0.01$	−0.94	−11%	$p < 0.01$
2011–13	−0.53	−12%	$p < 0.01$	−0.67	−8%	$p < 0.01$
			Comparison with annual, 2011–13			
1983–87	−0.06	−2%	$p = 0.72$	−0.56	−8%	$p < 0.01$
1992–98	0.05	1%	$p = 0.44$	−0.27	−4%	$p = 0.01$
1954–56	0.6	15%	$p < 0.01$	0.67	8%	$p < 0.01$
			Comparison with spring, 2011–2013			
1983–87	−0.23	−5%	$p = 0.93$	−0.65	−8%	$p < 0.01$
1992–98	−0.12	−3%	$p = 0.09$	−0.5	−6%	$p = 0.03$
1954–56	0.53	12%	$p < 0.01$	0.67	8%	$p < 0.01$

Diff = Difference in value between the two time periods; % Diff = Percent difference between the two time periods
A value of −17% in the first row and column means that wind speeds in 1983–87 are 17% lower than wind speeds in 1954–56

3.2. Trend analysis

A statistically significant (p-value < 0.01) general downward trend is apparent in both the 50th and 90th percentile wind speeds between 1948 and 2016 (Figure 3.2.). The 50th and 90th percentile wind speeds declined at a rate of approximately 0.006 and 0.0095 ms^{-1} $year^{-1}$ or 1.25% and 1.36% per decade, respectively (trend line values shown in Table A-3).

The estimated downward trend in 50th and 90th percentile wind speeds came from surface winds speeds averaged over 87 meteorological stations, spread across several regions of the Mid-Continental USA. A sensitivity analysis in which 11 coastal stations in Texas were excluded from the trend analysis revealed that downward trends remained analogous when the 11 coastal stations were excluded. In this sensitivity analysis, the trends in 50th and 90th wind speeds were essentially the same as those for all 87 stations, declining at a rate of 0.0061 and 0.0099 ms^{-1} $year^{-1}$, respectively (Figures A-2, A-3b, and Table A-3). The second sensitivity test, which involved the removal from the long-term trend analysis of 23 stations that exhibited data gaps between 1960s and 1970s, suggested that similar rates of stilling exist when these stations are excluded. Removal of these stations resulted in a slightly reduced decline in 50th and 90th wind speeds, which decreased by 0.0059 and 0.0090 ms^{-1} $year^{-1}$, respectively ((Figure A-3c and Table A-3).

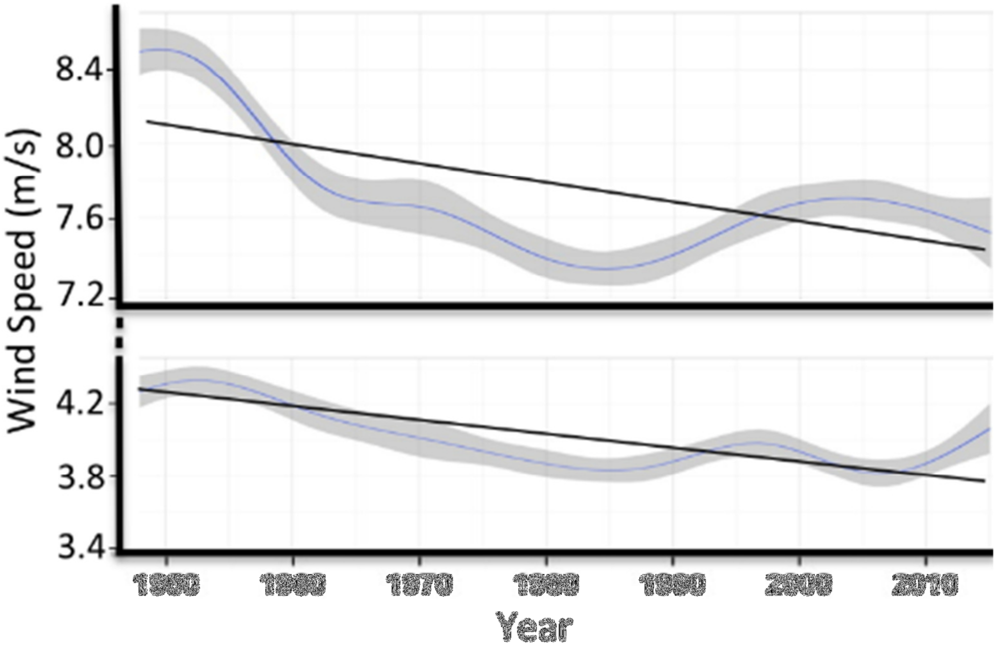

Figure 3.2. **Average annual 50th percentile (bottom) and 90th (top) percentile wind speeds (m/s) between 1948 and 2016 estimated from 87 meteorological stations in the Mid-Continental USA. A trend line is shown in black and one standard deviation from average annual 50th percentile and 90th percentile wind speed is shown in grey (trend line values are shown in Table A-3)**

3.3. NCEP reanalysis composite analysis

Using the annual time series of the regionally averaged monthly 90th percentile wind speeds, I identified five years with the fastest (1952, 1953, 1954, 1955, and 1988) and slowest (1963, 1973, 1975, 1995, and 2006) annual wind speeds between 1948 and 2016. Distinct patterns in composite plots of sea-level pressure, precipitation, surface temperature, and PDSI were observed for the annual, spring, and winter seasons for the drought versus wetter and fastest versus slowest time periods. The strongest patterns in composite plots were observed during the spring and winter and are discussed here.

Comparison of annual and seasonal NCEP reanalysis composites between drought (1954–1956 and 2011–2013) and wetter (1983–1987 and 1992–1998) periods as well as fastest and slowest wind speed periods revealed anomalously high annual, spring, and winter sea-level pressures in the North Pacific Ocean, during periods of drought (Figure 3.3.a–c), centered between 30°–50°N and 130°–170°W. This pattern was also more prominent during the springtime of the 1950s drought when compared to the 2010s drought (Figure 3.4.h) and more prominent during the wintertime of the 2010s drought when compared to the 1950s drought. This feature, which likely represents a strengthening of the North Pacific high-pressure system, was also present during annual and winter fastest wind speed periods when compared with the slowest wind speed periods (Figure 3.4.d,f).

The fastest wind speed years and seasons also had anomalously low PDSI values (i.e., drier conditions) within the study region (Figure 3.5.d–f). Surface temperatures within the study region were also anomalously higher during drought periods and fastest wind speed years, and these differences were most prevalent during spring and winter months (Figure 3.6.a–f). Spring precipitation patterns during fastest wind speed years were also drier along the known trajectory pathways of winds over the East Pacific (which led to higher winds and dust events in deserts of the southwest USA) (Figure 3.6.e). Patterns in annual, spring, and winter surface precipitation were similar between the 1950s and 2010s droughts, with the exception of increased precipitation at the Texas coastline during spring and winter periods of the 1950s drought (Figure 3.6.h,i). Variations in annual, spring, and winter PDSI and surface temperatures were not discernable between the 1950s and the 2010s droughts (Figure 3.4.g–i and Figure 3.5.g–i).

