A Surface Wind Extremes ("Wind Lulls" and "Wind Blows") Climatology for Central North America and Adjoining Oceans (1979–2012)

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ABSTRACT

This study explores long-term deviations from wind averages, specifically near the surface across central North America and adjoining oceans (25°–50°N, 60°–130°W) for 1979–2012 (408 months) by utilizing the North American Regional Reanalysis 10-m wind climate datasets. Regions where periods of anomalous wind speeds were observed (i.e., 1 standard deviation below/above both the long-term mean annual and mean monthly wind speeds at each grid point) were identified. These two climatic extremes were classified as wind lulls (WLs; below) or wind blows (WBs; above). Major findings for the North American study domain indicate that 1) mean annual wind speeds range from $1–3 \, \mathrm{m \, s^{-1}}$ (Intermountain West) to over $7 \, \mathrm{m \, s^{-1}}$ (offshore the East and West Coasts), 2) mean durations for WLs and WBs are high for much of the southeastern United States and for the open waters of the North Atlantic Ocean, respectively, 3) the longest WL/WB episodes for the majority of locations have historically not exceeded 5 months, 4) WLs and WBs are most common during June and October, respectively, for the upper Midwest, 5) WLs are least frequent over the southwestern United States during the North American monsoon, and 6) no significant anomalous wind trends exist over land or sea.

1. Introduction

The Intergovernmental Panel on Climate Change defines a climatic extreme as an "occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" (IPCC 2012, p. 3). Most studies have concentrated on quantifying such extremes in terms of only two basic climatic variables, temperature and precipitation (Peterson et al. 2012), through examination of long-duration occurrences such as heat waves or droughts. For example, in meteorological studies, "drought" has been defined as "a period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance" (Glickman 2000, p. 238). While investigation of such long-term phenomena is critical, particularly in terms of a warming Earth (e.g., Svoma et al. 2013), the conceptual

scope of the "extremes" definition implies that other climate variables could be examined in a similar fashion.

The term "wind lull" is defined as "a marked decrease in the wind speed" (Glickman 2000, p. 845). If we adapt that definition for long-term surface winds, we can define a wind lull as an extended period of abnormally calm or weak surface winds. The concept of protracted weak or calm winds could exacerbate poor air-quality conditions (e.g., Chen and Xie 2013; Munir et al. 2013; Onat and Stakeeva 2013; Zhu and Liang 2013) or cause intermittent wind-farming energy generation (e.g., Archer and Jacobson 2007; Katzenstein et al. 2010). Conversely, prolonged periods of abnormally strong winds, referred to as "wind blows" in this study, can also be of societal and meteorological significance when considering "flash" droughts (e.g., Mozny et al. 2012) or general drought stress for crops (e.g., Maes and Steppe 2012), where elevated surface wind speeds accelerate evapotranspiration rates (W. Wang et al. 2012). Also, according to Katzenstein et al. (2010), the economy of wind farming is sensitive to long periods of above-normal winds. In addition, one major contributor to wildfire behavior is surface wind speeds, where extreme fire activity has been linked with both "wind
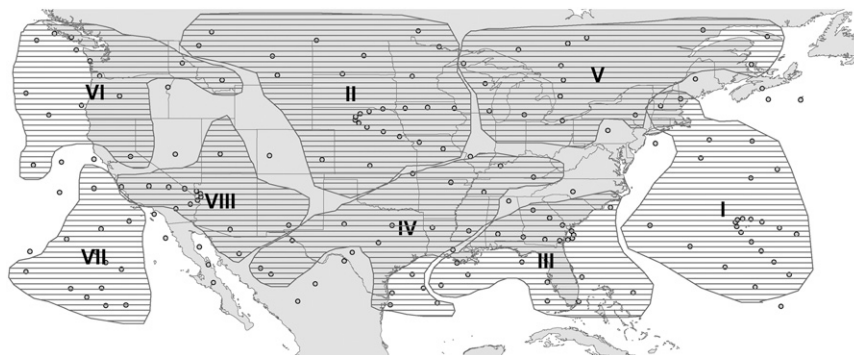
FIG. 1. The study domain, covering central North America and adjoining oceans. Boundaries are also given for eight PCA-identified wind regions (I–VIII) as discussed in the text. Circles indicate the 172 sampled grid points for the PCA analysis. The centroid for each region is identified by the location of the Roman numeral specified for each region (I: 33.8°N, 66.9°W; II: 44.8°N, 100.6°W; III: 29.6°N, 82.8°W; IV: 32.2°N, 95.5°W; V: 78.0°N, 45.1°W; VI: 44.5°N, 123.5°W; VII: 29.5°N, 123.8°W; and VIII: 35.1°N, 112.2°W).

driven'' and ''plume dominated'' wildfires that are influenced by periods of high or low winds, respectively (Diaz and Swetnam 2013). Another point concerns periods of severe wind-chill values occurring during the cold season caused by high winds (e.g., Peterson et al. 2014). Also, from a broad climatological viewpoint, establishment of long-term wind extremes may lead to new climate-change metrics (Peterson et al. 2012; Alexander et al. 2006) or at the very least may serve to aid in filling a knowledge gap regarding wind extremes that was noted by Vose et al. (2014) and may address North American wind speed uncertainty characterization (Archer et al. 2014).

In accord with these goals, our study identifies the long-term variations in the extremes of surface wind speed over central North America and adjoining oceans, including the contiguous United States. In fundamental terms, we provide an initial climatological assessment of surface wind lulls (WLs) and wind blows (WBs) by examining the historical frequency, mean duration, and magnitude of WL and WB events from 1979 through 2012.

2. Data

With the maturation of reanalysis methods (e.g., Mesinger et al. 2006), detailed long-term variations in wind climatic extremes can be identified. We consequently employ the high-resolution North American Regional Reanalysis (NARR) 10-m-elevation zonal (u) and meridional (v) wind climate datasets (Mesinger et al. 2006). The NARR results are considered to be improvements to the National Centers for Environmental Prediction Global Reanalysis (Kalnay et al. 1996) for the North American region by utilizing a higher-spatial-resolution 32-km grid with 45 vertical layers that are combined with the Regional Data Assimilation System

(Mesinger et al. 2006). In addition, the NARR incorporates 10-m wind observations into its reanalysis. The NARR 10-m wind speeds demonstrate good agreement with over 400 observation sites across the NARR domain with less than $-0.5\,\mathrm{m\,s^{-1}}$ bias (Mesinger et al. 2006).

Our research concerns central North America and surrounding water bodies. Our spatial domain extends from 60° to 130.0°W longitude and from 25° to 50°N latitude (Fig. 1). This domain is covered by 17 231 grid points from the NARR dataset, given its resolution of 0.3° latitude by ~0.3° longitude (dependent on latitude).

3. Mean near-surface winds

To establish definitions of long-term wind extremes, we emulate analogs to precipitation-extreme classification. For example, absolute values of rainfall are often not adequate to define a regional moisture deficit or surplus (e.g., according to the National Climatic Data Center, Yuma, Arizona, receives only 76.4 mm of precipitation per year but is not in perpetual drought). Therefore, it was necessary to establish the long-term mean annual wind speeds for every grid point of the NARR dataset (Fig. 2a) within the research domain to establish regional anomalous winds.

