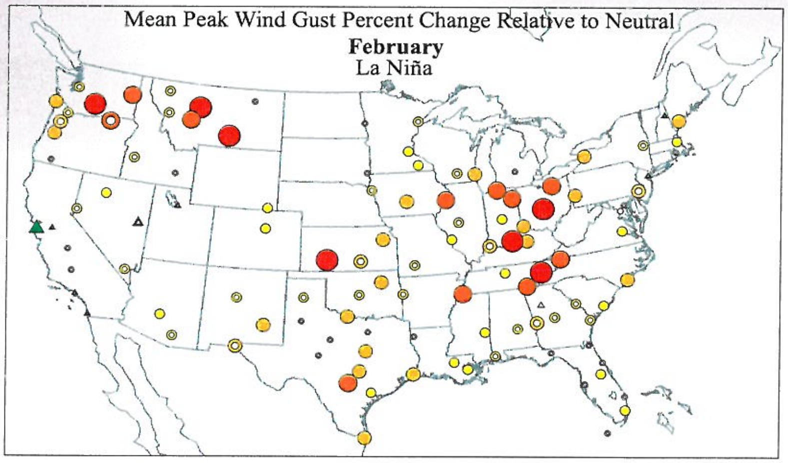
El Niño/Southern Oscillation Impacts on Peak Wind Gust in the United States



Jesse Enloe, Shawn R. Smith, and James J. O'Brien

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THE FLORIDA STATE UNIVERSITY

TALLAHASSEE, FL 32306, USA

DIRECTOR: DR. JAMES J. O'BRIEN

ENSO IMPACTS ON PEAK WIND GUSTS IN THE UNITED STATES

By

JESSE GORDON ENLOE

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ABSTRACT

Changes in the peak wind gust magnitude are identified over the contiguous United States in association with the warm and cold phases of the El Niño/Southern Oscillation (ENSO). All calculations of the peak wind gust are differences in the extreme phases of ENSO (warm and cold) relative to neutral for all stations in the study that pass the completeness criteria. Monthly composites were created for all years in the study (1 January 1955 through 31 August 1998). The differences in the mean peak wind gust are calculated for each month. A non-parametric statistical test was invoked to determine significant shifts in the extreme phase distributions. Differences in the frequency of gale force wind gusts were also calculated. Hypotheses are presented to relate physical processes associated with ENSO and the observed signals in the study. There is an evident relationship between the influence of the jet stream and the patterns observed in the peak wind gust.

The results show a dominant, ENSO cold phase, wintertime signal. Regions most greatly affected are the Pacific Northwest, Southwest, the Great Plains, and the Ohio River Valley including the Great Lakes and Texas. During the cold phase months from November to March, these regions experience an overall increase in the gustiness of the winds. The warm phase is associated with overall decreased gustiness in the Pacific Northwest during these months; however, the signal is of a lesser magnitude. There is

also an observed decrease in the Central Great Plains during the warm phase months of April and June. These results along with improved ENSO forecasting can work towards mitigating adverse effects of strong wind gusts and increase utilization of wind power.

1. INTRODUCTION

The study is motivated by a desire to better understand the impact of ENSO on the climate United States. The El Niño/Southern Oscillation (ENSO) cycle has been shown to have significant impacts on various atmospheric parameters over the continental United States. Past studies have shown the association of ENSO with temperature (Ropelewski and Halpert 1986, Sittel 1994), precipitation (Ropelewski and Halpert 1995, Smith et al. 1998), snowfall (Smith and O'Brien 2001), Lake-Enhanced Snow (Najuch 2002), hurricane land falling (Bove 1998), and even tornadic activity (Bove 1998) over the United States. The present study focuses on wind; more specifically, on the upper tail of the wind distribution, the peak wind gust magnitude, to identify patterns associated with the ENSO cold and warm phase cycles.

Wind gusts may have a wide range of influence on human activities. Structural engineers must have detailed knowledge of wind potential, as the force on a structure is proportional to the square of the wind speed. Multiple days of high wind gusts have a much different impact on bridges, buildings, or other structures than a constant wind average. Knowledge of wind gust magnitudes and frequencies is critical in the construction of various structures.

Potential magnitude of the wind gust is critical to the transportation industry. This knowledge is crucial to airport operators, as well, as a strong burst of wind can prove fatal in take off and landing. A sudden severe gust of wind, gale-force, for example, can overturn small sea craft; complicate operation of tractor-trailers, motorhomes, or other high-profile vehicles; even aid in the spread of forest fires. Recreational activities, such as hang gliding or sky diving, is also be greatly impacted by gusts of wind. Foreknowledge of this parameter can also prove valuable to those who harness the energy created by wind.

Being able to identify the relationship between cycles that impact our atmosphere and their effects on climate and weather can lead to better forecasting ability. This study identifies the relationships of ENSO and its association with peak wind gusts over the contiguous United States. The study considers the change in the monthly mean peak wind gust and the frequency of gale force wind gusts. The region most impacted is the Pacific Northwest. Our results, stated in Section 4, show a dominating cold phase signal during the fall and winter months countered by a weaker, less persistent, warm phase signal. With this new information on the association between ENSO and the peak wind gust, coupled with the increased capacity for forecasting ENSO warm and cold phases, improvements in forecasting can be made, thereby mitigating financial impacts, increasing safety awareness, and potentially increasing the benefits of wind power.

2. DATA

Daily peak wind gust magnitude data were obtained from the First Order Summary of the Day (FSOD) dataset (NCDC 1998) provided by the National Climatic Data Center. The FSOD peak wind gust magnitude is defined as the highest, five-second time-averaged magnitude of wind speed recorded in knots by a station's anemometer for a given 24-hour period. The FSOD data contain observations from stations worldwide collected by certified observers from the National Weather Service (NWS), U.S. Air Force (Air Weather Service), U.S. Navy (Navy Weather Service), and the Federal Aviation Administration (FAA). The present study focuses on the contiguous United States.

First Order station data dates back to 1948. However, prior to 1 January 1955, the recorded units of the data are unclear. The data's documentation states that prior to 1955, the stations' recorded wind speeds are in miles per hour, whereas from 1955 until the end of the dataset, wind speed are recorded in knots. The exception is that the Navy stations consistently used knots as their unit of measure for the entire period of record. In the list of stations provided, differentiation of Navy stations was not clear. Consequently all data preceding 1955 are excluded. The units problem limits the period of the present study to 1 January 1955 through the end of the dataset, 31 August 1998.

The number of active stations varies throughout the study period. Of the stations that exist for the entire period, most have some missing data. A 90% completeness criterion is invoked to ensure a level of quality of the monthly averages computed from the data. Any month with less than 90% of the data is not included in the climatological calculations for that month. A total of 169 stations pass this criterion and are included in the present study.

The classification of ENSO events followed in our study is defined by the Japan Meteorological Agency (JMA) Sea Surface Temperature (SST) index. The JMA index is found to be more sensitive to La Niña events than all other indices (Hanley et al. 2002). The JMA SST Index defines phases of ENSO based on sea surface temperature anomalies in the region 4° N to 4° S and from 150°W to 90°W. A warm (cold) phase is defined when the five-month running mean of SST anomalies in the defined region is greater than 0.5°C (less than –0.5°C) for at least six consecutive months – otherwise, the ENSO phase is classified as neutral (Marine Department, Japan Meteorological Agency, 1991). The event must begin before the start of the ENSO year (October) and include October, November, and December (Sittel 1994).

Extremes in ENSO typically develop during summer, climax in the fall, and subside in the following spring. Therefore, an ENSO year is defined as beginning in October of the onset year and continuing through September of the following year (Green 1996). For example: the 1997 warm event year begins in October 1997 and ends in September 1998. This year is used to highlight the effects of the ENSO event from its maturity in the fall.

3. METHODOLOGY

Monthly averages of the peak wind gust were computed for the 169 stations. The averages were then classified according to ENSO phase (Table 1). For the 44 years of data, from 1 January 1955 to 31 August 1998, there are ten cold phases for each month (9 for October, November, and December, since the data do not begin until January of the 1954 cold phase year), 23 neutral phases, and eleven warm phases (10 for September, since the data set ended in August of the 1997 warm phase).

Table 1. ENSO phases based on the JMA SST index for the period 1954-98. Each year indicates the beginning of the ENSO year (e.g., 1982 indicates a warm phase from October 1982 to September 1983).

Cold Phase	Neutral Phase	Warm Phase
1954, 1955, 1956, 1964, 1967, 1970, 1971, 1973, 1975, 1988	1958, 1959, 1960, 1961, 1962, 1966, 1968, 1974, 1977, 1978, 1979, 1980, 1981, 1983, 1984, 1985, 1989, 1990, 1992, 1993, 1994, 1995, 1996	1957, 1963, 1965, 1969, 1972, 1976, 1982, 1986, 1987, 1991, 1997

Long-term, monthly averages are computed for each phase. Calculating a station's long-term, monthly mean for the warm (neutral, cold) phase requires a minimum of three (seven, three) months to have peak wind averages during a warm (neutral, cold) phase. For example, to compute the January warm phase long-term, monthly average for Spokane, WA, there would need to be at least three warm phase Januarys that passed the

90% criterion in the Spokane daily peak wind. Calculations using higher thresholds (5 warm, 10 neutral, 5 cold and 7 warm, 12 neutral, 7 cold) were also examined and revealed the same patterns as with the lesser criteria.

Maps are generated to plot differences in the ENSO extreme event (warm, cold) peak wind gusts relative to neutral spatially (Fig. 1). The neutral phase is used as the base for this study since mean values are influenced by the extremes. The percent change,

$$\frac{Monthly\ Mean\ Peak\ Wind\ Gust_{Extreme\ Event} - Monthly\ Mean\ Peak\ Wind\ Gust_{Neutral}}{Monthly\ Mean\ Peak\ Wind\ Gust_{Neutral}} \times 100\%,$$

is calculated for each month at each station. Since the differences are computed relative to neutral, a table of the climatological neutral values can be viewed in Appendix A. The raw differences can be calculated by station using this table.