When comparing the drought and wetter years with faster and slower wind speed periods during the composite analysis, specific years (e.g., 1954 to 1956) existed in both drought and fastest wind speed years. Furthermore, wind speeds during the 1950s were higher than during any other time period (Figure 3.3.). To determine if this overlapping of years imparted a bias on the results of the composite analysis, a subsequent composite analysis was conducted in which years from the 1950s were excluded from the calculation of five fastest wind speed years. When the 1950s were excluded, the next five fastest wind speed years (1961, 1964, 1971, 1996, and 2008) were compared to the five slowest wind speed years (Figure A-4). This comparison shows that patterns in sea-level pressure, surface temperature, and PDSI are not substantially different when the 1950s are excluded.

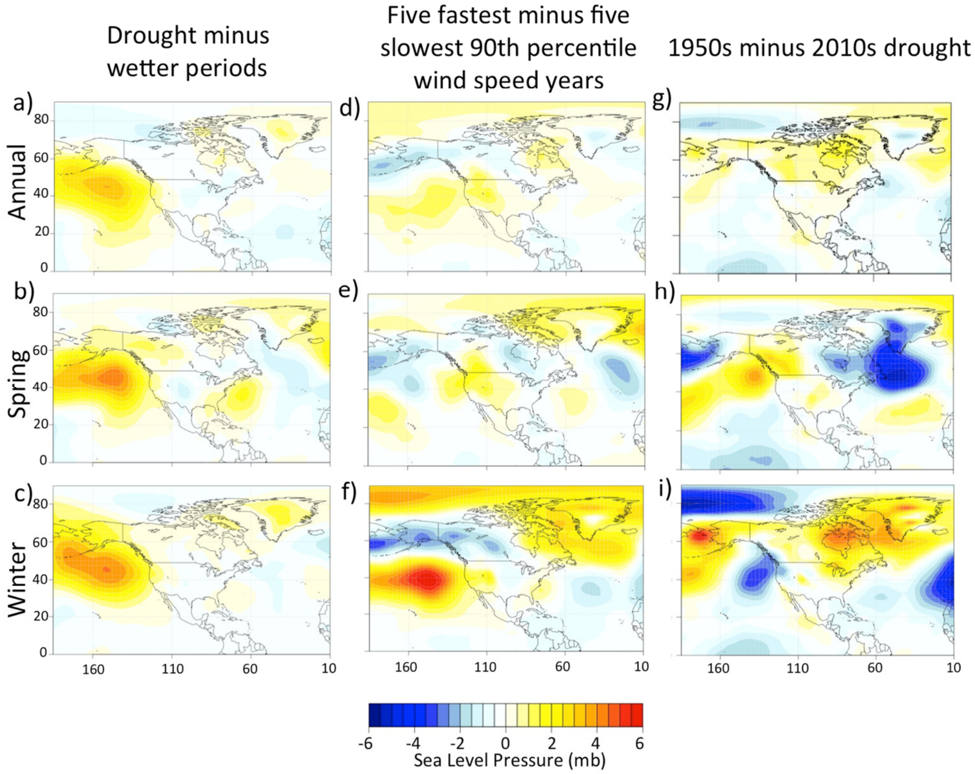

Figure 3.3. **Annual, spring, and winter NCEP sea level pressure anomalies (mb) between drier (1954–1956 and 2011–2013) and wetter (1983–1987 and 1992–1998) (a,b,c), between years with the five fastest and five slowest 90th percentile wind speeds (d,e,f), and between the 1950s drought (1954–1956) and the 2010s drought (2011–2013) (g,h,i) estimated from 87 meteorological stations in the Mid-Continental USA**

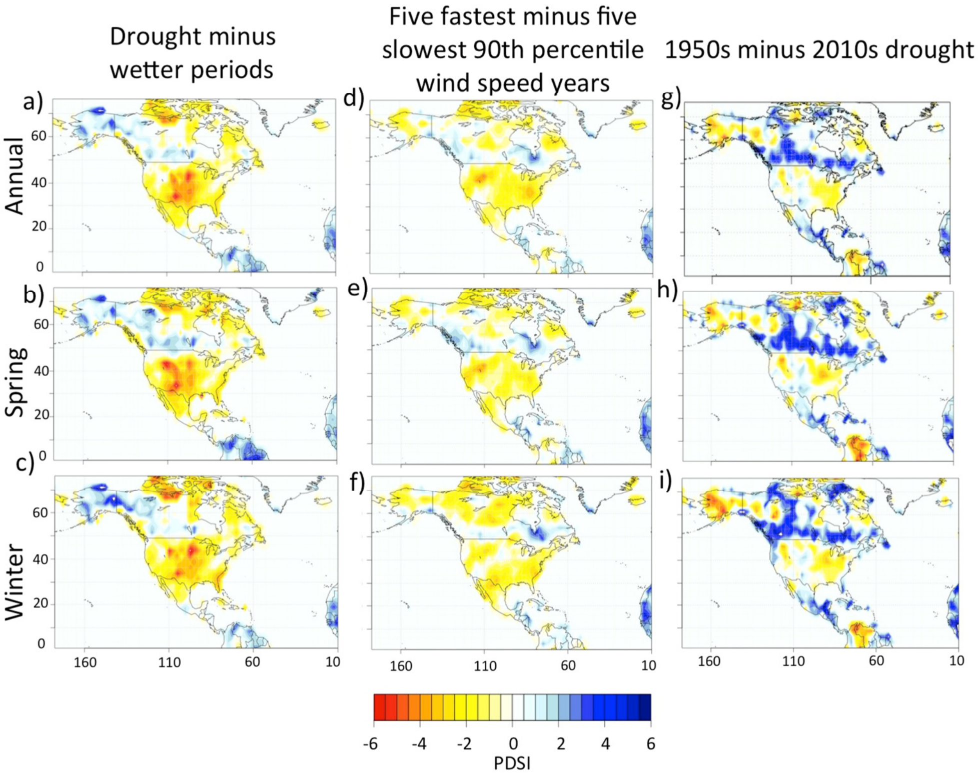

Figure 3.4. Annual, spring, and winter NCEP PDSI anomalies between drier (1954–1956 and 2011–2013) and wetter (1983–1987 and 1992–1998) periods (a,b,c), between years with the five fastest and five slowest 90th percentile wind speeds (d,e,f), and between the 1950s drought (1954–1956) and the 2010s drought (2011–2013) (g,h,i) estimated from 87 meteorological stations in the Mid-Continental USA