We observe a broad range in long-term mean annual wind speeds within our study domain (Fig. 2a). The highest mean annual wind speeds ($>7.0\,\mathrm{m\,s^{-1}}$) occur off the eastern and western coasts of North America, as previous research (Dvorak et al. 2010; Sheridan et al. 2012) has suggested. This result is due, for the west coast, to the land–sea pressure gradient that creates a persistent marine boundary layer (e.g., Dorman and Winant 1995; Dvorak et al. 2010; Jiang et al. 2008). The marine boundary layer is a strong inversion that is typically
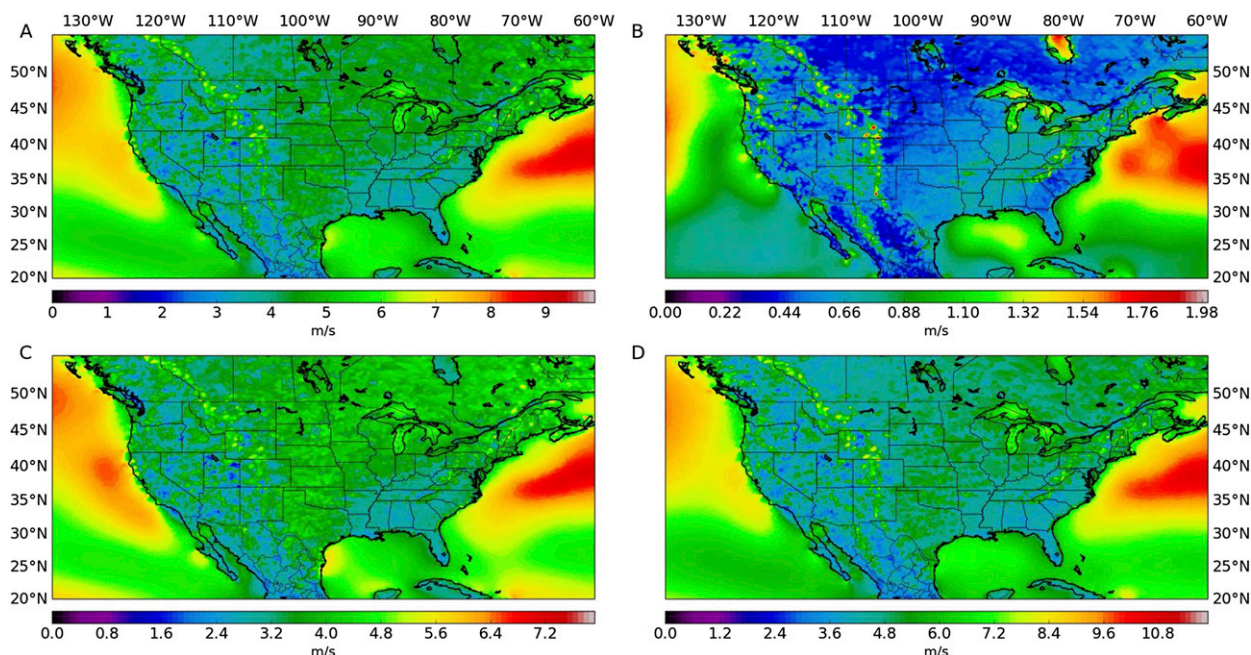
FIG. 2. Maps indicating (a) long-term mean annual surface winds (m s^{-1}) for the central North America region derived from the NARR 3-h, 10-m u- and v-wind datasets from 1979 to 2012; (b) the annual 1 std dev wind speeds (m s^{-1}); (c) the resultant maximum mean monthly wind speeds (m s^{-1}) required for WL conditions, where mean monthly wind speeds are at least 1 std dev below the long-term annual mean; and (d) the resultant minimum mean monthly wind speeds (m s^{-1}) required for WB conditions, where mean monthly wind speeds are at least 1 std dev above the long-term annual mean.

500 m above sea level and is caused by the cold ocean current running along the western coast of North America (Dvorak et al. 2010). Near the top of the inversion, higher winds become trapped and form a low-level jet that diminishes in intensity heading into open water away from the coastline (Jiang et al. 2008). In addition, along the California coast, wind speeds do increase during the summer months when the Pacific Ocean subtropical high begins to strengthen and expand toward the open Pacific. Such repositioning of the subtropical high enhances the winds within the marine boundary layer down the coast of California (Jiang et al. 2008). South of this region, Wang et al. (2011) note that variability in surface winds over the southeastern Pacific could be forced by variations in the Madden–Julian oscillation (MJO).

Off the Atlantic coast, greater wind speeds can likely be attributed to frequent low pressure system passages occurring between the autumn and spring months (Dvorak et al. 2012). Furthermore, sea breezes for coastal New England can be enhanced by the anticyclonic flow of the Bermuda–Azores subtropical high, especially in the warm season (Colby 2004). Coastal locations south of Long Island lack this sea-breeze enhancement as a result of relative positioning with the high pressure system (Dvorak et al. 2012). The abrupt drop in wind speeds found going inland from the two coasts is caused by the increased

surface roughness (higher friction) of land versus sea that decelerates surface winds (Braun et al. 1999).

The highest mean annual wind speeds for inland areas (5–7 m s^{-1}) are located along the Front Range of the Rocky Mountains, which is consistent with prior surface wind climatological studies (e.g., Balling and Cerveny 1984; Archer and Jacobson 2005). The elevated wind speeds are caused by the Rocky Mountains rising up to 4 km and being impacted by the prevailing westerlies (Barry 2008). Another contributing factor is the low-level jet that flows along the Front Range in response to intense heating of the elevated southern Rocky Mountains during the summer months (Higgins et al. 1997; Tang and Reiter 1984). Low-level jets are diurnal; that is, winds are typically nocturnally enhanced and are weakened during the day because of vertical mixing (e.g., Douglas 1995; Raman et al. 2011). Other factors increasing surface winds speeds along the Front Range, especially during the winter season, are associated with lee cyclogenesis (Schultz and Doswell 2000) and downslope chinook and bora wind formations (Barry 2008).

The largest areas of lowest mean annual wind speeds over land (2–4 m s^{-1}) at 10 m are found in the Intermountain West and the southeastern United States (Fig. 2a). Given the topographic configuration of the Great Basin, there are numerous sheltered valleys, as well as a lesser occurrence of mature cyclones. Valley
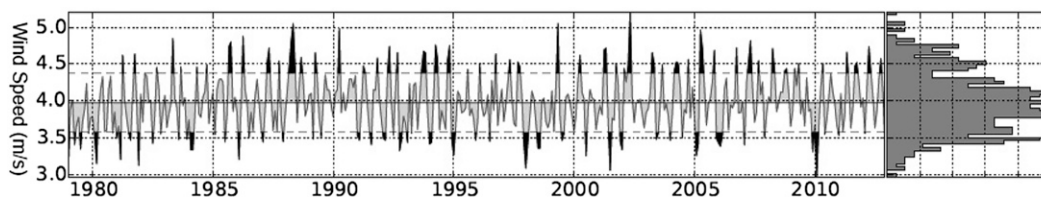
FIG. 3. Mean monthly wind speed ($m\,s^{-1}$) from 1979 to 2012 for the grid point closest to Hallock. The center horizontal line on the time series indicates the long-term annual 10-m wind speed. Dashed horizontal lines on the time series indicate the 1 std dev wind speeds above (WB) and below (WL) the long-term mean annual wind speed; extreme events are highlighted in black. The graph on the right indicates the overall distribution of wind events.

wind speeds within the Rocky Mountains can be 75% lower than at surrounding peaks and ridges (Barry 2008). Similar results concerning the above-mentioned areas of diminished winds were found by Archer and Jacobson (2003) on the basis of mean annual wind speeds for 10-m observation sites within the United States. The decreased wind speeds in the Southeast are likely caused by inherent lower-elevation terrain and high surface roughness, especially toward the more vegetated southeastern United States (e.g., Zhang et al. 2012). Also influencing the decreased wind speeds is the higher atmospheric stability associated with the Atlantic-based Bermuda–Azores high pressure system that may expand into the southeastern United States, particularly during the summer season (e.g., Svoma et al. 2013; Zhu and Liang 2013).