Stations that exhibit significant changes in peak wind during the extreme ENSO phases are determined by constructing monthly distributions for each phase at each station from the daily observations. The distributions are normalized and multiplied by 100 to reflect percentages. The Kolmogorov-Smirnov (K-S) test is used to ascertain whether the peak wind gust distribution of the ENSO extreme event for a given month is significantly different from the corresponding neutral distribution. The K-S test is a distribution-free test for general differences in two populations and tests the difference of the entire distribution (Hollander and Wolfe 1999). The test does not reveal significant differences at any particular percentile. For the present study, the observed significance level at which the distributions are considered significantly different is five percent. For further detail on the K-S test, see Appendix B. The results of the K-S test are plotted spatially with the difference in means (Fig. 1).

The difference in the probability of a severe occurrence (i.e., a high wind speed) between neutral and extreme phases is computed to quantify the upper tails of the distribution of peak wind gust. The occurrence selected for the present study is a peak wind gust that meets or exceeds a threshold of 28 knots, the minimum classification of a gale force (moderate gale) wind speed, according to the terrestrial-modified Beaufort wind scale (Ludlum 1991). A gale-force wind gust has potential adverse effects on industry, as well as recreation, for maritime or terrestrial activities. A monthly mean frequency of gale force gusts was computed at each station and classified by ENSO phase. The differences between the extreme and neutral phases are plotted spatially (Fig. 2). Since the differences are computed relative to neutral, a table of the climatological neutral values can be viewed in Appendix A. The raw differences can be calculated by station using this table.

Mean Peak Wind Gust Percent Change Relative to Neutral

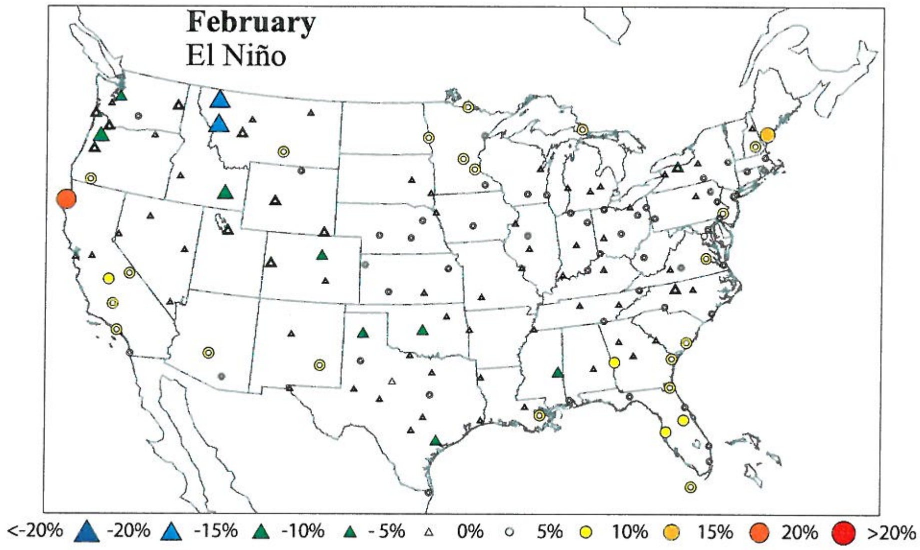


Figure 1. The map displays percent change in monthly mean peak wind gust for the El Niño phase relative to neutral phase. All stations plotted meet the completeness requirements stated in Sections 1 and 2. The magnitude and sign of the mean difference are represented by the size and shape of the symbols, respectively. Filled (hollow) symbols represent stations whose El Niño and neutral distributions are rejected (not rejected) as being equal at the 5% level of significance according to the K-S test.

28-Knot Peak Wind Gust Frequency Change Relative to Neutral

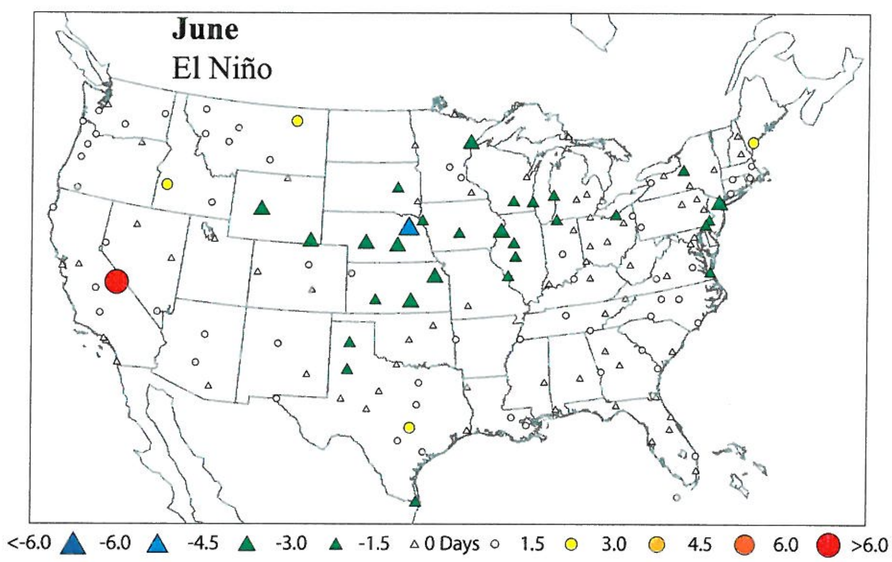


Figure 2. The map displays the difference in frequency of the number of days in the month that experience a minimum 28 knot wind gust for the El Niño phase relative to neutral phase. All stations plotted meet the completeness requirements stated in Sections 1 and 2. The magnitude and sign of the mean difference are represented by the size and shape of the symbols, respectively.

4. RESULTS

The strongest, most persistent peak wind gust signals occur during the fall and winter for both extremes of ENSO. It is not uncommon for patterns associated with ENSO to have their peak magnitudes in these colder months, as both the warm and cold phases reach maturity during the fall (Glantz 1988, Philander 1990). Other wintertime peaks in observed signals associated with ENSO over the contiguous United States have been noted in previous studies, such as temperature (Sittel 1994, Green 1996) and precipitation (Sittel 1994, Smith et al. 1998). The peak wind gust patterns associated with the warm phase are not equal and opposite to those observed with the cold phase. There is a clear, dominant, cold phase, wintertime signal. Relative to neutral, the cold phase is characterized by more stations that demonstrate significant shifts in distribution, larger positive differences in the monthly mean, and higher frequency of gale force wind gusts than occur during a warm phase. The signals associated with El Niño lack consistency in temporal and spatial patterns. The region with the highest contrast in signals between the two extreme phases is the Northwest (Washington, Oregon, Idaho, Montana, Wyoming, and Colorado). The area is comprised of large, positive shifts in the mean and frequency of gale force gusts during the cold phase cold months, while in the warm phase fall and winter months, smaller magnitudes of negative values dominate.

a. La Niña Impact

The strongest signal associated with the cold phase is focused about the Northwest in the fall and winter months of the year (Fig. 3). A second region is also observed to exhibit a cold phase signal during the period from October through March over the Ohio River Valley, from the Great Lakes extending southwestward into Texas. Over most of the year and over most of the country, La Niña is associated largely with positive differences in monthly means of the peak wind gust and the frequency of gale force wind gusts (Fig 4). There is an exception in late summer when the presence of these positive differences is not as evident.

The observed signals associated with the cold phase of ENSO are characterized by larger magnitudes of differences in the monthly mean than are observed with warm phase signals, particularly from November to March. During an average, neutral February, Astoria, Oregon experiences a daily peak wind gust of 22.9 knots (Appendix A). A cold phase February peak wind gust in Astoria averages 25.7 knots, a 12.2% increase.

During the cold phase, the months from November to March display the highest percentage of stations that report a difference in means of greater than 10% (Fig. 5a). Consequently, the computation of the K-S test reveals these months to exhibit the highest percentage of stations whose cold phase and neutral phase distributions are significantly different (Fig. 5b). The highest concentration of stations with these large differences in the mean and significant shifts in distribution occur in the in the West, Southern Great Plains, and the Ohio River Valley. A signal could not be determined over the Northern Great Plains due to the lack of data.

The patterns observed in this study experience a degree of month-to-month variability. During the La Niña January, positive differences over California are replaced by negative values along the Pacific Coast, but these differences are restricted to ~42°N latitude, southward (Figs. 3c and 4c). The strong positive differences (greater than 20%) remain in the Pacific Northwest creating a north-south oriented dipole pattern with values of –5 to –15% present along the Pacific Coast in California. The signal observed in the Southern Great Plains to the Ohio River also subsides in this month (Figs. 3c and 4c). In the proceeding two months, the strong, positive values return to the Southern Plains, while the absence of these large differences in the Southwest remains (Figs. 3d and e).

The occurrence focused on in this study is a daily peak wind gust that meets or exceeds a 28-knot threshold. A gale-force wind gust can be of great concern for operators of small sea craft, tractor-trailers, and airplanes during take off and landing. The difference in frequencies of such an occurrence between the neutral and extreme phases mimics the pattern observed by the difference in means of the monthly peak wind gust (Fig. 4). An average, neutral February in Astoria, Oregon has 7.7 days that meet or exceed a peak wind gust of 28 knots (Appendix A). However, during a cold phase February, Astoria will average 11.6 days that produce a minimum 28-knot wind gust.

b. El Niño Impact

The observed patterns associated with the warm phase of ENSO are not as robust as signals observed during the cold phase. The differences in the warm and neutral monthly means are small and not persistent from month to month (Fig. 6). The surface observation stations record these percent changes as relatively weak, rarely of greater magnitude than –10% (Fig. 5a). Though strong differences in means are not observed, there is a general reduction in peak wind gust in the contiguous United States during El Niño, as well as a reduction in occurrences of gale force wind gusts (Fig. 7). As in La Niña, this general effect is persistent throughout all seasons with the exception of the July-August-September summer, when there is primarily a positive shift. Performing the K-S test reveals far fewer stations having significant differences in the warm and neutral phase distributions than seen between the cold and neutral phases (Fig. 5b).