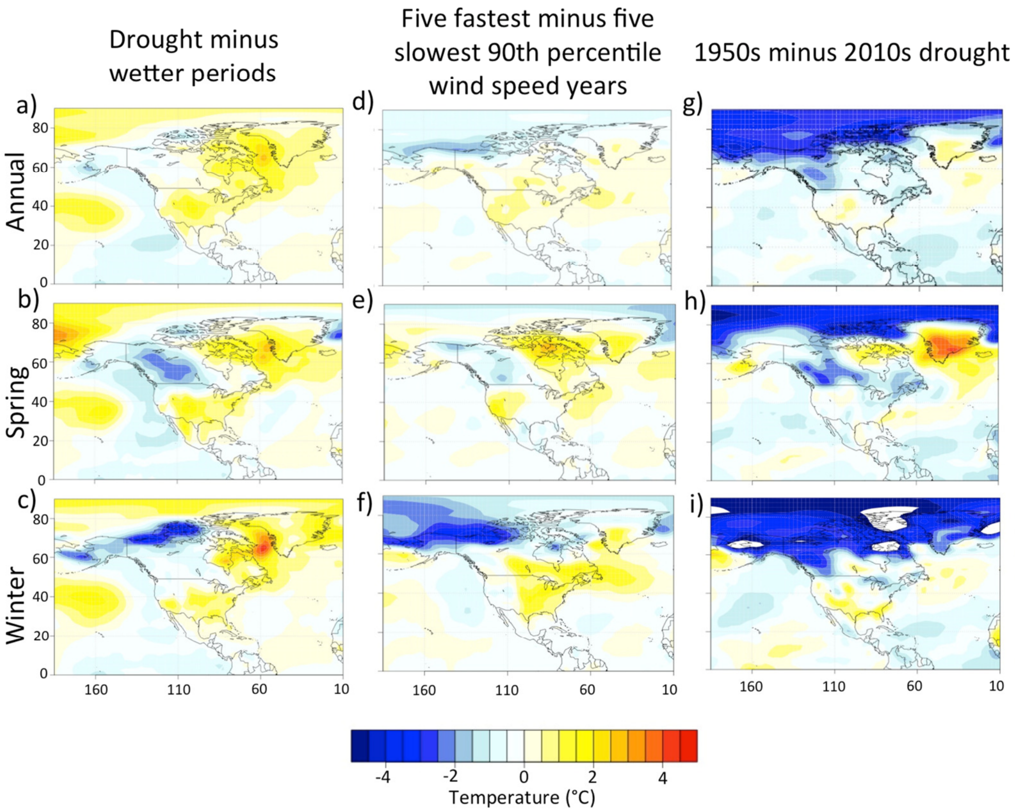

Figure 3.5. **Annual, spring, and winter NCEP surface temperature anomalies (°C) between drier (1954–1956 and 2011–2013) and wetter (1983–987 and 1992–1998) periods (a,b,c), between years with the five fastest and five slowest 90th percentile wind speeds (d,e,f), and between the 1950s drought (1954–1956) and the 2010s drought (2011–2013) (g,h,i) estimated from 87 meteorological stations in the Mid-Continental USA**

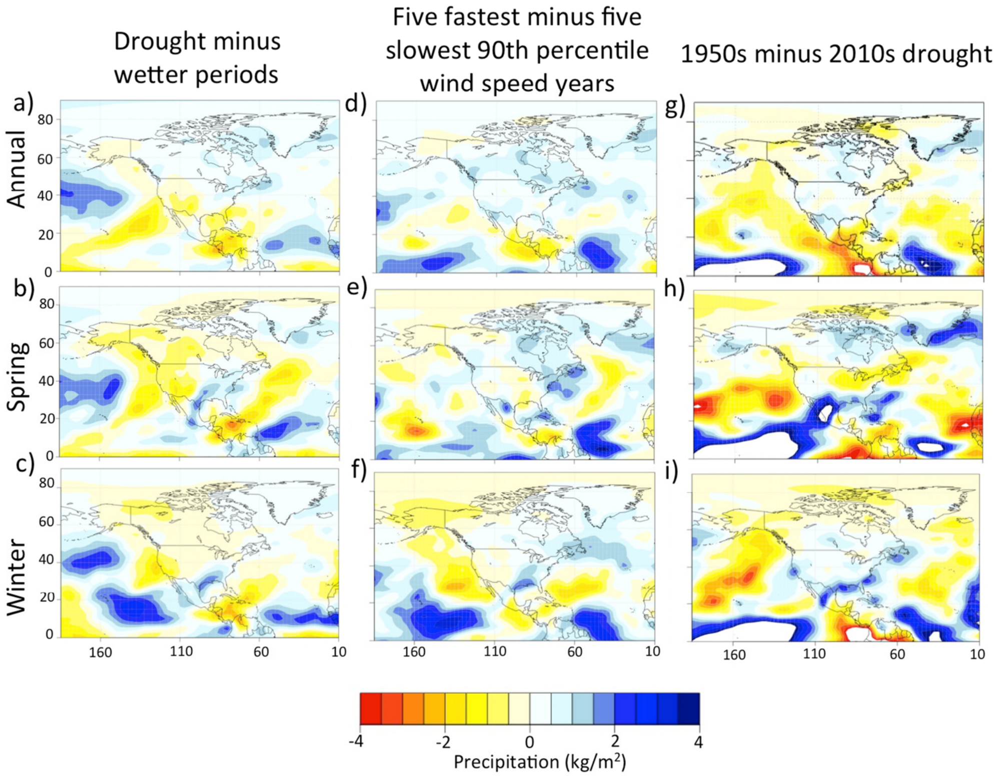

Figure 3.6. **Annual, spring, and winter NCEP precipitation anomalies (kg/m2) between drier (1954–1956 and 2011–2013) and wetter (1983–1987 and 1992–1998) periods (a,b,c), between years with the five fastest and five slowest 90th percentile wind speeds (d,e,f), and between the 1950s drought (1954–1956) and the 2010s drought (2011–2013)(g,h,i) estimated from 87 meteorological stations in the Mid-Continental USA**

Chapter 4.

Discussion

Two important patterns are revealed from this analysis. First, drought periods tend to have significantly higher extreme (90th percentile) surface wind speeds when compared with wetter climate periods. Second, the 1950s drought had significantly higher 50th and 90th percentile surface wind speeds when compared with all other time periods. For this discussion, I will first examine how changes in historical land management practices that affect land-surface conditions might have created higher extreme winds during the 1950s drought. I will examine how climate-related feedbacks may affect wind behaviour indirectly through changes in surface roughness during drought periods or directly through changes in synoptic-scale weather systems and atmospheric general circulation patterns. I will then show how my observations compare with the ubiquitous pattern of atmospheric stilling that has been observed in many mid-latitude settings. Finally, I will consider the potential implications of my two results on dust production in the Mid-Continental USA.

4.1. Changes in historical land management

One key observation from this analysis is the distinctive nature of the higher wind speeds during the 1950s drought when compared with both wetter periods and the 2010s drought. The high wind speeds during the 1950s drought could have resulted from a combination of climate-related feedbacks on surface roughness, but also from anthropogenic factors altering land cover resulting in substantially higher wind speeds (and lower wind speeds thereafter).