We defined our surface wind extremes (WLs and WBs) on the basis of the standard deviation of the long-term mean annual wind speed at each location from a 408-month period of record. For this study we have explicitly defined a *wind lull* as a mean monthly 10-m wind speed that is at least 1 standard deviation below the calculated long-term mean annual 10-m wind speed during the study period for a grid point. Conversely, we have defined a *wind blow* as a mean monthly 10-m wind speed that is at least 1 standard deviation above the calculated long-term mean annual 10-m wind speed during the study period for a grid point. This procedure follows Klink (2007), who used standard deviations to distinguish monthly 70-m wind speed anomalies for Minnesota from 1995 to 2003.

To verify this concept with past research, we identified a grid point close to a specific location that Klink (2007) evaluated for her wind-abnormality study, specifically Hallock, Minnesota. Our analysis of wind variability for the time period 1995–2003 at the closest NARR grid point to Hallock shows similarities to Klink's research. For example, both studies indicate periods of abnormally weak winds from 1997 to 1998 with anomalously strong winds occurring between 2001 and 2002 (Fig. 3). Klink (2007) linked weaker (stronger) winds over Minnesota with lower (higher) 500-hPa gradients and a negative (positive) Arctic Oscillation. This agreement indicates that our

definitions of wind lulls and blows as based on standard deviations from the mean are applicable at a specific location and permit us to adapt them to all grid points of our NARR domain.

4. Near-surface wind speed variability

Regional wind speed variability was determined by the standard deviation from the long-term mean annual wind speed (n equal to 408 months) across our domain (Fig. 2b). High variability is evident in the Pacific Ocean (standard deviations between 1.3 and $1.5\,m\,s^{-1}$), southern Wyoming ($1.5–1.8\,m\,s^{-1}$), the Great Lakes ($0.88–1.3\,m\,s^{-1}$), Hudson Bay ($>1.76\,m\,s^{-1}$), and off the Atlantic seacoast ($1.3–1.8\,m\,s^{-1}$), with isolated high variability along the Front Range of the Rockies, in the coastal Northwest, and in the Appalachians. In general, wind speed variability would be caused by seasonal changes in the latitudinal temperature and pressure gradient that intensifies over North America during winter and spring and diminishes from summer into autumn (Klink 1999; Li et al. 2010), but other regional factors that affect wind speed fluctuations may be present such as ocean-current variability, topography, and seasonal ice cover. For example, wind variability for the northern Pacific Ocean is related to the strength and positioning of the Pacific high pressure system, affecting the low-level jet associated with the marine boundary layer, particularly from northern to southern California (e.g., Jiang et al. 2008), and altering the storm track for the Pacific Northwest (e.g., Dorman and Winant 1995). Marine boundary layer winds are strongest when the Pacific high strengthens and moves northward during the summer months and away from the coast (Jiang et al. 2008). This movement acts to pull the storm track to the north of the Pacific Northwest and thereby diminishes cyclonic activity (and higher winds) for that region (Dorman and Winant 1995).

Over land, largest variability, as with highest annual wind speeds, is found along the Front Range of the Rockies and the Great Lakes region. As mentioned previously, the latitudinal temperature and pressure gradients

tend to relax during the summer months. This has the effect of weakening the prevailing westerlies and would lower the overall wind speeds when compared with the other seasons (e.g., Barry 2008). Adding to wind variability, contrasting air densities in complex terrain create diurnal mountain–valley wind systems that involve katabatic and anabatic winds (Barry 2008). For the Great Lakes area, winds are enhanced because of land–sea breezes, with the strongest wind occurring over the open water (Li et al. 2010) as a result of decreased friction (e.g., Stull 2000). During the winter months, land–sea breezes are shut down as ice expands on the surface of the lakes, but decreased friction associated with ice and snow landscapes would ultimately increase overall wind speeds in and around the Great Lakes region (Li et al. 2010).

The lowest variability in wind speeds is evident in an expansive area extending from central Canada southward into the Great Plains and the southeastern United States. In general, standard deviations range between 0.22 and 0.66 m s^{-1}. This consistency in wind speeds is likely due to 1) the lack of confounding variables (e.g., topography and land/sea frictional effects) for the Canadian provinces and northern plains and 2) the semipermanent presence of the Bermuda–Azores subtropical high for the southern plains and southeastern United States (e.g., Diem 2006; Katz et al. 2003; Zhu and Liang 2013).

5. Wind lulls and wind blows

When we combine the NARR mean annual wind speeds (Fig. 2a) and the annual wind speed variability (Fig. 2b), we can establish threshold wind speeds across our domain for definitions of WLs and WBs. For this initial study of the WL and WB concept, we first focus our definitions by using annual mean wind speeds in a manner to give broad insight into the general characteristics for expected winds across the central North American region. We subsequently apply WL–WB definitions to monthly wind speeds for determining seasonal characteristics (section 6).

A wind lull is defined as an event for which the mean monthly wind speed is 1 standard deviation *below* that grid point's long-term annual mean. When using our definitions that involve annual mean and standard deviations, the wind speed thresholds for WLs across our study domain ranged from 1.6 (Great Basin) to 7.5 (mid-Atlantic) m s^{-1} (Fig. 2c). Conversely, a wind blow is defined as an event for which the mean monthly wind speed is 1 standard deviation *above* that grid point's long-term annual mean. The wind speed thresholds for wind blows across our study domain ranged from 2.0 (Great Basin) to 11.0 (mid-Atlantic) m s^{-1} (Fig. 2d).

To address attributes for long-duration wind-extreme-events, first we define the frequency of WLs or WBs. Second, we determine the mean time span for WLs and WBs, which represents the typical residence time for previous WL or WB events at each grid point. Third, we consider the potential magnitude of wind extremes by examining the maximum duration in the study period for a grid point when WL or WB criteria were met.

Because our analysis was conducted on the entire domain of 17 231 grid points over the temporal range of monthly values from January 1979 to December 2012, we cannot in this paper examine and discuss each grid cell for its specific variability in WLs and WBs. Therefore, to regionally examine WLs and WBs over the domain we reduced the domain to a more manageable set of eight classes from which regional similarities and differences in WLs and WBs could be drawn. This was accomplished through a principal components analysis (PCA; Richman 1986) for 172 sampled points (see Fig. 1) from the entire domain. The nearest-neighbor ratio R for the 172 sample grid points was 1.23, indicating that the distribution fell between random ($R = 1$) and uniform ($R = 2.13$) with $R = 0.0$ indicating a clustered sample.