One persistent warm phase signal, though weak, is observed in the Northwest (Fig. 6a). Beginning with the start of the warm phase year (October) through February, a general weak reduction in the monthly mean peak wind gust (usually 0 to –5%) spans most of the country. However, percent changes of –5% to –10% are more common in the Northwest, with some magnitudes as great as –15% to –20% occurring during these months. In the month of November, during a neutral phase, Pocatello, Idaho averages a daily peak wind gust of 22.4 knots (Appendix A). During the warm phase, this average is reduced to 20.1 knots. This is in direct contrast to the increase in the monthly mean peak wind gust observed during the cold phase. There is also a lower frequency of days that meet or exceed the 28-knot threshold (Fig 7a). In November, Pocatello averages 8.5 days that experience a minimum 28-knot wind gust during a neutral event (Appendix A). The warm phase November averages only 6.2 days. This pattern persists through February (Fig. 1), with slight variation (the signal is weakened in the month of January).

The Great Plains also experiences a reduction in the mean peak wind gusts in the fall and winter months, as in the case of November (Figs. 6a and 7a). The signal during these months in this region, however, is not as strong in magnitude or as persistent from month to month as what is observed in the Northwest. A similar pattern is also noted in the Central Great Plains during the spring (Figs. 2, 6c, and 7b). The signal of reduced mean gust and reduced frequency in gale force gusts is present during April and June, but lacking in the month of May.

Though negative differences are present over most of the country for the month of October, weak, positive peak wind gust differences are present in the southwestern-most region of California. Through the winter, the positive values migrate northward through California. By January, the positive values extend to the Canadian border (possibly even further north, but the data is limited to the United States) on the windward side of the Cascade Mountains (Fig. 6b). Negative differences (–5 to –15%) remain on the eastern, leeward side of the mountains, creating a very weak, east-west dipole pattern in the Northwest during the month of January with small, positive values (mostly 5 to 10%) on the western, windward side of the Cascades. These weak, positive values are present in the Pacific Northwest during January, subside in February (Fig. 1), giving way to negative differences in Oregon and Washington, and then return in March. An analysis of shorter time periods (less than one month) may reveal signals that are more robust.

Mean Peak Wind Gust Percent Change Relative to Neutral

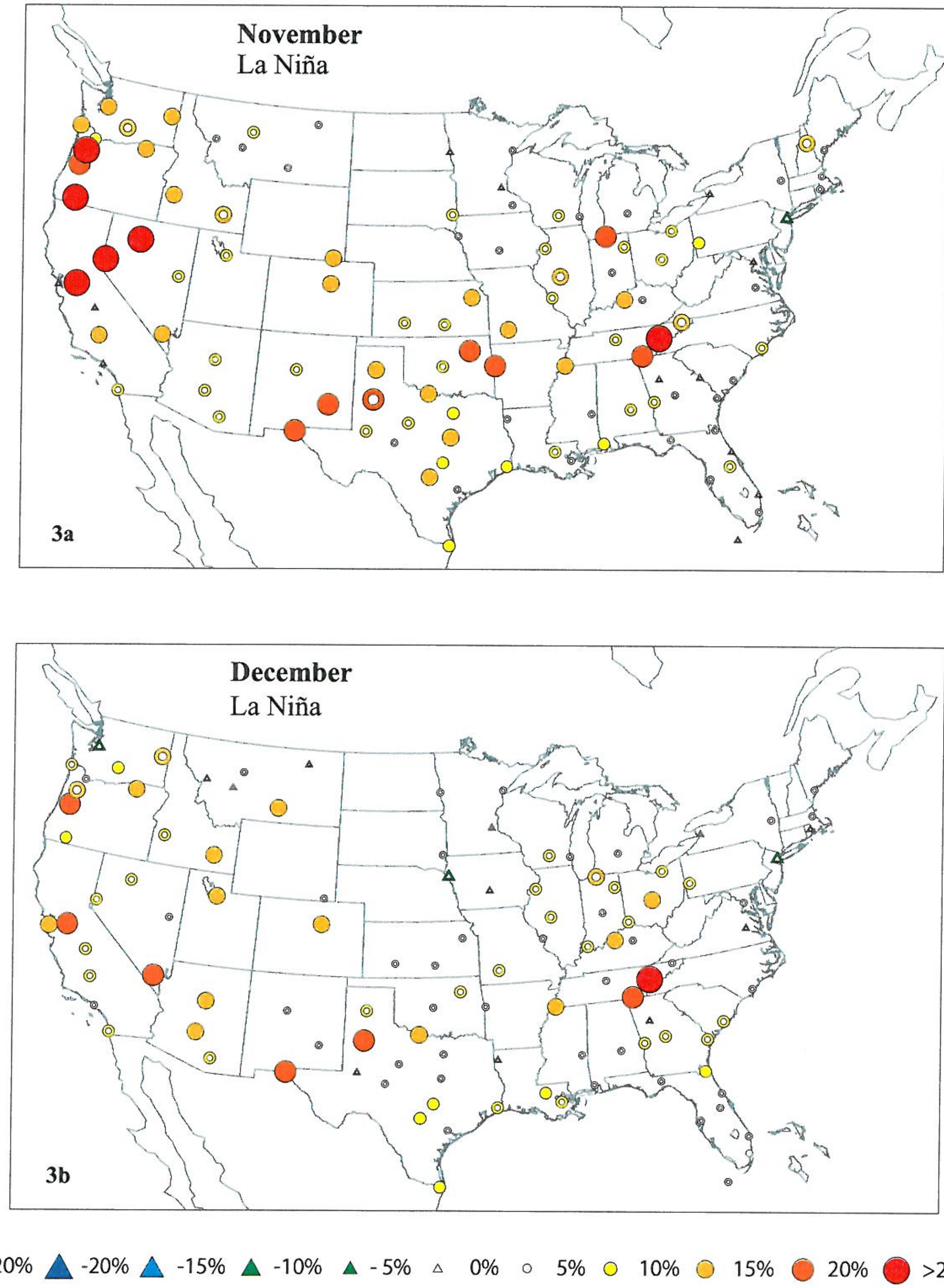
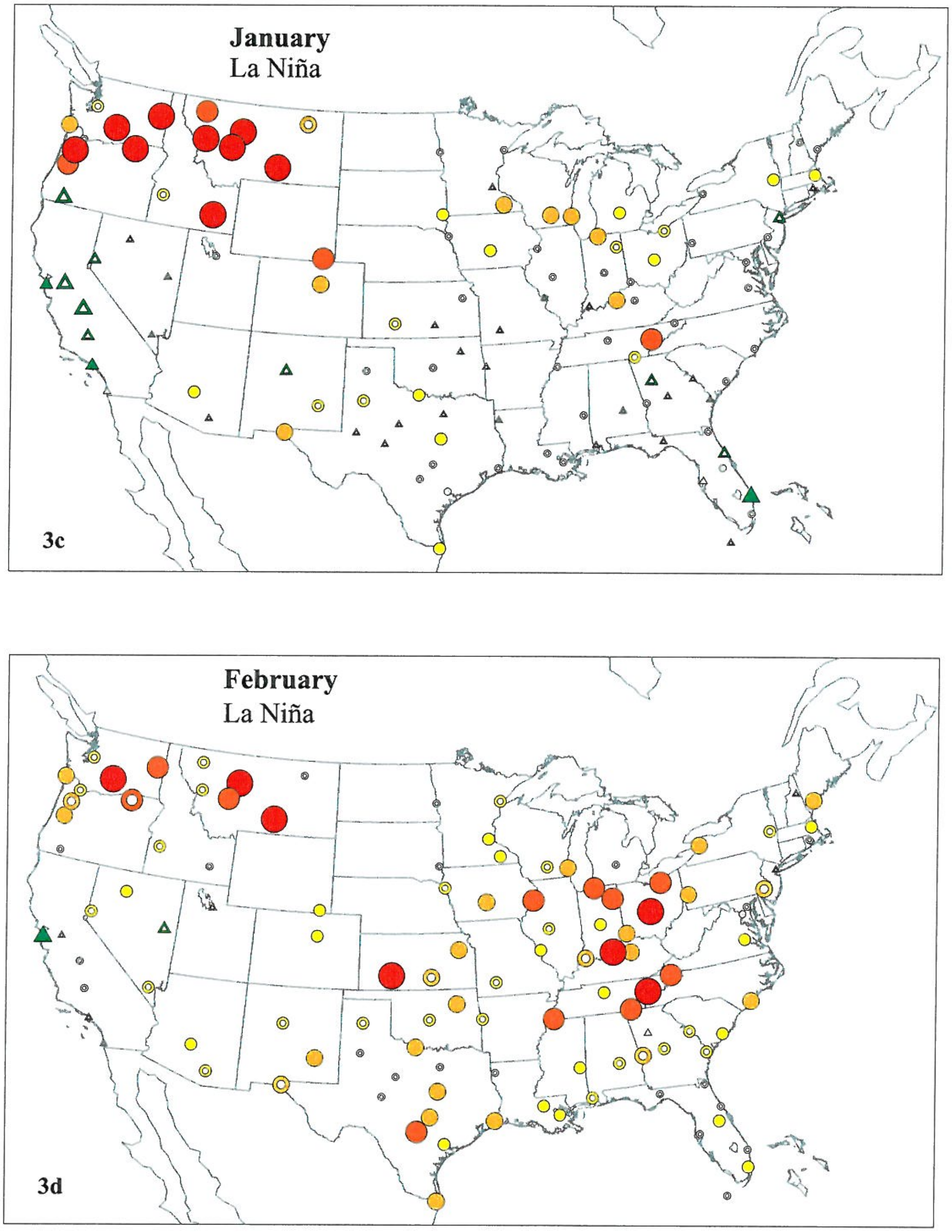


Figure 3. The map displays percent change in monthly mean peak wind gust for the La Niña phase relative to neutral phase for a) November, b) December, c) January, d) February, and e) March. All stations plotted meet the completeness requirements stated in Sections 1 and 2. The magnitude and sign of the mean difference are represented by the size and shape of the symbols, respectively. Filled (hollow) symbols represent stations whose La Niña and neutral distributions are rejected (not rejected) as being equal at the 5% level of significance according to the K-S test.

Mean Peak Wind Gust Percent Change Relative to Neutral



<-20% -20% -15% -10% - 5% 0% 5% 10% 15% 20% >20%

Figure 3--continued.