Anthropogenic land degradation is considered a key contributor to the dust storms of the 1930s Dust Bowl (Cook et al., 2009; Lee & Gill, 2015). In the 1920s, the agricultural expansion throughout the Great Plains saw the replacement of many drought-resistant prairie grasses with extremely drought-sensitive wheat. When a climate-forced precipitation deficit accelerates losses in vegetation, surface winds can also increase due to the lack of surface roughness (Burnette & Stahle*,* 2012).

Subsequent decreases in surface wind speeds (Figure 3.3.) could have resulted from changes in land use practices that increased surface cover and therefore also surface roughness. Throughout the late 1930s and 1940s, the US Soil Conservation Services and the US Forest Service's Prairie States Forestry Project were tasked with addressing land management issues through terracing, contour ploughing, and tree-planting, as well as purchasing farms to encourage resettlement to less drought sensitive areas (McLeman et al., 2013). Non-climatic influences on soil hydrology through improvements in irrigation following the Dust Bowl and 1950s drought may have resulted in slower surface wind speeds through increases in surface roughness that were independent of hydroclimatic variability (Cook et al., 2007). These activities would have taken years to become effective and potentially contributed to the reduced 50th and 90th percentile wind speeds observed following the 1950s drought. Furthermore, the rapid expansion of infrastructure and buildings throughout the Mid-Continental USA (in the near field of meteorological stations) could have contributed, to some extent, to the apparent slowing of winds between the two severe drought periods (DeGaetano, 1998).

4.2. Influence of climate-related changes in surface roughness and synoptic-scale weather systems

Variations in vegetation cover in the Mid-Continental USA can affect surface wind behaviour and would be affected by large-scale ocean-atmosphere climate variability, which influences North American temperature and moisture regimes. Furthermore, several climate-related factors could contribute to higher 50th and 90th percentile wind speeds observed during drought periods, including variations in large-scale pressure patterns and SSTs across the northern Pacific Ocean (Cook et al., 2009).

Sea-level pressures during both drought and fastest wind speed years displayed enhanced pressures patterns in the North Pacific high-pressure system (Figure 3.3.). The pressure gradient between the North Pacific high-pressure and North America low-pressure systems tends to push northerly winds toward the North American coast and suppresses atmospheric moisture across western portions of the continental USA (Tong, Wang, Gill, Lei, & Wang, 2017). This pattern has been hypothesized to promote an increased flow of dry continental air from the northwest toward the southeast of the USA, as well as from above through subsidence, resulting in enhanced drying (Tong et al., 2017). This enhanced drying could further promote drought-like conditions and alter land cover, resulting in greater wind speeds.

Previous work has also suggested that broad-scale changes in sea-surface temperature conditions, such as cool central Pacific and warm Atlantic SSTs, could influence drought conditions in the Mid-Continental USA (Schubert, Suarez, Pegion, Koster, & Bacmeister, 2004; Lee & Gill, 2015). During the 1950s drought, cooler SSTs stretched from the west coast of the USA up to the Gulf of Alaska, while warmer SSTs were present in the western and central North Pacific Ocean (Fye, Stahle, & Cook, 2004). During this cool phase of the Pacific Decadal Oscillation (PDO), a pattern of ocean-atmosphere climate variability in the Pacific Ocean, the coldest anomaly occurred in the equatorial Pacific in the winter of 1955–56 (DJF), a period when the study region experienced its lowest PDSI values and highest 90th percentile wind speeds. Three of the five windiest springs in the study region (1953, 1954, and 1956) took place during severe droughts when the El Niño–Southern Oscillation (ENSO) was in a negative, colder phase (NOAA, 2015). The resulting moisture deficit during this climate-forced drought may have resulted in the accelerated loss in vegetation and subsequent increase in surface winds due to the lack of surface roughness.

Historical changes in vegetation within the Mid-Continental USA have been documented through aerial photography, field observations, and image analysis techniques (Park et al., 2009). In areas most affected by the 1950s drought (e.g., Texas), woody plant cover decreased by 4-10% between 1941 and 1960 and then increased at a rate of 300–800% between 1960 and 1983 (Asner, Archer, Hughes, Ansley, & Wessman, 2003), corresponding with observed increases in PDSI within the study region (Figure 2.3.). Reductions in surface wind speeds are observed during the wetter period between 1983 and 1987, as are decreases in both the 50th and 90th percentile surface wind speeds during this same, post-drought time period (e.g., 1960 to 1983) (Figure 3.3.). This suggests that increased vegetation cover could have contributed to reduced surface-level wind speeds.

Vegetation reductions are also documented using satellite remote sensing and inverse modeling for the 2010s drought (Karl et al., 2012). Here, climate-related increases in early spring temperatures stimulated an early “greenup," followed by rapid and persistent deterioration of vegetation in the summer months. These drought-induced vegetation losses were present within the Mid-Continental USA during the summer months of 2011 and even more so during 2012 (Wolf et al., 2016), when 90th percentile wind speeds were statistically greater than the two previous wetter periods (1983 to 1987 and 1992 to 1998). During the onset of the 2010s drought, the spring thunderstorm season failed to arrive, further increasing the soil moisture deficit and exacerbating drought conditions and vegetation loss (Tadesse, Wardlow, & Brown, 2015). Thus, climate-induced changes in vegetation (and associated fluctuations in surface roughness) may be a factor in above-average surface winds during the 1950s and 2010s drought as well as reduced winds during wetter periods.

The discussion above focuses on the effects of large-scale, climate-related conditions that may have an indirect effect on surface wind speeds through their influence on vegetation cover. Large-scale climate conditions may also influence surface winds directly through synoptic-scale cyclone activity (Takemi & Seino, 2005). The enhancement of surface pressure gradients in the Mid-Continental USA might intensify frontal activity (i.e., cyclogenesis), which may contribute to stronger surface winds during drought and windy periods. The amplification of sea level pressure gradients between the North Pacific and North America was observed during the annual, spring, and winter drought periods as well as the faster wind speed time periods during winter (Figures 3.3. a-c,f). Intensification of this pressure pattern may alter the path of storms originating from the Pacific Ocean as well as introduce faster/drier winds into more dust-prone regions of the Mid-Continental USA (Tong et al., 2017). However, a more detailed investigation into the effect of climate conditions on cyclogenesis, and ultimately surface wind behaviour within the study region, is required.