PCA was applied to a matrix of 408 rows, 1 for each month from January 1979 to December 2012, and 172 columns, 1 for each of our sampled points. We selected an eight-component solution (to give us a reasonable number of regions) and conducted an "equimax" rotation. The amount of variance explained by each component ranged from 8.4% to 11.6%, and combined they accounted for 78.3% of the variance in the matrix of wind speeds.

For each of the components, we mapped the grid points having loadings above +0.5 or below −0.5. The loadings for each component were skewed either positively or negatively, and therefore the eigenvectors did not have loadings above 0.5 and below −0.5. This precludes any eigenvector from having a station that is negatively related to other stations in that region. The results are shown in Fig. 1 where these eight wind regions compose the majority of the study area. Again, we note that the wind lull/blow computations discussed in the next section were conducted on the entire domain of 17 231 grid points. These eight regions, extracted from PCA of the original wind data, are provided as an objective means of broadly discussing variations in wind lulls and wind blows across the entire study domain. As an aid to the discussion of WLs and WBs, we selected the centroid locations of each region and constructed time series plots of the wind speed variability over the temporal domain of the NARR dataset (1979–2012) (Fig. 5, described in more detail below).
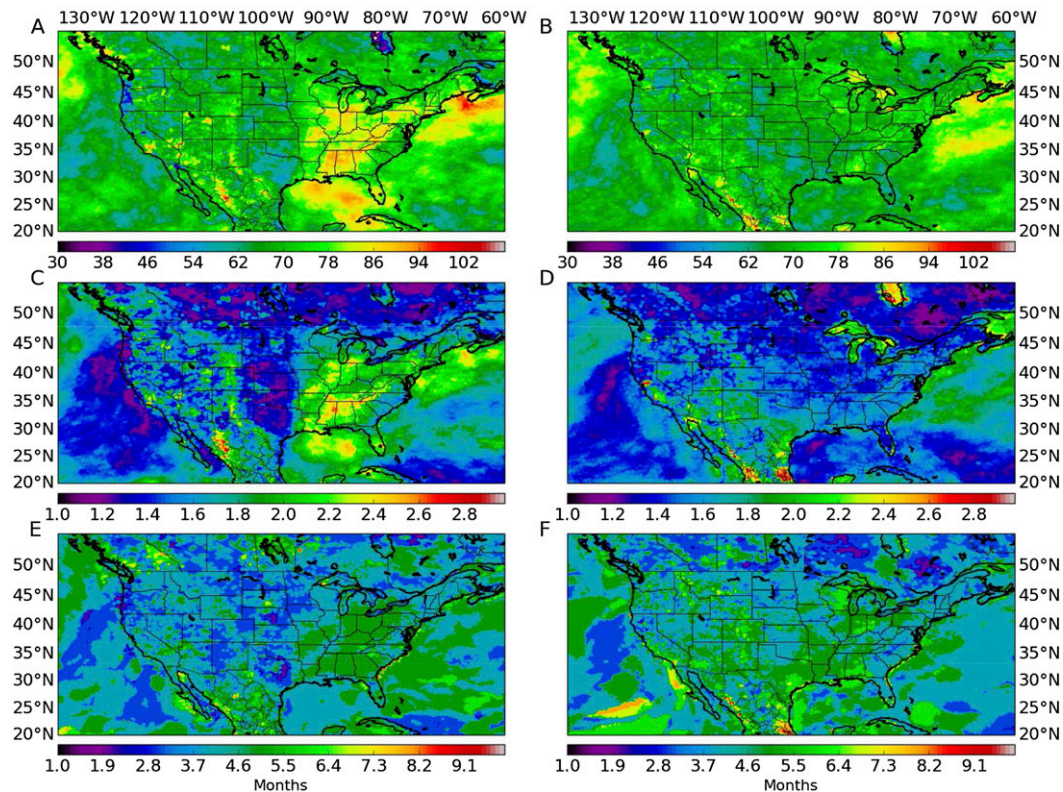
FIG. 4. Maps showing results for three 10-m wind-extreme analyses for central North America: 1) frequency, or how many months during the period of record that would have been classified as either (a) a WL or (b) a WB event; 2) mean duration, or the average monthly residence time for (c) WL and (d) WB events; and 3) magnitude of (e) WL and (f) WB events that correspond to the longest consecutive monthly period when WL and WB criteria were met.

a. Frequencies of wind lulls and wind blows

Using our calculated wind speed extremes criteria, we determined the frequency of monthly values above and below defined thresholds that yielded the historical count for WLs (Fig. 4a) and WBs (Fig. 4b) across central North America. The most months experiencing WL conditions are, for the entire domain, found offshore from Maine with a maximum of more than 100 total months of wind lulls from a 408-month record. Over land, areas with the most months experiencing WL conditions extend from the Great Lakes southward to the Gulf Coast with over 80 months of wind lulls (19.6% of total). Conversely, the highest number of months experiencing WB conditions, for the entire domain, is an isolated region in the Mexican state of Sinaloa with over 102 months of WB. Most of the domain, however, has experienced at least 75 months of wind blows (18.4% of total) since 1979.

With regard to the total occurrence of WL events, the primary PCA region of highest WL instances is region III, which can be broadly termed the "southeastern United States." The time series of wind events for region III's centroid (29.6°N, 82.8°W) is given in Fig. 5c. In comparison with the other seven centroid time series, region III does demonstrate a higher frequency of monthly wind speeds below the WL threshold (74 months), which is likely in part linked to the seasonal influence of the subtropical high. Recent studies (e.g., Li et al. 2010; Svoma et al. 2013) have demonstrated an expansion of the subtropical high pressure belt. Such an expansion could account for a greater predominance of WL events in and around the southeastern United States. It is interesting that this region has some of the lowest observed WB occurrences (60 months) relative to other regional centroids, which when combined with a tendency for increased WLs, may point to vulnerability in potential wind energy.