Mean Peak Wind Gust Percent Change Relative to Neutral

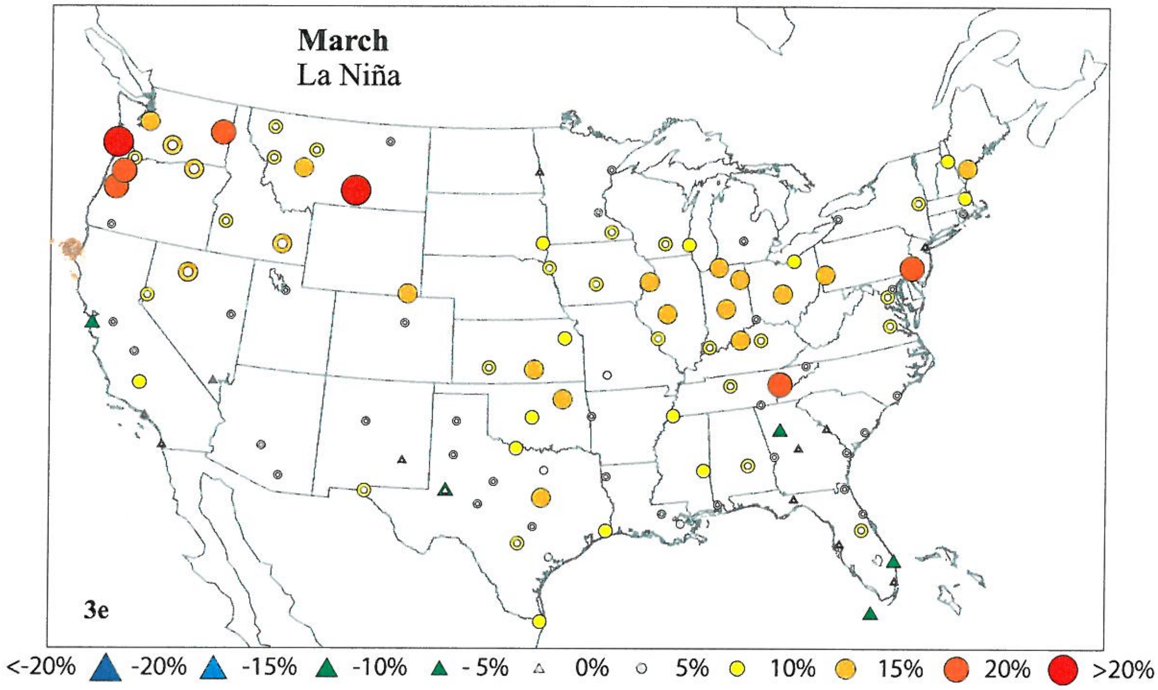


Figure 3--continued.

28-Knot Peak Wind Gust Frequency Change Relative to Neutral

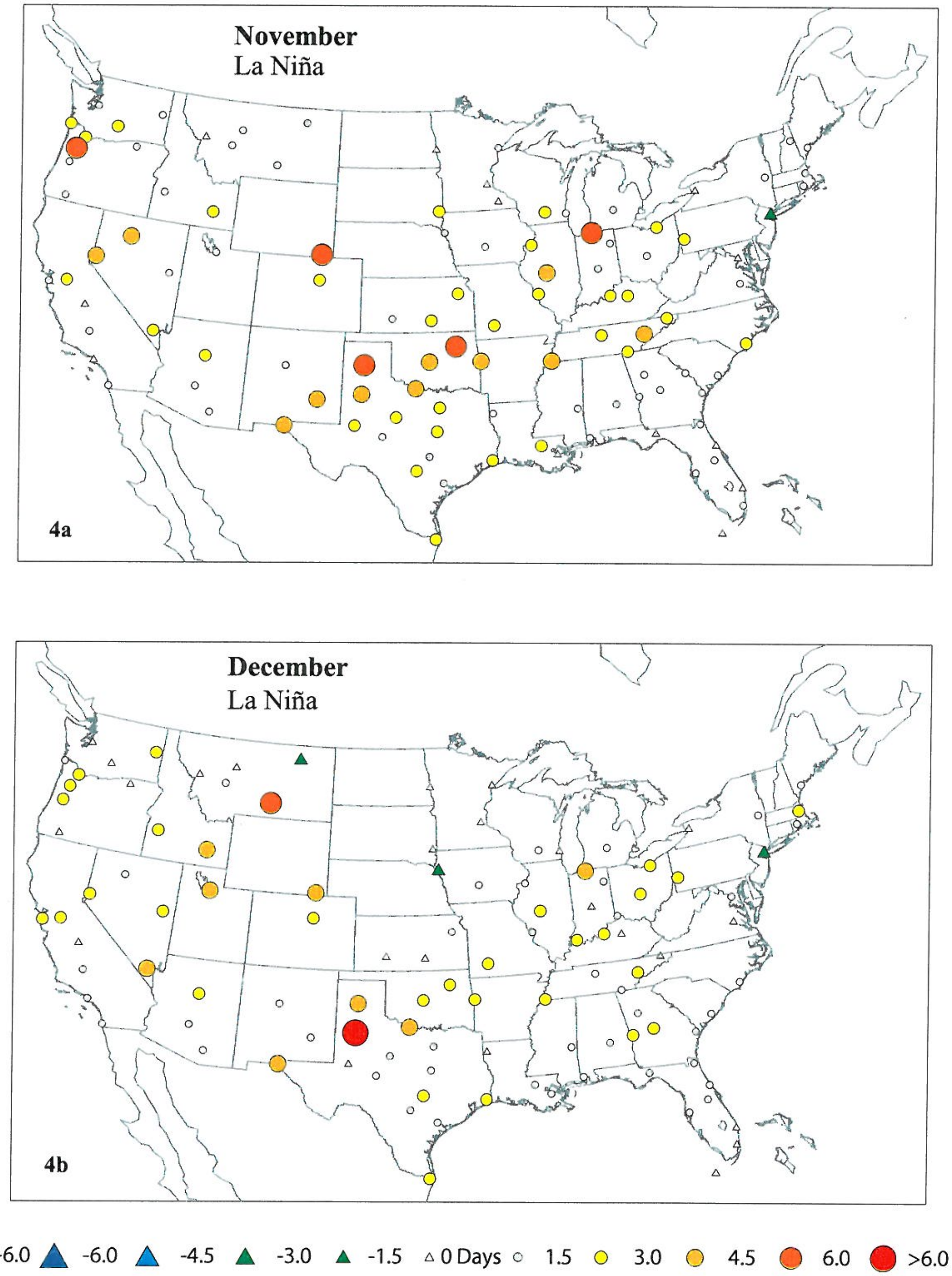


Figure 4. The map displays the difference in frequency of number of days that experience a minimum 28 knot wind gust for the La Niña phase relative to neutral phase for a) November, b) December, c) January, d) February, and e) March. All stations plotted meet the completeness requirements stated in Sections 1 and 2. The magnitude and sign of the mean difference are represented by the size and shape of the symbols, respectively.

28-Knot Peak Wind Gust Frequency Change Relative to Neutral

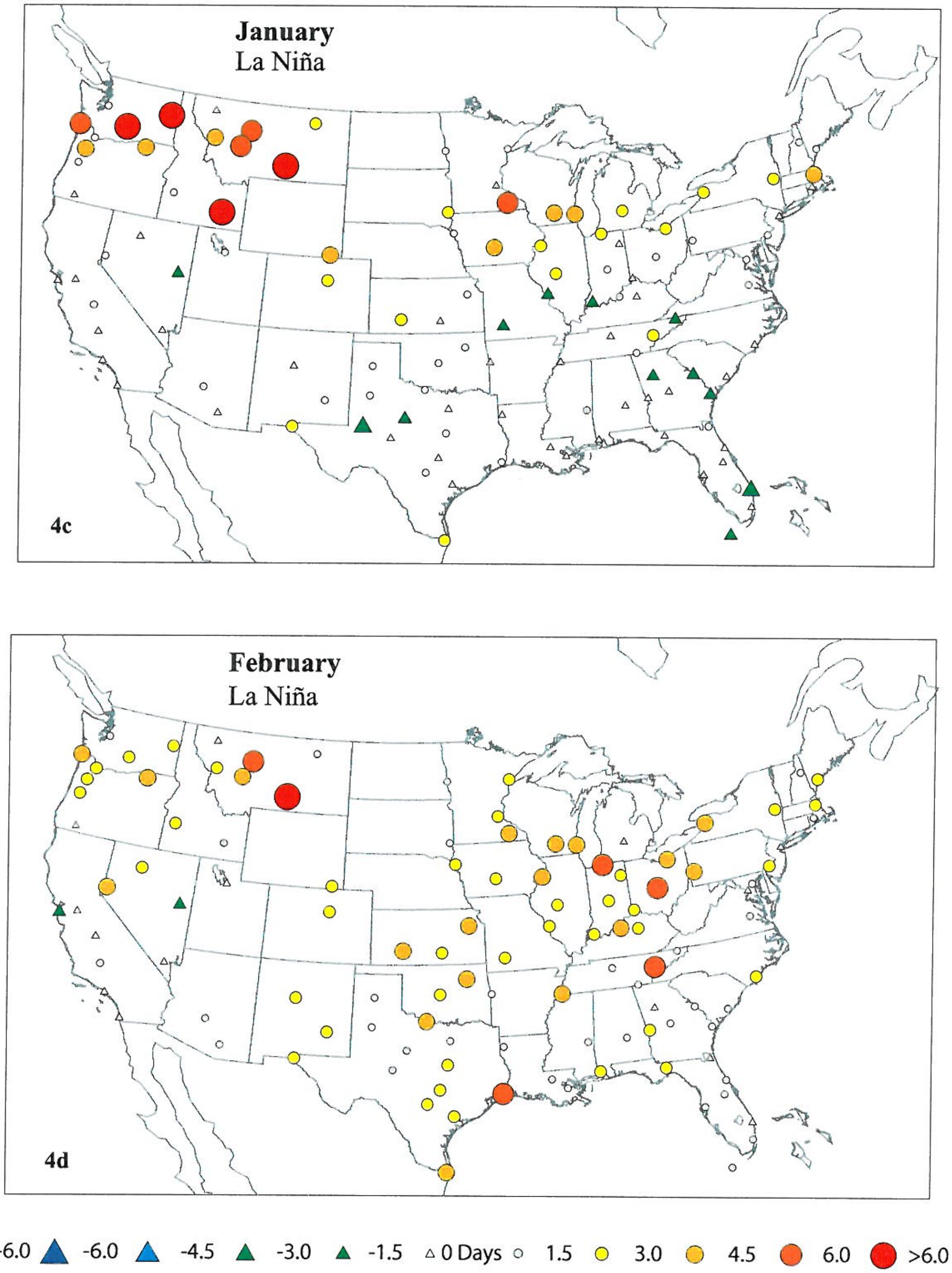
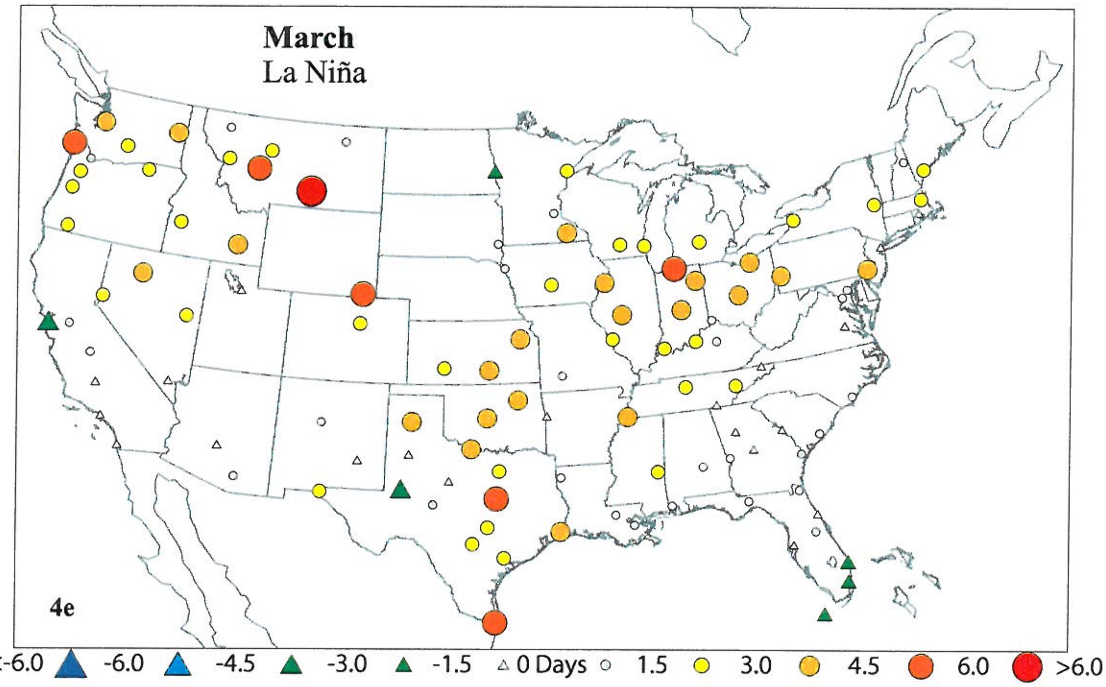