4.3. Atmospheric stilling

Statistically significant differences in wind speeds between the two drought periods are consistent with the pattern of atmospheric stilling that has been observed in many mid-latitude settings (Vautard et al., 2010). For the contiguous USA, Pryor et al. (2009) observed a significant downward trend in both the 50th percentile (approximately –0.7% per year) and the 90th percentile (approximately 0.6% per year) wind speeds between 1973 and 2005. Using near-surface, hourly wind speed data from 1979 to 2008, Vautard et al. (2010) observed a decline in annual mean surface wind speed of 0.07 ms^{-1} $decade^{-1}$ or a decrease of 1.8% per decade across North America. I observed a decline in 50th and 90th percentile wind speeds within the study region of approximately 0.06 and 0.095 ms^{-1} $decade^{-1}$ or 1.25% and 1.36% per decade, respectively, between 1948 and 2016 (Figure 3.3.). When corrected for this long-term trend, mean annual 50th and 90th percentile surface wind speeds were 1.5% and 0.2% higher during the 1950s when compared with the 2010s drought. These wind speed differences are less than the difference calculated during the second sensitivity analysis where 23 stations that exhibited data gaps between the 1960s and 1970s were removed (< 4%).

The decline in surface wind speeds between the two drought periods may be less a result of direct changes in atmospheric general circulation and more a result of changes in biomass and surface roughness, an idea suggested previously for stilling trends analyzed over the shorter time period of 1973 to 2005 (Vautard et al., 2010). In this previous work, NCEP reanalysis of North American free troposphere (850 hPa and above) wind speed observations, which have a high connectivity to surface winds, showed inconclusive stilling trends between 1973 and 2005 (Vautard et al., 2010). In contrast, long-term changes in SST between 1948 and 2008 have resulted in drier regions of the Mid-Continental USA becoming wetter due to westerly winds supplying increased moist, maritime air to the region (Huang, Winter, Osterberg, Horton, & Beckage, 2017). This increase in moist maritime air may result in an increased biomass and resulting surface roughness. Increases in urbanization within the Mid-Continental USA between the two drought periods would also increase surface roughness and contribute to the observed stilling trend (Lopes, Saraiva, & Alcoforado, 2011).

4.4. Implications of changes in surface wind speeds on dust production

Surface wind speeds, in particular wind gustiness, influence the frequency and intensity of dust storms. While gustiness data are not readily available, high-velocity surface winds can be inferred from 90th percentile wind speeds, which comprise the highest percentile surface gust speeds able to meet the threshold velocity for dust emission. This threshold velocity, which is strongly dependent on soil type, soil moisture, and vegetation cover, has been estimated to be between 6.63 ± 0.67 and 9.08 ± 1.08 m/s (Engelstaedter, Tegen, & Washington, 2006; Bouet et al., 2012).

The two drought periods experienced higher frequencies of 90th percentile wind speeds within this threshold velocity range, when compared with the two wetter periods (Table 3.1.). These observations suggest that wind conditions were more frequently sufficient to raise dust during both drought periods, and especially during the 1950s drought. Between 1952 and 1956, the overall frequency of days with blowing dust (i.e., when visibility is limited to 10 km or less) increased in many states including Kansas and Texas to as high as 40 days a year in 1955 and

1956 (Gillette & Hanson, 1989). Within our study region, 1952 to 1954 were also the years with the fastest average annual 90th percentile wind speeds (Figure 3.3.). During the 2010s drought I also observed greater 90th percentile wind speeds, particularly during winter and spring months. Similarly, most dust storms occurred between December and April during this drought (NOAA, 2016).

While the 1950s and 2010s droughts both had relatively higher winter and spring wind speeds when compared with annual wind speeds in our study region, these two drought periods experienced slightly different timing in the seasons of highest dust production. During the 1950s drought, dust production was highest between March and May when planted crops would first be sprouting (Gillette & Hanson, 1989). The presence of vegetation implies that threshold velocities required to produce dust storms would have been higher than in winter months. However, since wind speeds were comparatively faster, and drought conditions were prevalent during this time period, dust storms still propagated throughout the US Southern Great Plains. In contrast, dust production during the 2010s drought was greatest from January to March, when biomass had not yet developed (NOAA, 2015). A reduction in seasonal snow cover may lead to decreased soil moisture, reduced vegetation, and an overall reduction in the threshold velocity required for dust storms (Sud, Mocko, Lau, & Atlas, 2003). Therefore, even though 90th percentile wind speeds were slower during the 2010s drought when compared to the 1950s drought, the heightened drought conditions during the winter and spring months still may have allowed for prevalent dust storms. Monthly mean dust emissions in the southern USA increased by 46.5% from the summer of 2010 to the summer of 2011, influenced by an increase in surface winds over dust source regions as well as drought-influenced decreases in soil moisture (Wang et al., 2016).

Various investigations have both predicted and observed increases in climate-induced droughts and subsequent dust emissions within the Mid-Continental USA, particularly in more arid environments (Cook et al., 2007; Hand et al., 2016; Tong et al., 2017). The stilling observed in this investigation as well as others (Pryor et al., 2009; Vautard et al., 2010) is likely more of a general trend observed over continental areas resulting from changes in surface roughness attributable to changes in land management practices. While land management practices are a primary factor in controlling dust storms in the Mid-Continental USA (Nordstrom & Hotta, 2004) and may be responsible for reduced dust emissions in the Southern High Plains of North America between 1961 and 2001 (Stout & Lee, 2003), recent large-scale climate-forced changes in aridity within southwestern North America may contribute to increased dust emissions (Tong et al., 2017).

Chapter 5.

Conclusion

In this paper, I compared historic and modern surface wind speeds to determine how wind-driven dust-producing conditions may have changed during the strongest drought and wetter periods between 1954 and 2016. This investigation showed that drought periods tended to have significantly higher extreme (90th percentile) surface wind speeds when compared with wetter climate periods. This difference was driven largely by the fact that the 1950s drought had significantly higher 50th and 90th percentile surface wind speeds when compared with all other time periods. The higher wind speeds during the 1950s drought when compared to the 2010s drought may have been a consequence of anthropogenic factors, such as poor land management practices, that reduced surface roughness during the 1950s. Additionally, the large-scale ocean-atmosphere climate variability might have contributed to regional warming and drying, which decreased vegetation cover, reduced surface roughness, and led to higher wind speeds during drought periods. Subsequent decreases in wind speed conditions in the Mid-Continental USA following the 1950s drought are likely a result of changes in land use practices combined with climate-induced increases in vegetation cover.