The PCA region most reflective of highest WB occurrence (77 months) is region I ("open waters of the North Atlantic Ocean"). The time series of wind events for region I's centroid (33.8°N, 66.9°W) is given in Fig. 5a. Relative to the other seven regions, region I has consistently observed recurring WB periods at regular intervals during the winter season, suggesting an interseasonal oscillation at work. This is reasonable given that, geographically, the offshore Atlantic has the largest
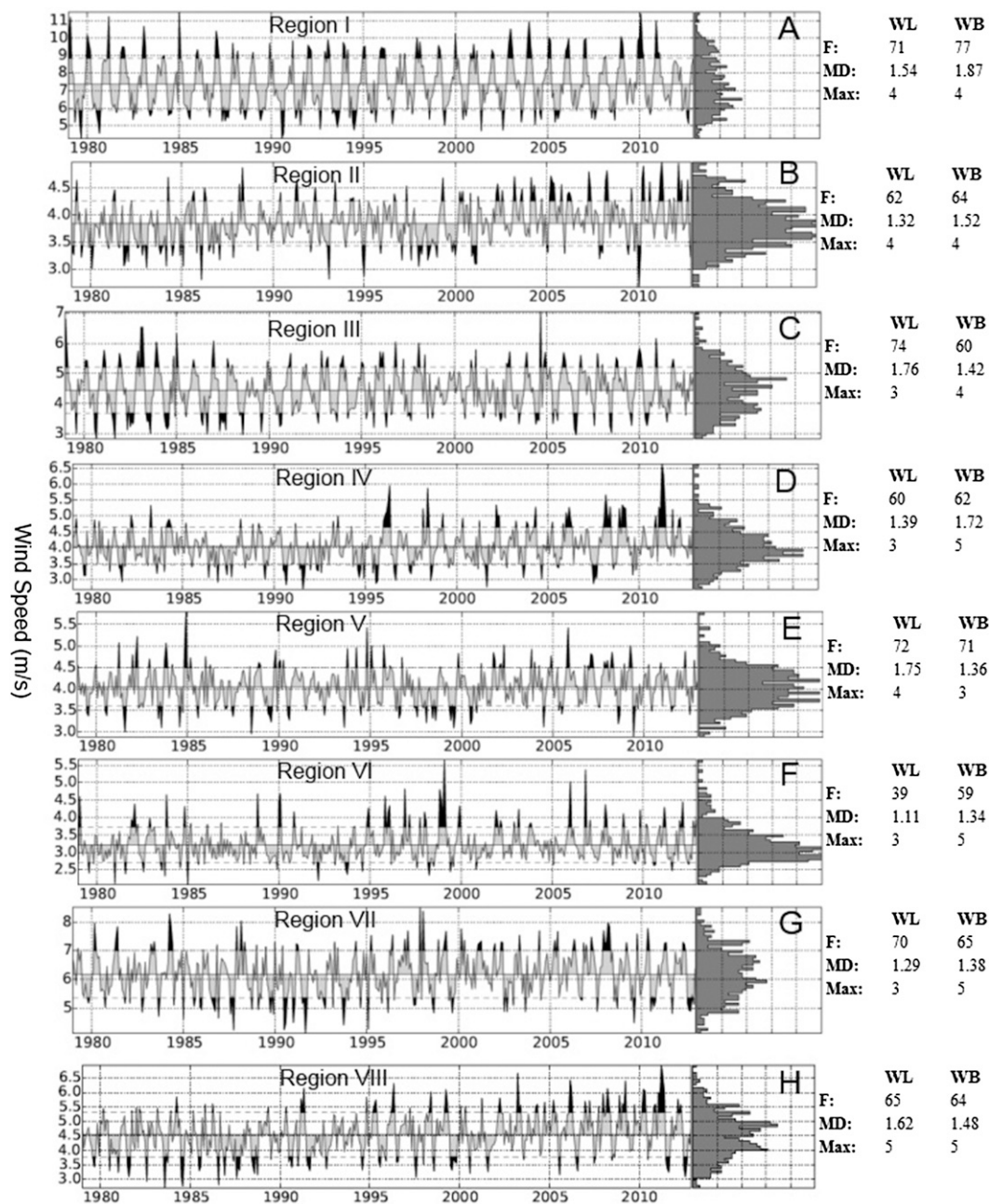
FIG. 5. Mean monthly surface wind speeds (m s^{-1}) from 1979 to 2012 for the centroid locations of eight identified wind regions in central North America (see Fig. 1). The center horizontal line on the time series indicates the long-term mean annual 10-m wind speed. Dashed horizontal lines on the time series indicate the 1 std dev wind speeds above (WB) and below (WL) the long-term mean annual wind speed; extremes are highlighted in black. The graph on the right indicates the overall distribution of wind events. Results for the three wind-extreme analyses [i.e., frequency (F), mean duration (MD), and historical longest (Max)] are shown at the far right of each regional time series.

variability in mean monthly wind speeds in our study domain (see Fig. 2b). Two significant synoptic features at work in this region to affect surface wind speeds would be the strength and presence of the warm-season-dominant Bermuda–Azores subtropical high and positioning of the storm track for the cool season (Dvorak et al. 2012). As a result, cool-season WBs for region I are likely due to frequent low pressure systems associated with an active and persistent storm track that appears to have varied little since 1979.

b. Mean duration of wind lulls and wind blows

The mean lengths of WL and WB episodes are shown in Figs. 4c and 4d, respectively. In terms of mean duration of WLs in our NARR domain, PCA region III not only has the most frequent WLs but also demonstrates the longest WLs, averaging 1.76 months per occurrence. Similar to the potential cause of frequent WLs discussed previously, the longer-duration WLs for the southeastern United States are likely influenced by the increasing presence of the Bermuda–Azores subtropical high in the area (e.g., Svoma et al. 2013).

Otherwise, WLs in the "upper Great Plains" (PCA region II: centroid location 44.8°N, 100.6°W), the "northwestern United States" (PCA region VI: centroid location 44.5°N, 123.5°W), and "southeastern North Pacific" (PCA region VII: centroid location 29.5°N, 123.8°W) demonstrate the most limited mean WL durations for the domain (1.32, 1.11, and 1.29 months, respectively) (Figs. 5b, 5f, and 5g). This suggests that wind-power industries located in these regions are less likely to experience extended periods of lower-than-normal wind speeds. This conclusion matches with current plans for increased power generation in those areas [e.g., Klink (2007) for the upper Great Plains, Sailor et al. (2008) for the northwestern United States, and Jiang et al. (2008), offshore California].

For WBs in our NARR domain, the region showing overall highest mean durations is region I (1.87 months). The mean duration length of nearly 2 months aligns with the finding described previously that the open waters of the North Atlantic are at an elevated risk for stronger winds and WBs during the winter period. Also, region VIII, which can be termed "the Southwest," appears to have a seasonal WB signature because WB events tend to have a 1.48-month average. The typical lengths for WB events correlate well with the temporal bounds associated with the North American monsoon seasonal cycle (e.g., Sampson and Pytlak 2009). This is demonstrated when considering that summer surface winds over the southwestern United States can be greatly influenced by the low-level jet originating from the Gulf of California (Adams and Comrie 1997; Douglas 1995). The time series of wind events for region VIII's centroid (35.1°N, 112.2°W) is given in Fig. 5h.

c. Duration extremes for wind lulls and wind blows

The locations of the longest-duration WL and WB events are displayed in Figs. 4e and 4f, respectively, both of which indicate that a vast majority of the study domain failed to observe a WL or WB event lasting longer than a 5-month period since 1979. In fact, all eight PCA regions seem to concur with this aspect, as historical WL or WB magnitudes, for either extreme, are limited to 3–5 months (Fig. 5). It seems that atmospheric mechanism(s) contributing to the unusual enhancement or depreciation of regional surface wind speeds across North America do not appear to last much beyond 5 months. There are clearly localized exceptions, particularly over Mexican territories. Most exceptions are very limited in spatial scale, and exploring each in detail goes beyond the intended scope of this paper.

For historically long WB periods, there was a large swath in the open waters southwest of California that observed an extended stretch of WBs (i.e., over 7 months at most locations). PCA region VII's (southeastern North Pacific) time series of wind events did have an event of particularly long duration in 2008, recording 5 months of WL conditions. Wang et al. (2011) demonstrated a pronounced peak wind event in 2008 for the equatorial region just south of this area that matches with this WB event. They attribute the variability in the equatorial winds of the eastern Pacific to variations in the MJO. Such equatorial variability may propagate northward and influence this region.