Figure 4--continued.

28-Knot Peak Wind Gust Frequency Change Relative to Neutral



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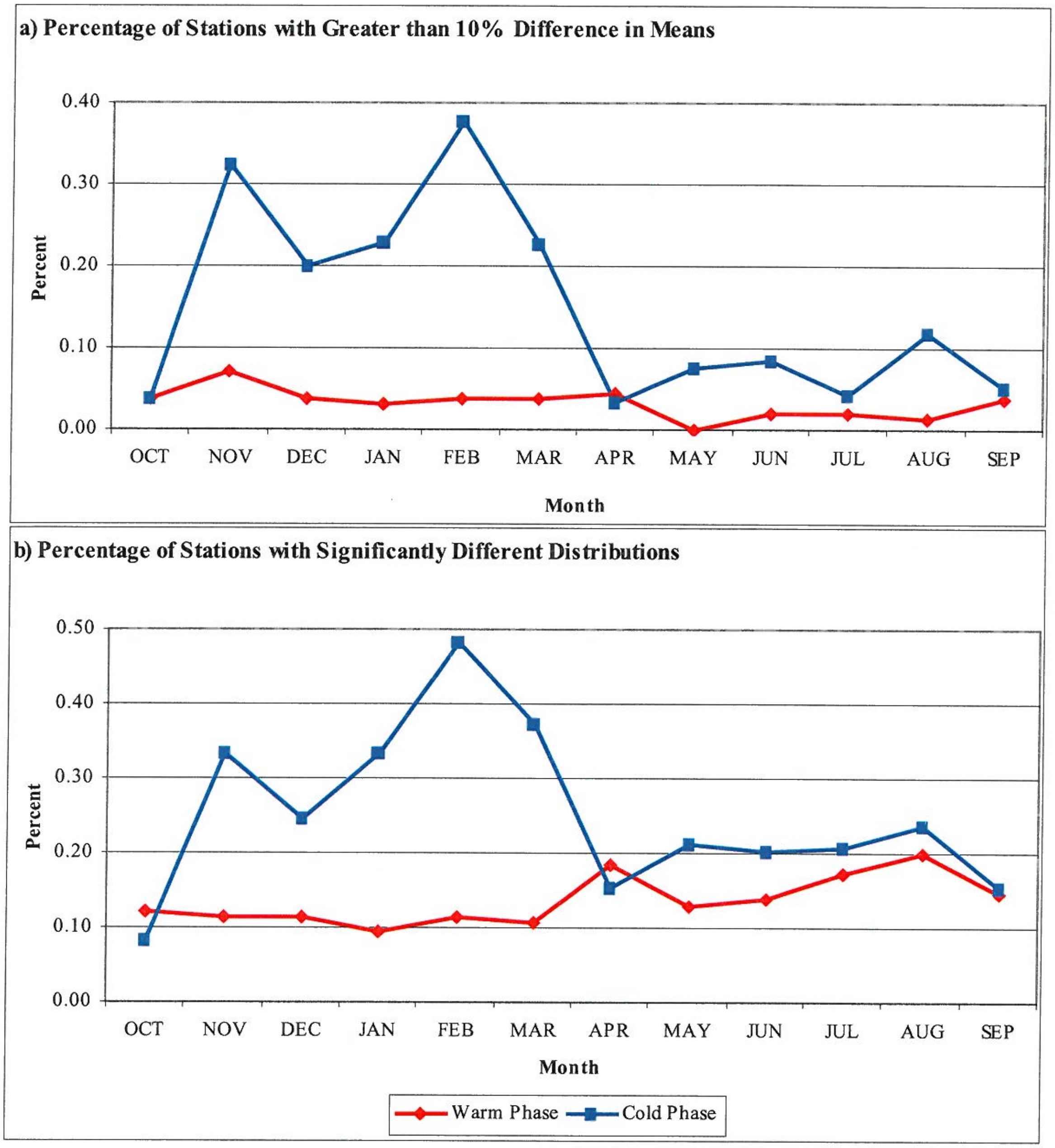
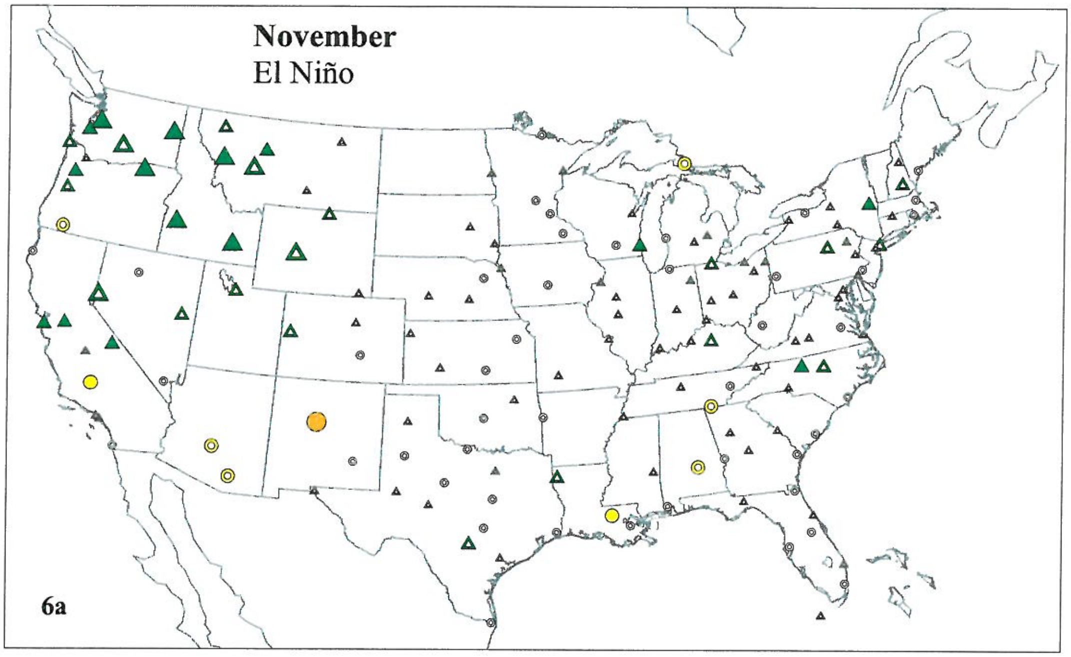
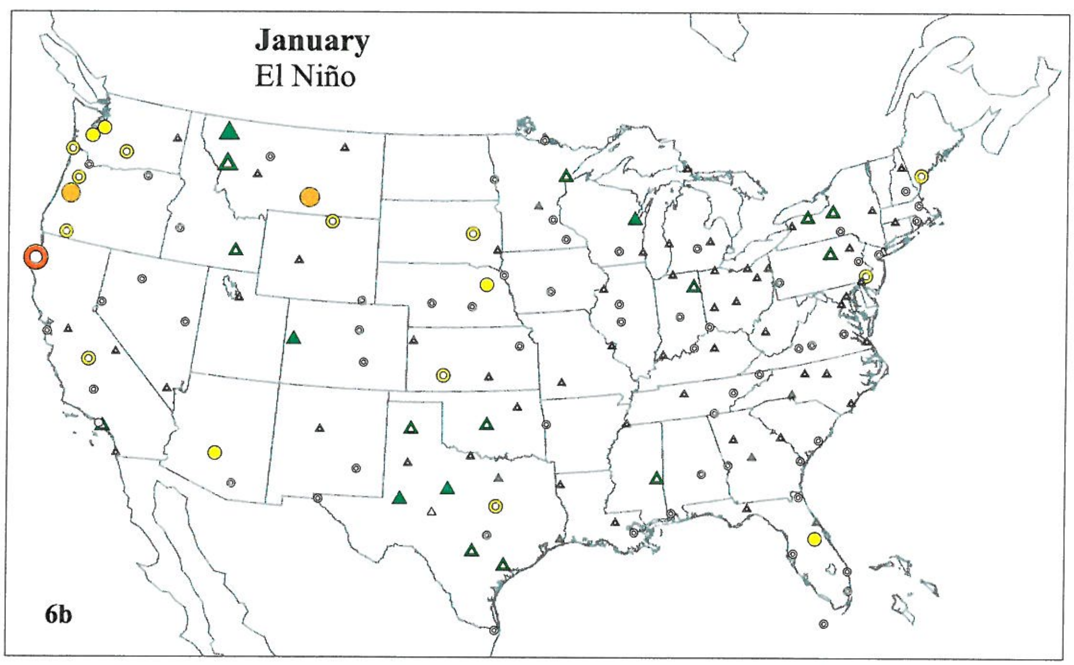