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Appendix A

Table A-1 Metadata from the final 87 meteorological stations that met completeness criteria. 11 coastal Texas stations removed are shown in bold

USAFID	WBAN	Lat	Long	Elev	STATION.NAME	CT	ST.CALL
690190	13910	32.4	-99.85	543	ABILENE DYESS AFB	US	TX
999999	**12917**	**29.95**	**-94.017**	**9**	**PORT ARTHUR JEFFERSON COUNTY**	**US**	TX**
999999	**12917**	**29.95**	**-94.017**	**9**	**PORT ARTHUR JEFFERSON COUNTY**	**US**	TX**
999999	93987	31.233	-94.75	89	LUFKIN ANGELINA CO	US	TX
999999	**12926**	**27.7**	**-97.267**	**10**	**CORPUS CHRISTI NAS**	**US**	TX**
999999	**12928**	**27.5**	**-97.8**	**18**	**KINGSVILLE**	**US**	TX**
999999	**12947**	**28.45**	**-99.217**	**141**	**COTULLA FAA AP**	**US**	TX**
722530	**12921**	**29.533**	**-98.467**	**242**	**SAN ANTONIO INTL**	**US**	TX**
722533	**12962**	**29.333**	**-99.167**	**280**	**HONDO MUNI**	**US**	TX**
722535	**12909**	**29.383**	**-98.567**	**207**	**LACKLAND AFB KELLY**	**US**	TX**
722536	**12911**	**29.533**	**-98.283**	**226**	**RANDOLPH AFB**	**US**	TX**
999999	**13958**	**30.3**	**-97.7**	**189**	**AUSTIN MUELLER MUNICIPAL AP**	**US**	TX**
722560	13959	31.617	-97.217	155	WACO RGNL	US	TX
722595	13911	32.783	-97.433	192	FORT WORTH NAS JRB	US	TX
722630	23034	31.367	-100.5	585	SAN ANGELO/MATHIS	US	TX
999999	13973	30.483	-99.767	522	JUNCTION	US	TX
722640	**93035**	**30.367**	**-104.017**	**1481**	**MARFA MUNICIPAL**	**US**	TX**
722650	23023	31.933	-102.2	871	MIDLAND/MIDLAND REG	US	TX
722656	23040	31.783	-103.2	859	WINKLER CO	US	TX
722660	13962	32.433	-99.683	534	ABILENE MUNICIPAL	US	TX
722670	23042	33.65	-101.817	988	LUBBOCK/LUBBOCK INT	US	TX
722680	23009	33.3	-104.533	1118	ROSWELL/INDUSTRIAL	US	NM
722686	23008	34.383	-103.317	1309	CANNON AFB	US	NM
722695	99999	32.283	-106.917	1358	LAS CRUCES INTL	US	NM

USAFID	WBAN	Lat	Long	Elev	STATION.NAME	CT	ST.CALL
722700	23044	31.8	-106.4	1194	EL PASO INTL ARPT	US	TX
999999	23160	32.116	-110.933	9999	TUCSON INTERNATIONAL AP	US	AZ
722745	23109	32.183	-110.917	782	DAVIS MONTHAN AFB	US	AZ
999999	23183	33.433	-112.033	339	PHOENIX SKY HARBOR INTL AP	US	AZ
723510	13966	33.983	-98.5	314	WICHITA FALLS/SHEPS	US	TX
723520	13902	34.65	-99.267	413	ALTUS AFB	US	OK
999999	93986	35	-99.05	474	HOBART MUNICIPAL AP	US	OK
723530	13967	35.4	-97.6	397	OKLAHOMA CITY/W. RO	US	OK
723540	13919	35.433	-97.383	383	TINKER AFB	US	OK
723550	13945	34.65	-98.383	360	FORT SILL	US	OK
723560	13968	36.2	-95.9	206	TULSA INTL ARPT(AW)	US	OK
723566	93950	34.883	-95.783	235	MC ALESTER RGNL	US	OK
723630	23047	35.233	-101.7	1099	AMARILLO INTL	US	TX
723650	23050	35.05	-106.667	1620	ALBUQUERQUE INTL	US	NM
999999	23090	36.75	-108.233	1675	FARMINGTON MUNICIPAL AP	US	NM
999999	23184	34.65	-112.433	1530	PRESCOTT MUNICIPAL AP	US	AZ
999999	23194	35.017	-110.733	1489	WINSLOW MUNICIPAL AP	US	AZ
724510	13985	37.767	-99.967	790	DODGE CITY(AWOS)	US	KS
724515	23064	37.933	-100.733	880	GARDEN CITY RGNL	US	KS
724550	13947	39.05	-96.767	324	FT RILEY/MARSHALL A	US	KS
999999	13996	39.067	-95.633	267	TOPEKA MUNICIPAL AP	US	KS
724585	93997	38.867	-98.817	568	RUSSELL MUNI	US	KS
999999	23070	37.25	-104.333	1749	TRINIDAD LAS ANIMAS COUNTY AP	US	CO
999999	23065	39.367	-101.7	1115	GOODLAND RENNER FIELD	US	KS
724660	93037	38.817	-104.7	1881	COLORADO SPRINGS/MU	US	CO
999999	23063	39.65	-106.917	1980	EAGLE COUNTY AP	US	CO
999999	93129	37.7	-113.1	1713	CEDAR CITY MUNICIPAL	US	UT

USAFID	WBAN	Lat	Long	Elev	STATION.NAME	CT	ST.CALL
					AP		
999999	23066	39.117	-108.533	1478	GRAND JUNCTION WALKER FIELD	US	CO
999999	14942	41.3	-95.9	304	OMAHA EPPLEY AIRFIELD	US	NE
725520	14935	40.967	-98.317	566	GRAND ISLAND COUNTY	US	NE
999999	24023	41.133	-100.7	850	NORTH PLATTE LEE BIRD FIELD	US	NE
999999	24030	41.133	-103.033	1262	SIDNEY MUNICIPAL AP	US	NE
725640	24018	41.15	-104.817	1876	CHEYENNE/WARREN AFB	US	WY
725660	24028	41.867	-103.6	1206	SCOTTSBLUFF/HEILIG	US	NE
725690	24089	42.917	-106.467	1612	CASPER/NATRONA COUN	US	WY
725720	24127	40.783	-111.967	1288	SALT LAKE CITY INTL	US	UT
999999	24027	41.6	-109.067	2056	ROCK SPRINGS ARPT	US	WY
725755	24101	41.117	-110.25	1459	HILL AFB	US	UT
999999	24021	42.817	-108.733	1694	LANDER HUNT FIELD	US	WY
725810	24193	40.733	-114.033	1292	WENDOVER/AF. AUX. F	US	UT
726510	14944	43.583	-96.733	435	SIOUX FALLS/FOSS FI	US	SD
999999	24024	44.05	-101.6	672	PHILIP 1 S	US	SD
999999	14936	44.383	-98.217	395	HURON MUNICIPAL ARPT	US	SD
726546	14946	44.917	-97.15	530	WATERTOWN MUNI	US	SD
726546	14946	44.917	-97.15	530	WATERTOWN MUNI	US	SD
999999	14929	45.45	-98.433	396	ABERDEEN MUNICIPAL ARPT	US	SD
999999	24090	44.05	-103.067	964	RAPID CITY REGIONAL ARPT	US	SD
726625	24006	44.133	-103.1	979	ELLSWORTH AFB	US	SD
999999	24029	44.767	-106.967	1202	SHERIDAN COUNTY ARPT	US	WY
726770	24033	45.8	-108.533	1088	BILLINGS/LOGAN INT.	US	MT
999999	24132	45.783	-111.15	1359	BOZEMAN GALLATIN FIELD	US	MT
727530	14914	46.9	-96.8	274	FARGO/HECTOR FIELD	US	ND