6. Seasonality of wind lulls and wind blows

Because of the flexibility of the WL and WB concept, alternative definitions (such as involving a given month's long-term mean and standard deviation rather than the annual mean and standard deviation) can be employed that might be of more applicability to a climatologist rather than to an applied user such as one involved with wind-power generation. For example, by using annual mean wind speeds alone, important seasonal and monthly characteristics may not be revealed in our analyses. To touch on this seasonal aspect, we have also developed time series of month-versus-same-month anomalies (e.g., the 1979 mean January wind speed anomaly derived from the long-term mean January standard deviation) for our eight separate regions (Fig. 6). The NARR fortunately provides a long-term monthly-mean dataset (also provided via the Earth System Research Laboratory Physical Sciences Division) with seasonal values for each grid point, making the seasonal-trend removal trivial.

This analysis is meant to give the climatological behavior of prior periods when unusually enhanced or diminished wind activity has occurred on a month-by-month basis. Of course, a specific caveat for applied users other than climatologists is that this climatological approach creates products in which the y-axis values are now given in deviations from means rather than in units of raw wind speed. These monthly-based time series shown in Fig. 6 will uniquely reveal 1) whether any trend toward either increased or weakened winds is occurring
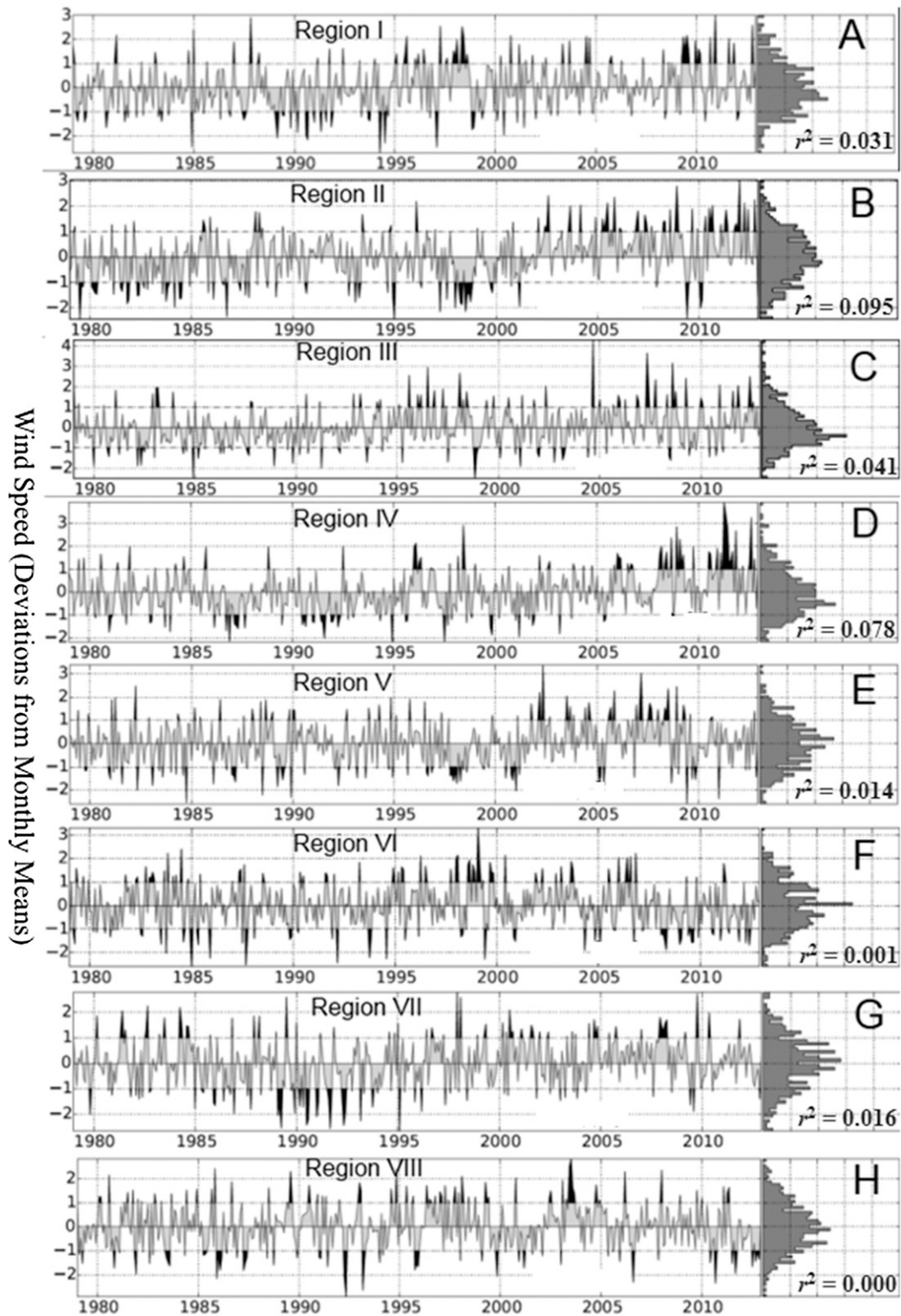
Fig. 6. Mean monthly surface wind speed anomalies (deviations from monthly means) from 1979 to 2012 for the centroid locations of eight identified wind regions in central North America (see Fig. 1). The center horizontal line on the time series indicates the long-term mean monthly 10-m wind speed. Dashed horizontal lines on the time series indicate the 1 std dev wind speeds above (WB) and below (WL) the long-term mean monthly wind speed; extremes are highlighted in black. Temporal trend (linear regression against time) correlations are given for each region (r^2 values). The graph on the right indicates the overall distribution of wind events.

TABLE 1. Occurrences of WLs and WBs, as well as the total (T = WL + WB), for the eight (I–VIII) regions defined in this study, by month.

Month	I WL	WB	T	II WL	WB	T	III WL	WB	T	IV WL	WB	T	V WL	WB	T	VI WL	WB	T	VII WL	WB	T	VIII WL	WB	T
Jan	5	7	12	3	4	7	7	5	12	7	5	12	7	5	12	5	5	10	6	9	15	5	7	12
Feb	7	6	13	5	6	11	5	6	11	5	6	11	6	7	13	4	4	8	4	4	8	6	6	12
Mar	7	5	12	7	5	12	6	6	12	6	12	4	6	3	9	7	5	12	4	6	10	5	7	12
Apr	4	7	11	5	7	12	6	5	11	3	5	8	5	4	9	6	6	12	7	5	12	7	5	12
May	5	7	12	7	6	13	2	3	5	5	5	10	4	5	9	6	8	14	6	6	12	5	6	11
Jun	7	5	12	4	7	11	6	5	11	3	4	7	5	6	11	4	5	9	7	5	12	7	7	14
Jul	5	5	10	5	5	10	5	4	9	6	8	14	5	5	10	5	5	10	4	3	7	3	6	9
Aug	6	6	12	7	7	14	4	4	8	4	5	9	8	7	15	6	4	10	6	7	13	5	4	9
Sep	5	5	10	6	6	12	4	2	6	6	7	13	6	9	15	4	6	10	4	6	10	3	7	10
Oct	6	6	12	7	4	11	5	8	13	6	7	13	8	7	15	7	5	12	8	6	14	5	7	12
Nov	6	4	10	7	6	13	4	6	10	7	6	13	8	5	13	5	6	11	7	5	12	6	3	9
Dec	3	3	6	6	5	11	4	5	9	6	4	10	4	5	9	7	6	13	5	4	9	7	5	12

since 1979, 2) whether WLs/WBs are tied to certain seasons, and 3) whether these wind attributes differ among regions I–VIII. All three aspects are pertinent for, but not limited to, anticipating wind speed uncertainty for wind energy as well as dispersion for air-quality purposes.

a. Trends for wind speed anomalies (1979–2012)

We applied linear regression to each region's deseasonalized-anomalies time series to help to determine whether a positive, a negative, or no trend exists in anomalous wind speeds over the period of record. This statistical method revealed no statistically significant trends being observed at any of the eight regions encompassing the central North American study domain since 1979. All regions, except region VI, had positive correlation coefficients r ranging from 0.021 to 0.307 (-0.035 for the northwestern United States), but overall explained variances (r^2 values) were very low, from near 0% in the southwestern United States up to only 9.5% for the upper Midwest (see Fig. 6 for region-specific values).