Figure 5. The Charts show (a) percentage of stations studied with a greater than 10% change in the monthly mean peak wind gust relative to neutral for El Niño (red) and La Niña (blue) and (b) percentage of stations studied with significantly different warm and neutral phase distributions (red) and cold and neutral phase distributions (blue), as determined by the K-S test.

Mean Peak Wind Gust Percent Change Relative to Neutral





<-20% -20% -15% -10% - 5% 0% 5% 10% 15% 20% >20%

Figure 6. The map displays percent change in monthly mean peak wind gust for the El Niño phase relative to neutral phase for a) November and b) April. All stations plotted meet the completeness requirements stated in Sections 1 and 2. The magnitude and sign of the mean difference are represented by the size and shape of the symbols, respectively. Filled (hollow) symbols represent stations whose El Niño and neutral distributions are rejected (not rejected) as being equal at the 5% level of significance according to the K-S test.

Mean Peak Wind Gust Percent Change Relative to Neutral

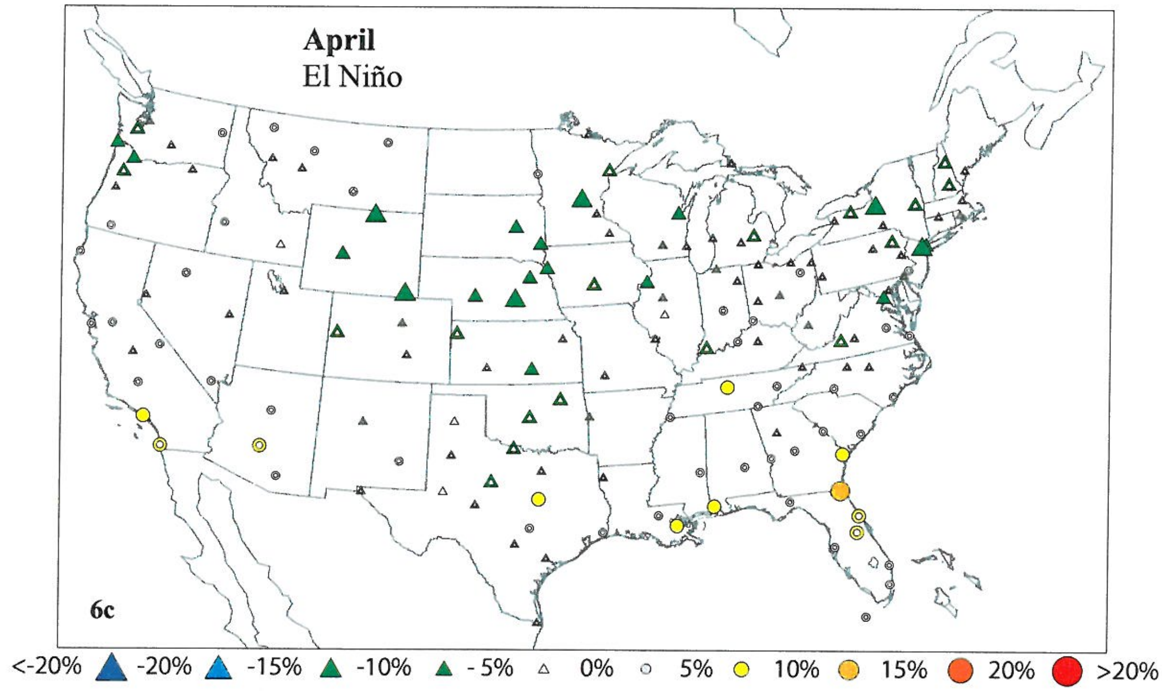


Figure 6--continued.

28-Knot Peak Wind Gust Frequency Change Relative to Neutral

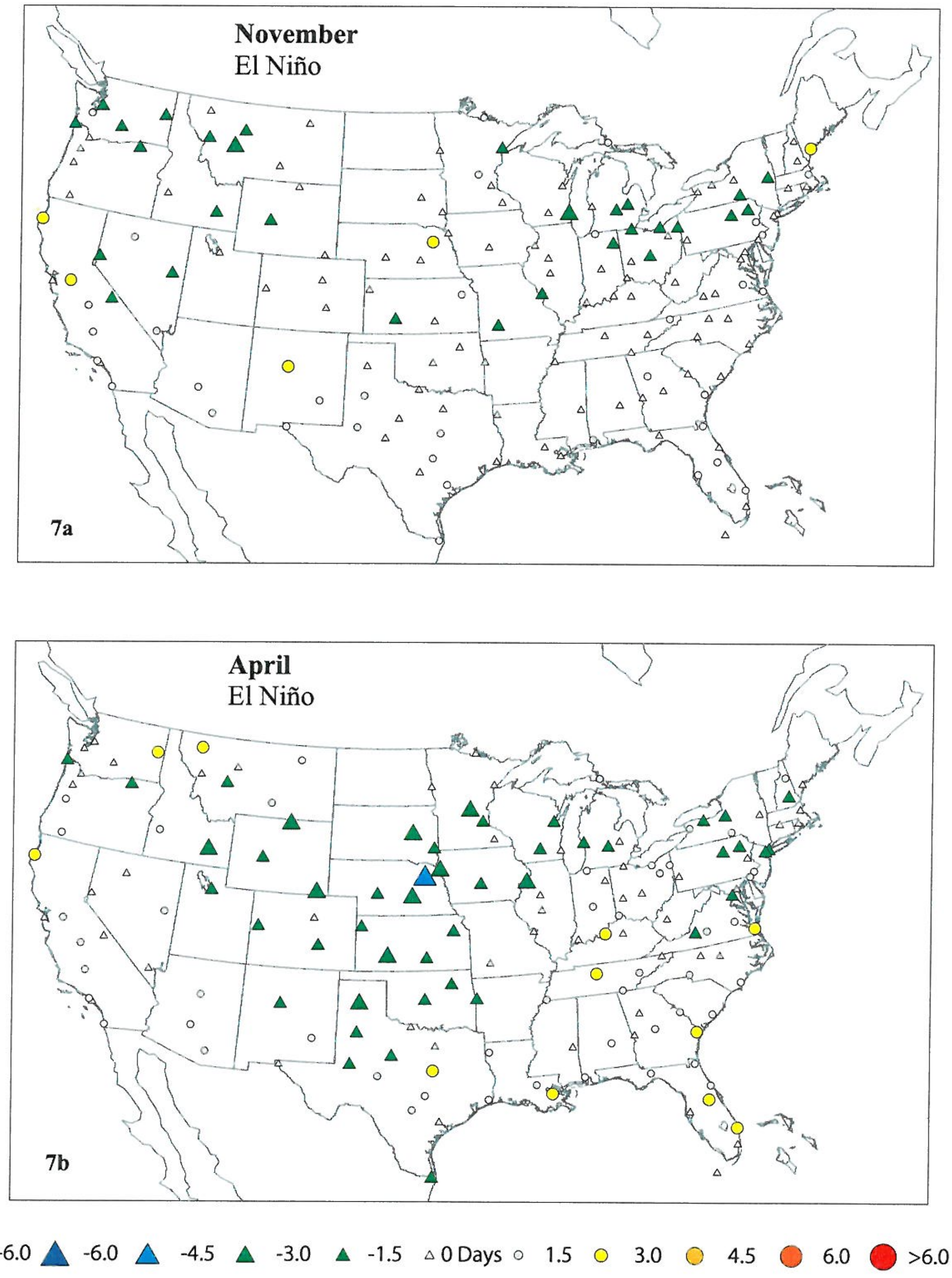


Figure 7. The map displays the difference in frequency of number of days that experience a minimum 28 knot wind gust for the La Niña phase relative to neutral phase for a) November and b) April. All stations plotted meet the completeness requirements stated in Sections 1 and 2.

5. DISCUSSION

In addition to the identification of wind gust signals associated with the ENSO warm and cold phases, explanations of the observed patterns in this study are essential in order to improve ENSO forecasting. In this section, hypotheses are presented to propose physical connections between the atmosphere and the observed changes in the peak wind gust distribution. The goal is to hypothesize a relationship between known circulation pattern anomalies associated with ENSO and the patterns identified in this study. Association does not prove causation, but they are reasonable propositions to explain the physical mechanisms that could be influencing the results and may give direction to future study on peak wind gusts. Explanations of the observed patterns may help lead to improved ENSO forecasting ability, increasing benefits, and mitigating negative impacts.