USAFID	WBAN	Lat	Long	Elev	STATION.NAME	CT	ST.CALL
999999	14919	46.917	-98.683	455	JAMESTOWN MUNICIPAL ARPT	US	ND
999999	24012	46.8	-102.8	793	DICKINSON MUNICIPAL AP	US	ND
727640	24011	46.767	-100.75	506	BISMARCK MUNICIPAL	US	ND
999999	24013	48.25	-101.283	526	MINOT FAA AP	US	ND
727680	94008	48.217	-106.617	700	GLASGOW INTL ARPT	US	MT
999999	24144	46.6	-112	1167	HELENA ARPT	US	MT
999999	24153	46.917	-114.083	977	MISSOULA JOHNSON-BELL FLD	US	MT
999999	24143	47.483	-111.35	1124	GREAT FALLS INTL ARPT	US	MT
727755	24112	47.5	-111.167	1054	MALMSTROM AFHP	US	MT
999999	24146	48.3	-114.267	904	KALISPELL GLACIER PK INT'L AR	US	MT
727796	24137	48.6	-112.367	1175	CUT BANK MUNI	US	MT
742300	24037	46.433	-105.867	801	MILES CITY	US	MT

USFID, WBAN = Station ID, Lat = Latitude, Long = Longitude, Elev = Elevation, STATION.NAME = Station Name, CT = Country, St.Call = State

Table A-2 Average annual and seasonal monthly 50th and 90th percentile wind speeds (m/s) for select time periods from 76 stations (excluding Coastal Texas) across the Mid-Continental USA

Season	Time period	Average 50th percentile wind speed (m/s)			Average 90th percentile wind speed (m/s)		
		All 87 stations	76 stations	% difference	All 87 stations	76 stations	% difference
Annual	1954-56	4.48	4.51	-0.67	8.51	8.57	-0.71
	1983-87	3.82	3.9	-2.09	7.28	7.33	-0.69
	1992-98	3.93	3.96	-0.76	7.57	7.68	-1.45
	2011-13	3.88	4.03	-3.87	7.84	7.69	1.91
Spring	1954-56	5.01	4.99	0.40	9.36	9.35	0.11
	1983-87	4.25	4.23	0.47	8.07	8.04	0.37
	1992-98	4.36	4.35	0.23	8.22	8.19	0.36
	2011-13	4.48	4.49	-0.22	8.72	8.73	-0.11
Summer	1954-56	4.4	4.41	-0.23	7.86	7.88	-0.25
	1983-87	3.68	3.65	0.82	6.67	6.64	0.45
	1992-98	3.81	3.84	-0.79	7.02	7.03	-0.14
	2011-13	3.76	3.72	1.06	7.25	7.21	0.55
Fall	1954-56	4.26	4.28	-0.47	8.27	8.31	-0.48
	1983-87	3.68	3.66	0.54	7.04	7.02	0.28
	1992-98	3.76	3.73	0.80	7.42	7.4	0.27
	2011-13	3.46	3.44	0.58	7.34	7.31	0.41
Winter	1954-56	4.25	4.27	-0.46	8.54	8.55	-0.12
	1983-87	3.68	3.69	-0.27	7.34	7.35	-0.14
	1992-98	3.79	3.77	0.53	7.62	7.6	0.26
	2011-13	3.77	3.75	0.53	7.97	7.95	0.25

Table A-3 **Trends in average annual 50th percentile and 90th percentile wind speeds between 1948 and 2016 for all 87 stations, 76 stations (excluding 11 coastal Texas stations), and 64 stations (excluding the 23 stations that exhibited data gaps between the 1960s and 1970s) and difference values between the two sensitivity analyses and the original 87 stations**

	All 87 stations (ms^{-1} year^{-1})	76 Stations (excluding 11 coastal Texas stations) (ms^{-1} year^{-1})	Difference from all 87 stations (ms^{-1} year^{-1})	64 stations (excluding 23 data gap stations) (ms^{-1} year^{-1})	Difference from all 87 stations (ms^{-1} year^{-1})
50th percentile winds	-6.24E-03	-6.14E-03	-0.10E-03	-5.96E-03	-0.28E-03
90th percentile winds	-9.50E-03	-9.93E-03	0.43E-03	-9.08E-03	-0.41E-03

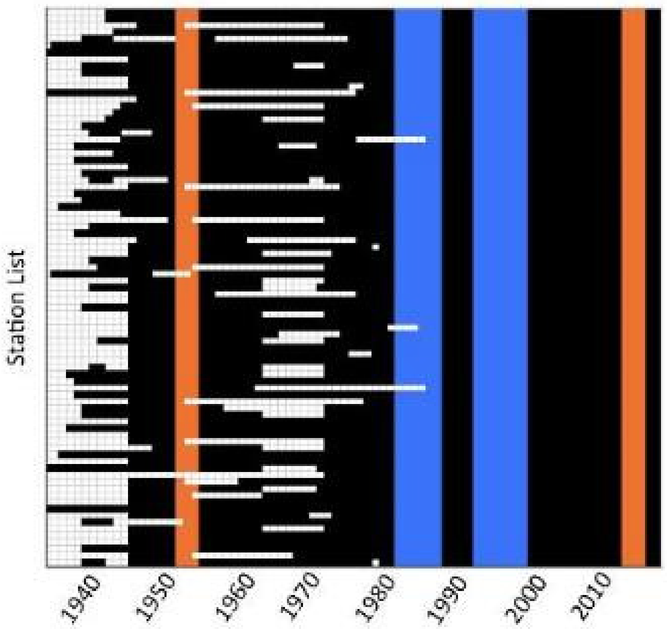

Figure A-1 **Data range of 87 selected stations. Black represents periods of complete data and white spaces represent data gaps. Drought periods are shown in orange and wetter periods are shown in blue**

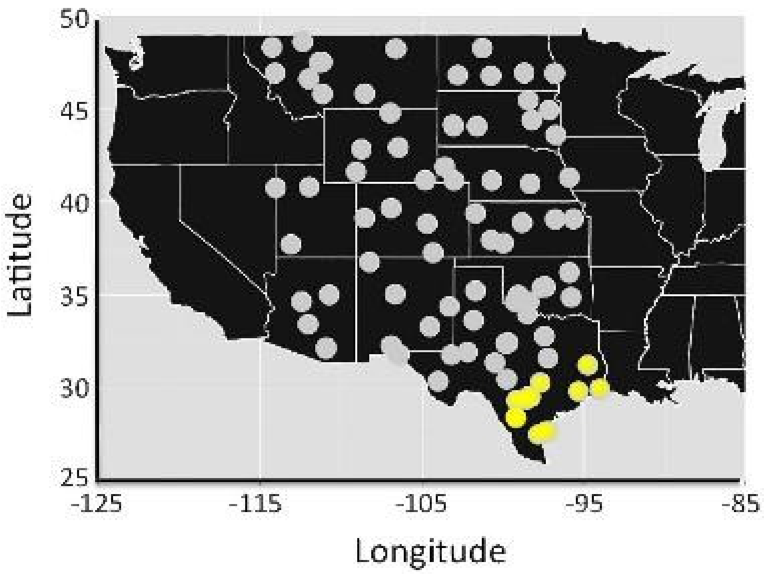

Figure A-2 Study area showing the 11 coastal meteorological stations in Texas excluded for the sensitivity analysis described in Section 2.5