Although confidence is low for any notable trend for wind speed anomalies across the eight regions since 1979, there are still some interesting near-term trends (last 5–10 yr) worth mentioning that stand out for some areas as based on visual inspection of their time series shown in Fig. 6. For instance, the open waters of the Atlantic Ocean (Fig. 6a) have been characterized by intermittent periods for both WLs and WBs, with a recent tendency to observe more months having greater positive anomalies. Results from Young et al. (2011) did note an increasing trend in monthly-mean wind speeds (between 1991 and 2008), especially for wind speeds in the 99th percentile, over the oceanic regions of the world, including the North Atlantic. Conversely, prior research has indicated a decreasing trend in annual mean wind speeds (Pryor et al.

2009). The northwestern United States (Fig. 6f) is unique relative to the other eight regions in that it is the only region indicating a sudden propensity toward negative monthly wind speed anomalies. On the other hand, the upper Midwest (Fig. 6b) and southern Great Plains and lower Mississippi River valley (Fig. 6d) show a clear inclination for increased duration (i.e., sequential months), interannual frequency, and magnitude of observed positive anomalies, especially for region IV. The regions that have maintained typical month-to-month variability with no apparent bias include the southeastern United States (Fig. 6c), the southeastern North Pacific (Fig. 6g), the Great Lakes region (Fig. 6e), and the southwestern United States (Fig. 6h).

b. Region I (open waters of the North Atlantic Ocean)

On a seasonal basis for region I, similar numbers of WLs and WBs for any given month have occurred since 1979 (Table 1). It is clear, however, that during the early winter large wind speed anomalies are relatively rare; only six cumulative wind lulls and wind blows are evident for December between 1979 and 2012. By January and through early spring, higher variability in wind speed is apparent as the number of WL and WB occurrences doubles from what has historically been observed in December. As the year heads into mid- to late spring (i.e., April and May), negative wind speed anomalies tend to dominate. The rest of the year indicates increased but equal recurrences for both WLs and WBs. This result suggests that over the open waters of the Atlantic Ocean stable wind speeds can be expected during the early-winter period, with higher variability possible for other months of the year that is likely associated with 1) the strength and position of the Bermuda–Azores high (Diem 2006; Katz et al. 2003), 2) storm-track variation influenced by El Niño–Southern Oscillation (Hirsch et al. 2001) and the North Atlantic Oscillation (Y.-H. Wang

et al. 2012), and 3) frequency of tropical cyclone passages (Keim et al. 2004; Mei et al. 2014). A better understanding behind seasonal wind variability for this region and related causes will be vital for assessing wind-energy potential offshore from the U.S. east coast (e.g., Archer et al. 2014).

c. Region II (upper Midwest)

The winter period for the upper Midwest during January has historically been marked by greatly decreased instances of either abnormally strong or weak winds, relative to the rest of winter. The rarity in the number of WLs and WBs demonstrates that major deviations from January mean wind speeds are likely not governed by interannual mechanisms but rather possibly by interdecadal climatological oscillations. Indeed, Lareau and Horel (2012) indicate that El Niño and La Niña are linked to variability in the jet stream across the continental United States during the winter season, in which a zonal southern storm track is correlated with El Niño events and an amplified northern-favored storm track position occurs during La Niña periods.

June and October stand out because they are the only periods that have relatively atypical WL-versus-WB abnormalities, with early summer observing greater WL instances and October having more WBs. Summer WLs are likely tied to weaker winds under the Bermuda–Azores high (e.g., Zhu and Liang 2013) and autumn WBs are associated with an active storm track (e.g., Lareau and Horel 2012). Otherwise, similar WLs and WBs ranging between five and seven instances over the period of record have occurred.

d. Region III (southeastern United States)

Region III exhibits the least abnormality when compared with the other seven regions in our study on the basis of the cumulative WLs and WBs throughout the historical record (i.e., 115 total WLs and WBs as compared with a range from 132 to 140 among the other seven regions). As a result, deviation from mean monthly wind speeds is less common for the southeastern United States. An interannual pattern in WL and WB activity is apparent, however. Beginning in autumn around October and lasting through the winter months, WLs are much more common. This has consequences for air quality as periods of weak winds resulting in stagnation combined with cool-season inversion formation may lead to the accumulation of pollutants (e.g., Gillies et al. 2010; Wu et al. 2013), especially over metropolitan areas. After April, observed WLs and WBs drop off sharply. In general, from late spring through early autumn one observes reductions in both WL and WB counts. Of interest is that there is a noticeable spike, however, in wind speed

variability during June that does not continue into the summer. This could be related to the strength and position of the Bermuda–Azores high at that time; its presence is known to create stagnation events over the Southeast (Zhu and Liang 2013). The fact that there are abrupt increases and decreases in potential wind speed variability during the year (e.g., April vs May and September vs October) indicates that seasonal weather patterns influencing wind speeds across the Southeast are likely prevalent on an annual basis and tend to establish themselves quickly.

e. Region IV (southern Great Plains and lower Mississippi River valley)

There appears to be little inclination toward either WLs or WBs throughout the year for the southern Great Plains region and lower Mississippi River valley. The range between WLs and WBs for any given month of the year is at most two (Table 1). The autumn, winter, and early-spring seasons do mark a stretch of higher instances for extreme deviations from normal (i.e., 10–13 combined WLs and WBs being observed for each month from September through March). During the summer, fluctuations between the numbers of wind episodes from month to month have been large. For example, extremes are relatively rare in June (seven combined WLs and WBs), but then double and are more prevalent than in any other month in July (14 combined WLs and WBs). This has implications for wind-energy output. Recent research done by Louie (2014) demonstrated that power output from wind-energy plants tends to reach a minimum during the summer months, making potential WLs at this point in the year more likely to have greater consequences. With the exception of July, April–August are more likely to experience wind speeds within expected normal (i.e., within 1 standard deviation of the monthly mean).

f. Region V (Great Lakes region)

This region stands out with the most occurrences of monthly wind-extreme events, with 140 combined WLs and WBs. December and the spring season (March–May) represent the most stable months in terms of lower counts for anomalously heightened or weakened winds. Past WL incidents reach a minimum during this time, with only four being observed for both December and May. In addition, WBs are not as common and historically are very unusual for March, with only three being recorded. Conversely, late winter and from August through autumn are punctuated by much greater variability. A majority of months in this span have double to triple the number of WLs and WBs relative to each respective wind extreme's monthly minimum. Wind lulls during this span ranged

from five to nine, peaking in September, whereas WBs varied between six and eight for a given month. Similar to the two Midwest regions, seasonal energy output derived from wind-farming operations is lower during summer (Louie 2014), placing these areas at increased susceptibility for a diminished power supply under active WLs.