Uccellini (1990) has shown ascending motion is associated with the entrance and exit regions of a core of stronger winds in the jet stream. The jet stream provides the upper-level dynamics necessary for positive vertical motion in the atmosphere as well as momentum in the middle and upper levels. Regions on the south (north) side of the entrance (exit) of a zonally positioned jet in the Northern Hemisphere experience large scale rising motion. This dynamic lift and the related synoptic scale vorticity patterns are often associated with cyclonic activity. Cyclones that form are comprised of large-scale vertical motion. Downscaling from within the synoptic scale system to individual, mesoscale, convective events result in transfer of the jet stream momentum through storms whose cloud tops reach into the middle and upper levels of the atmosphere. These individual storms can transfer the jet stream momentum from the middle and upper levels through their downdrafts when the rising air cools in the upper-troposphere and falls, bringing colder, higher velocity air to the surface.

Composite monthly means of the 250 hPa winds (magnitude and direction) over the United States were produced from National Center for Environmental Predicion reanalysis (NCEPR) data (Kistler et al. 2001) to determine position and strength of the jet stream. The monthly composites were created from all warm and cold events in the present study (Figs. 8 and 9). These maps are used to lend support for the hypotheses presented. Other atmospheric parameters play a role in the gustiness of surface winds (i.e. thermal gradients), but the focus of our hypothesis is on the role of the upper-level jet.

a. The Pacific Northwest

The region of greatest contrast in peak wind gust between the two extreme phases is the Northwest during the fall and winter months (Figs. 3a-e, 4a-e, 6a, and 7a). The position of the jet stream in this region changes radically between the two ENSO phases and can be related the PNA pattern. The Pacific/North America (PNA) Pattern is a stationary Rossby wave teleconnected to the El Niño/Southern Oscillation (Horel and Wallace 1981, Wallace and Gutzler 1981). During the warm phase fall and winter, this pattern is characterized by the deepening of the Aleutian Low and its displacement southward, while a ridge sits in place over the Northwest. This orientation directs the polar jet further north, up into Canada, removing its dynamical forcing from the northwestern United States. There is a lack of upper level wind support (Fig. 8) and large-scale descending motion due to ridging over the Pacific Northwest. This decreases the potential for storm-producing systems in the area during El Niño. The decrease in storm activity and weaker upper level winds, by the authors' hypothesis, decreases the potential for momentum transfer from the middle and upper levels to the surface, thereby decreasing overall gustiness in the region in the fall and winter months (Figs. 1, 6a, and 7a).

In contrast, during the La Niña fall and winter, the polar jet stream's positioning is directly over Washington and Oregon (Fig. 9). The likelihood of increased upper dynamics enhancing the vertical motion is reflected by an increase in snowfall (Smith and O'Brien 2001) and overall precipitation (Sittel 1994, Smith 1998) in the Pacific Northwest. It follows logically that an increase in momentum transfer from the upper atmosphere would also occur, resulting in increased gustiness of the wind (Figs. 3 and 4).

In the La Niña January, a north-south dipole patter forms in the Pacific Northwest (Figs. 3c-e and 4c-e), with increased (decreased) gustiness to the north (south). It should also be noted that this dipole pattern is also seen in precipitation patterns during the La Niña winter (Sittel 1994) with increased (decreased) precipitation to the north (south) of the California-Oregon border. In the month of January, the 250 hPa level winds decrease in magnitude over the Southwest by 3 to 6 ms^{-1} (Fig 9c) as compared to December (Fig 9b) and January (Fig 9d). The lack of upper-level winds over the Pacific Coast could play a role in this decrease of precipitation and gustiness in the region. From the 250 hPa level winds, it is not evident why the east-west dipole pattern is observed in the Pacific Northwest during the warm phase January.

b. The Southern Great Plains and Ohio River Valley

The Ohio River Valley from the Great Lakes southwest into Texas experiences overall, increased gustiness during the cold phase of ENSO (Figs. 3 and 4). The east-west positioned jet during the cold phase, over the Central Eastern United States, places the south-west quadrant of the jet core (associated with rising motion) directly over the Southern Great Plains (Fig. 9). Through scale interaction, the dynamic lifting yields the potential for increased gustiness over the region. The influence of the increased upper dynamics on vertical motion is again reflected by an increase in snowfall (Smith and O'Brien 2001) and overall precipitation (Sittel 1994, Smith 1998) in the region. In contrast, during the warm phase, as noted in Section 5c, the influence of this quadrant of the jet is shifted far to the south, thereby removing the dynamical forcing that is present during the cold phase (Fig. 8)

c. The Central Great Plains

The other pattern revealed by the present study is the decrease in gustiness in the Great Plains during the warm phase spring. In the transitional months of spring, strong temperature gradients are present, particularly in the middle of the country due to the region's high continentality (Bryson and Hare 1974). A strong temperature gradient is an essential ingredient for severe storms. Ropelewski and Halpert (1986) show that the warm (cold) phase decreases (increases) the temperature gradient between the Gulf Coast and the Great Plains. During the warm phase a very strong core of 250 hPa winds (of greater magnitude than during the cold phase) resides to the south of the country (Fig. 8). By the thermal wind argument, this implies that the temperature gradient would be stronger during the warm phase than in the cold. However, plots of the winds in the lower levels (500 hPa and 700 hPa) were also examined. These plots show that the magnitudes of the winds over the Southern Great Plains at these levels are nearly equivalent.

Reasoning behind decreased gustiness can again be attributed to the jet stream and its position relative to the region during the ENSO warm phase.

During the warm phase, the subtropical jet stream shifts equatorward, reducing its dynamical effects over the Central United States (Fig 8). Coherence with the decrease in the influence of upper-level dynamics is presented in Bove (1998) where it is showed that there is a decrease in the frequency of tornadoes in the Great Plains during the spring warm phase. This implies a decrease in tornadic storms – a potential source for upper-level momentum transfer and strong wind gusts.

Composite NCEPR Warm Events Monthly Mean 250 hPa Wind Vectors

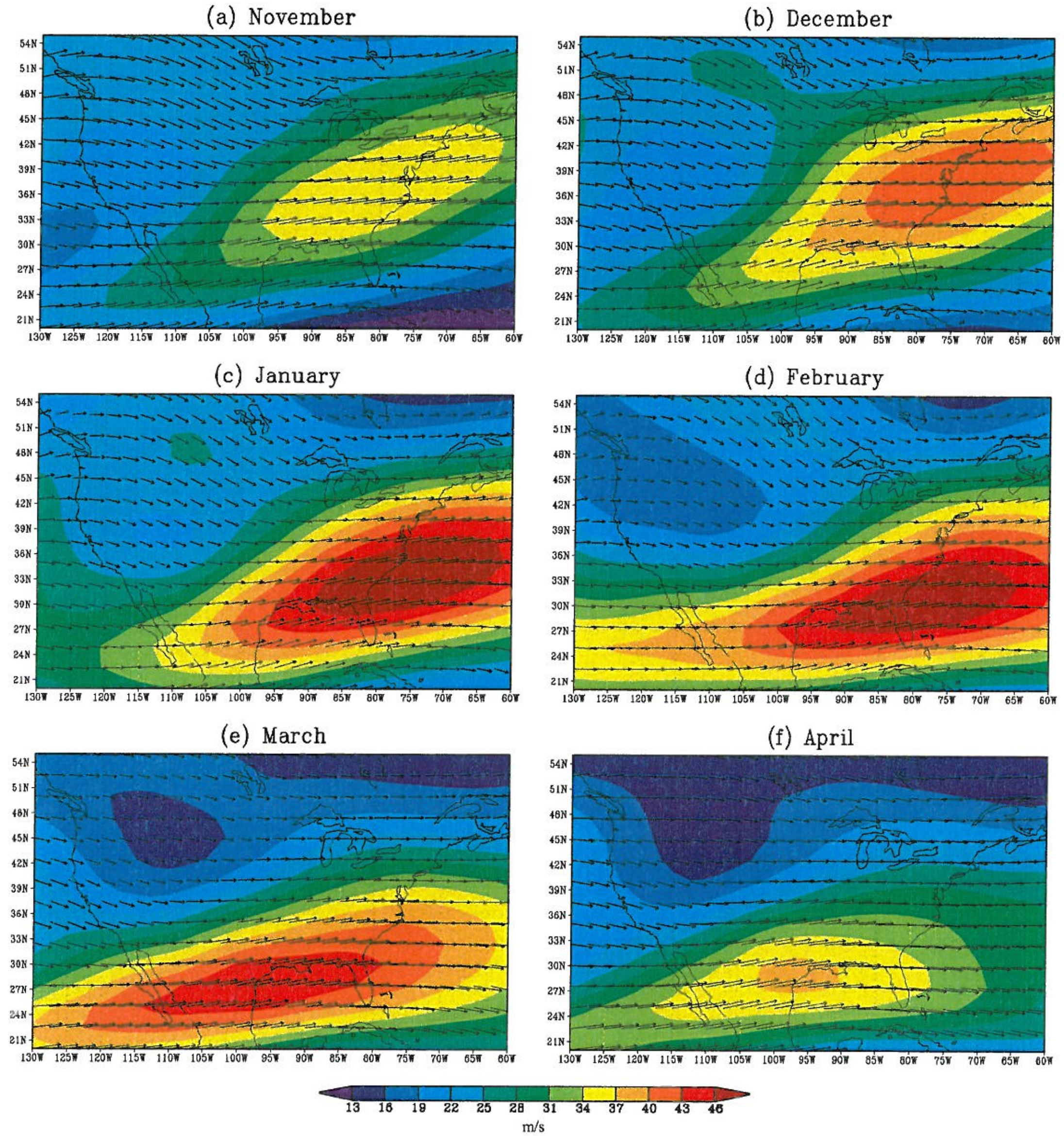


Figure 8. The map displays the vectors (arrows) and magnitude (contours) of the 200 hPa level winds averaged over (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April of all El Niño years in the present study.