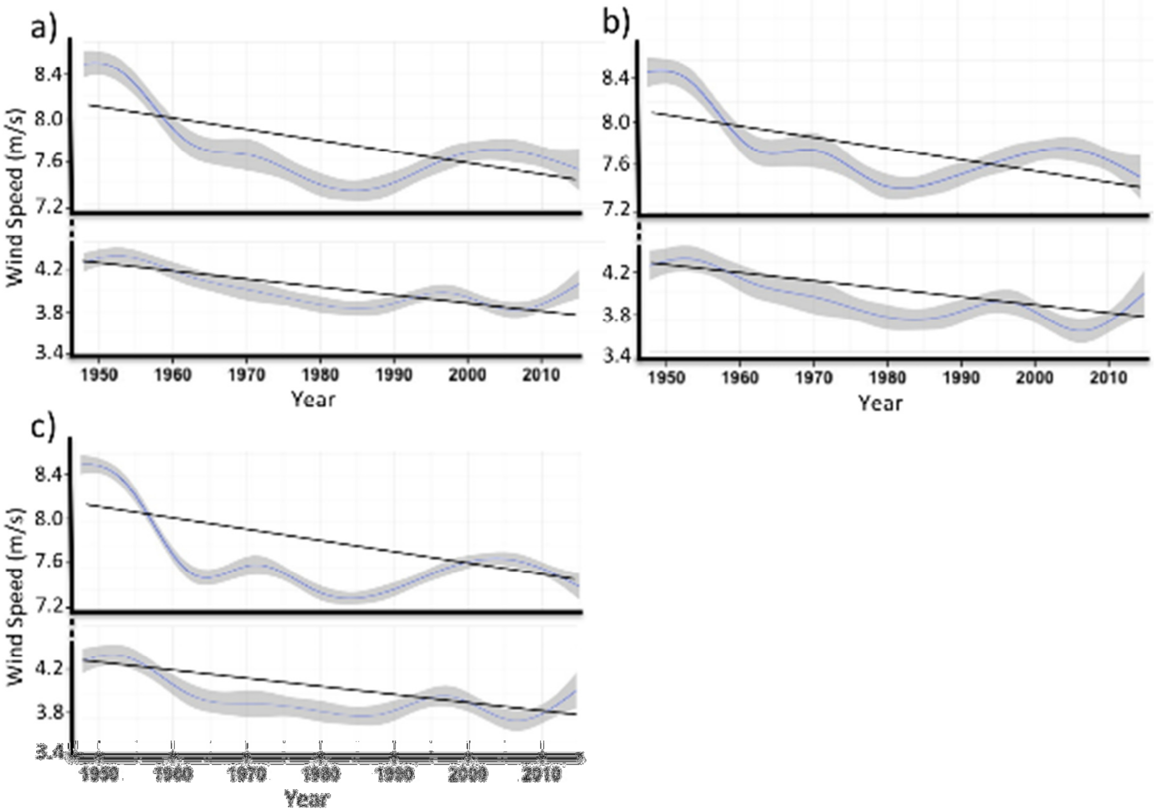

Figure A-3 Average annual 50th percentile (bottom) and 90th (top) percentile wind speeds (m/s) for all 87 stations (a), 76 stations (excluding 11 coastal Texas stations) (b), and 64 stations (excluding the 23 stations that exhibited data gaps between the 1960s and 1970s). The trend lines calculated from the average annual 50th percentile and 90th percentile wind speeds (m/s) for all 87 stations are shown in black on all 3 figures for comparative purposes. One standard deviation from average annual 50th percentile and 90th percentile wind speed is show in grey

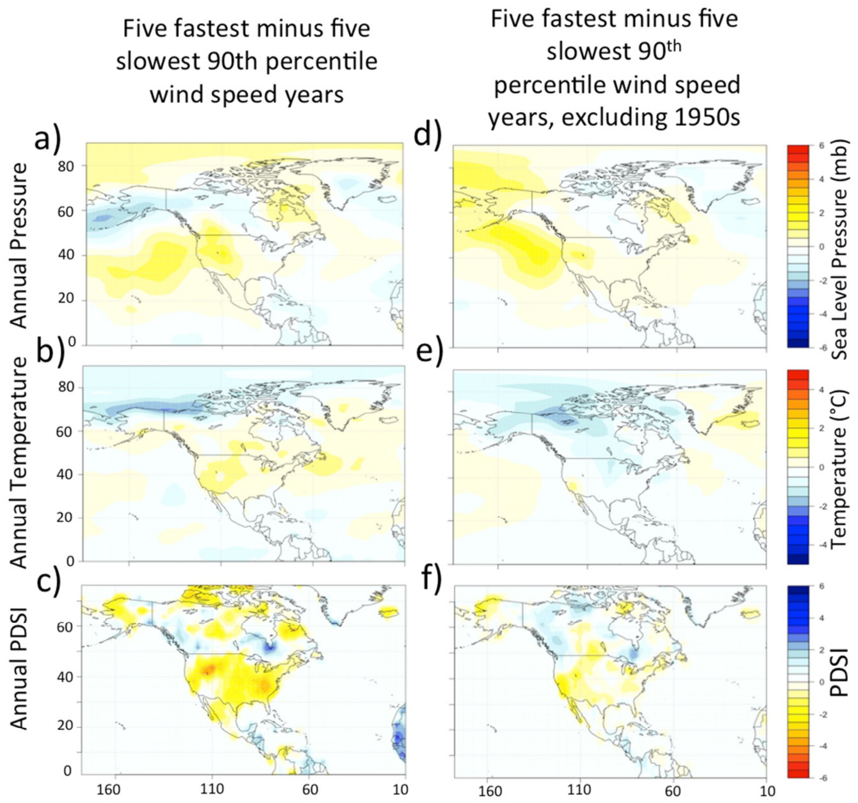

Figure A-4 Annual NCEP (a,d) sea level pressure (mb), (b,e) temperature (℃), and (c,f) PDSI anomalies comparing years with the five fastest (1952, 1953, 1954, 1955, 1988) and the next five fastest wind speeds years not in the 1950s (1961, 1964, 1971, 1996, 2008) with the five slowest (1963, 1973, 1975, 1995, and 2006) 90th percentile wind speeds estimated from 87 meteorological stations in the Mid-Continental USA