g. Region VI (northwestern United States)

As the winter season progresses in this region, there are fewer observed wind-extreme events. In fact, toward the end of winter in February, total months having anomalously mean wind speeds reach a minimum at 8 combined WLs and WBs (four each) versus 9–14 for other months. For WBs, this finding is somewhat at odds with current research conducted by Vose et al. (2014), in which an increase in extratropical storm activity in terms of frequency and intensity during the cold season was noted since 1979. It is certainly possible that, although storms are becoming more prevalent in this region, the overall adjustments to mean monthly wind speeds necessary to reach our defined WB criteria are not occurring. A pronounced increase in WLs and WBs is then apparent for the spring season. The transition to summer and continuing into early autumn represents the second-most stable period of the year, with June rivaling February in terms of cumulative WLs and WBs (four and five, respectively) occurring between 1979 and 2012. This makes sense given the poleward shift in the jet stream expected during this period (Dorman and Winant 1995).

The month with the highest number of WBs is May at eight events. Other months ranged between only four and six WBs. Of interest is that much greater annual variability is evident for WLs. Wind lulls reach a maximum of seven episodes in December, March, and October and a minimum of four in February, June, and September. This indicates that for the northwestern United States either multiple seasonal mechanisms may be controlling periods of anomalously low wind speeds or a single recurring intra-annual pattern may be at work.

h. Region VII (southeastern North Pacific)

The southeastern North Pacific has two distinct periods that demonstrate a lack of prior wind extremes relative to the rest of the year. They are late winter (February) and the middle of the summer season (July). On the other hand, January and October highlight spans during which wind speeds deviating significantly from normal are more probable. The monthly WL count variation is from four (February, March, July, and September) to eight (October), whereas WB instances are between three in July and up to nine for January. The WB-dominant month of January (i.e., nine WBs vs six WLs) appears to be the only time when a potential bias

for either positive or negative anomalies occurs. This finding does support results from the research of Vose et al. (2014) that indicate that cool-season storm systems have trended higher in frequency and duration over this area. All other months have historical WL and WB counts within two or less of each other.

i. Region VIII (southwestern United States)

Overall, this region has the potential to be highly variable in either positive or negative wind speed anomalies for most of the year. The exception is during the mid- to late summer (July and August). The 2-month duration of decreased WLs correlates well with the recurring North American monsoon seasonal cycle (Adams and Comrie 1997; Sampson and Pytlak 2009). As the monsoon develops, a general increase in regional winds can be expected (e.g., Tang and Reiter 1984; Adams and Comrie 1997), but the actual onset of the monsoon can be highly variable over the Southwest (Sampson and Pytlak 2009), along with the positioning and strength of the monsoon 500-hPa subtropical high circulation between June and September (e.g., Carleton 1986; Ellis and Hawkins 2001). This means that a given monsoon season may be early, intermittent, or extended.

This would help to explain why the transition months (i.e., June and September) have shown a greater frequency of significant deviations from normal wind speeds than have July and August (see Table 1). These findings indicate that this region is greatly influenced by this interannual phenomenon. Outside of the monsoon season, stronger winds would be reliant upon passing weather disturbances following a storm track that is periodically positioned far enough southward to affect the Southwest (e.g., Lareau and Horel 2012).

7. Conclusions

Building upon the concepts of long-duration extremes associated with temperature (cold waves and heat waves) and precipitation (drought and flood), we have developed an applicable classification scheme for near-surface winds. In this study we have constructed a historical climatological description for near-surface wind extremes for central North America and adjoining oceans, including the contiguous United States, from 1979 to 2012 using the North American Regional Reanalysis 10-m u and v wind datasets. We have defined events, which we have termed wind lulls and wind blows, as the monthly-mean wind speeds that are 1 standard deviation below or above that location's long-term mean annual wind speed. When applying our definition, it was possible to identify the spatial frequency, mean longevity, and magnitude of surface wind-extremes events that have occurred across

the United States and vicinity for the past three decades. In addition, a separate analysis was conducted that modified our definition to determine WLs and WBs by using the long-term mean monthly wind speed instead. This allowed us to identify relevant regional trends for anomalous winds along with seasonal characteristics that were potentially masked using the former method.

Major findings using the long-term annual-mean definition include the following: 1) a wide range of long-term mean annual wind speeds exists, spanning from 1–3 (Intermountain West) to over $7 \, \mathrm{m \, s^{-1}}$ (offshore the East and West Coasts), 2) from the time domain of 408 months, a maximum of nearly 20% of all months experienced WLs (in the southeastern United States) and a maximum of 25% of all months experienced WBs (in western Mexico), 3) long mean-duration WLs tended to occur in the southeastern United States and longer mean-duration WBs are prevalent over a large area of the open waters of the North Atlantic Ocean, 4) long WLs/WBs for most grid points in this study have historically not extended past 5 months, and 5) specific regional differences in the intensity, frequency, and duration of WLs and WBs can be identified.

Meaningful insights utilizing the long-term monthly-mean definition are as follow: 1) There is statistical evidence to support that no longstanding trend in anomalous winds has occurred since 1979 throughout the central North American study domain, whether on land or sea, but within the last decade the two regions composing the Midwest in our study indicate a clear majority of months experiencing positive anomalies while the opposite holds true over the northwestern United States. 2) Wind extremes are rare over the open waters of the Atlantic Ocean during early winter. 3) For the upper Midwest, WLs are most common in the early summer and WBs are most common in early autumn. 4) Relative to other regions in the domain, the southeastern United States had noticeably fewer wind-extreme episodes in the historical record. 5) Greater instances for WLs versus WBs exist during the autumn and winter seasons for the southeastern United States. 6) The southern Great Plains and lower Mississippi River valley have been affected by a similar number of WL and WB events, regardless of month or part of year. 7) There appears to be an elevated risk for WBs to occur during January for the southeastern North Pacific. 8) WLs are less frequent over the southwestern United States during the North American monsoon season.

These results are important in terms of establishing new measures of climate-change metrics similar to those created by the World Meteorological Organization (WMO) for use across the globe (Alexander et al. 2006; Klein Tank et al. 2009). While the WMO has created distinct extremes parameters for precipitation and temperature, our definition of WLs and WBs may aid in the extension of climate analysis for wind variables.

Beyond the theoretical concerns of climate-change extremes, the definition of WLs and WBs has practical applied significance to a variety of private and public stakeholders. For example, determination of these extremes may play a significant role in policy and monitoring because these events may influence air quality for populated regions. In addition, assessment of WLs and WBs may be of great importance to long-term establishment and planning for wind-farming operations because the sensitivity of the economy is dictated by long periods of both below- and above-normal winds. Furthermore, occurrence of WLs and WBs may also be linked to drought variations in that the desiccating effect of winds may exacerbate drought conditions. In addition, it has been documented that wildfire growth and behavior are greatly influenced by strong and weak winds. Another application involves winds and public health, such as wind-chill dangers. Diagnosis of long-term extremes in wind has fundamental implications for a large variety of practical and theoretical concerns.

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