Composite NCEPR Cold Events Monthly Mean 250 hPa Wind Vectors

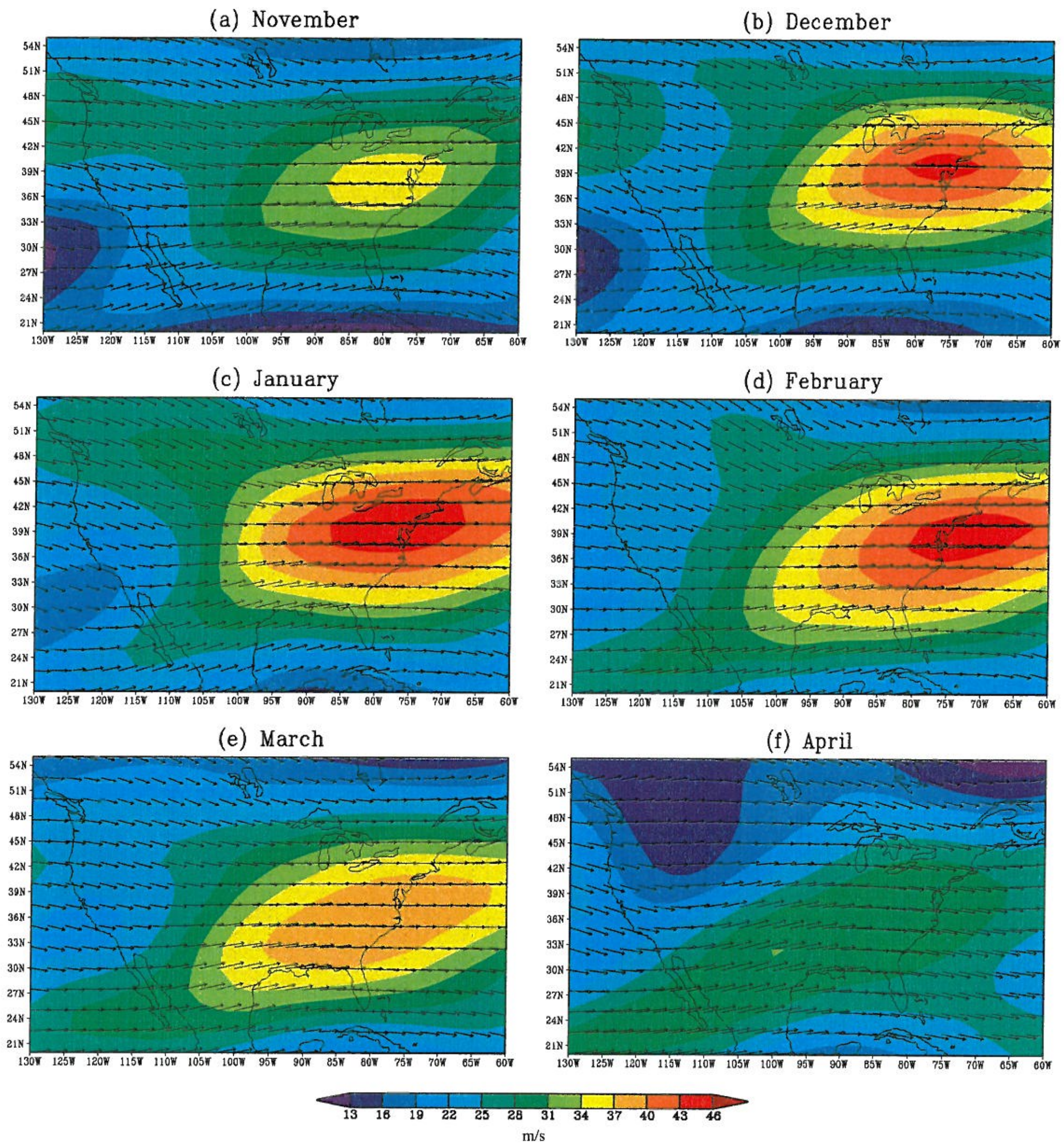


Figure 9. The map displays the vectors (arrows) and magnitude (contours) of the 200 hPa level winds averaged over (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April of all La Niña years in the present study.

6. CONCLUSIONS

Shifts in the distribution of peak wind gust are identified in association with the warm and cold phases of ENSO. The significant shifts were determined using the Kolmogorov-Smirnov test, which also highlighted the dominant La Niña wintertime signal (Fig. 5). Monthly mean peak wind gusts, as well as the frequency of gale force gusts, are found to increase (decrease) during ENSO cold (warm) phases over the West, particularly the Pacific Northwest, in the fall and winter. These changes can be associated with a stronger (weaker) polar jet in the cold (warm) phase over the region. Gustiness is also observed to increase over the Ohio River Valley, southwest into Texas during the La Niña fall and winter. The location of the southwest quadrant of the jet core residing over this region can be related to this pattern. Decreased gustiness relative to neutral years is noted over the Great Plains during the warm phase. The relationship hypothesized here is also correlated with the subtropical jet being displaced further south during the warm phase of ENSO.

Knowledge of the associated affects of ENSO on magnitude of the wind gust and frequency of severe occurrences is essential for improvements in city planning, transportation, and recreation safety. Increasing public awareness can mitigate potential negative effects caused by severe wind gusts. The foreknowledge of ENSO impacts on wind may also help in attempts at harnessing the energy created by wind, taking advantage of the effects. The authors wish to note that ENSO is not the only global ocean-atmosphere phenomenon altering tropospheric circulation patterns. Other oscillations, such as the North Atlantic Oscillation (Hurrell 1996) and the Pacific Decadal Oscillation (Gershunov and Barnett 1998), have also been found to impact flow patterns that affect weather globally and should be taken into consideration in forecasting methods.

APPENDIX A

List of neutral monthly means of a) peak wind gust and b) number of days that meet exceed a peak wind gust of 28 kts.

	Station	January		February		March		April		May		June		July		August		September		October		November		December	
AL	MOBILE REGIONAL AP	19.4	3.6	20.2	3.2	21.5	4.3	20.4	2.9	19.1	1.9	18.7	1.8	19.5	3.0	17.9	1.9	17.2	1.2	17.2	1.0	18.3	2.7	19.0	3.4
AL	MONTGOMERY DANNELLY	16.9	2.0	18.1	2.7	19.1	3.4	17.8	2.2	16.8	2.5	16.7	1.7	17.9	3.0	15.7	1.1	15.1	0.6	14.6	0.4	15.5	1.4	16.4	1.5
AR	FT SMITH MUNICIPL AP	18.6	3.4	19.5	3.6	22.6	7.5	22.5	6.7	20.1	4.7	18.4	2.7	17.9	2.3	17.7	2.2	17.4	1.5	17.4	1.8	18.5	3.6	18.5	2.3
AZ	FLAGSTAFF PULLIAM AP	N/A		N/A		N/A		22.7	6.9	N/A		23.2	6.3	N/A		N/A		N/A		17.9	1.3	18.4	2.9	16.4	1.8
AZ	TUCSON INTL ARPT	18.5	3.8	19.4	3.2	21.3	5.5	23.1	7.2	23.9	7.4	24.4	7.2	25.6	9.4	23.7	6.9	22.2	5.8	19.2	2.8	18.1	3.1	17.3	2.6
AZ	PHOENIX SKY HARBOR	13.7	0.9	15.0	1.5	17.5	3.6	18.4	2.9	19.3	2.7	18.6	2.6	21.9	6.6	20.6	5.8	17.6	2.6	15.2	1.3	14.0	1.1	13.1	0.5
CA	LONG BEACH DAUGHERTY	15.0	1.3	16.0	1.4	16.9	1.6	17.3	0.9	16.7	0.5	15.7	0.2	15.0	0.1	15.0	0.1	15.1	0.1	14.8	0.5	14.3	1.1	13.3	1.0
CA	BAKERSFIELD MEADOWS	13.5	1.5	14.6	1.6	15.9	2.1	16.9	1.1	18.2	1.8	17.0	0.4	16.0	0.1	15.0	0.1	14.8	0.1	13.3	0.3	12.6	0.8	12.8	1.2
CA	BISHOP AP	17.1	5.0	19.3	5.7	23.9	9.9	24.4	9.5	25.3	11.5	22.5	5.1	22.4	6.6	N/A		21.6	5.8	19.9	4.6	18.5	5.3	15.8	3.9
CA	LOS ANGELES INTL AP	16.0	2.2	17.6	2.2	18.6	2.3	18.8	2.0	18.1	0.9	17.0	0.2	16.7	0.0	16.9	0.1	16.7	0.0	16.3	0.9	15.9	1.6	15.3	1.6
CA	SAN DIEGO LINDBERGH	16.5	2.0	17.1	1.7	17.9	1.8	17.4	0.5	16.5	0.1	16.0	0.1	15.8	0.1	15.6	0.1	15.9	0.1	15.8	0.3	15.2	0.6	14.8	0.9
CA	SAN FRANCISCO INT AP	18.8	4.7	21.4	5.7	24.0	8.1	25.6	9.8	27.4	13.7	26.9	11.5	25.3	8.4	25.1	7.3	23.9	5.4	21.8	3.6	19.4	4.0	17.9	3.8
CA	STOCKTON METRO ARPT	15.7	3.0	16.6	3.3	18.1	2.9	19.6	2.2	21.1	2.4	20.5	1.6	18.3	0.3	17.9	0.9	16.4	0.6	15.6	1.3	14.4	1.2	14.7	2.3
CA	EUREKA WSO CITY	20.0	7.1	20.8	6.5	22.0	8.5	21.0	6.1	21.9	7.0	19.1	3.7	17.1	1.8	15.8	1.4	16.2	1.9	16.2	3.6	18.9	5.4	18.4	6.0
CA	FRESNO AIR TERMINAL	12.0	0.5	13.2	0.8	15.6	1.5	17.5	1.4	19.1	2.2	17.9	0.5	15.7	0.1	15.0	0.1	14.3	0.3	12.5	0.1	12.1	0.6	11.5	0.8
CO	ALAMOSA BERGMAN FLD	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A		20.6	6.7	N/A		N/A	
CO	DENVER STAPLETON AP	20.2	5.9	21.0	5.8	23.3	8.4	25.4	11.0	25.0	10.5	24.3	8.8	24.6	9.3	23.2	7.5	20.8	4.9	19.3	4.3	19.4	5.2	19.8	5.5
CO	GRAND JUNCTION WLKR	14.6	1.2	16.6	1.6	20.9	6.1	24.2	9.1	25.2	10.2	25.1	10.4	24.6	10.1	23.3	7.4	21.4	6.3	18.4	3.1	16.5	2.3	14.2	1.0
CO	PUEBLO MEMORIAL AP	19.9	6.3	22.0	7.1	26.6	12.6	29.4	16.2	28.9	17.0	29.2	15.6	29.3	16.1	26.8	12.7	23.3	8.3	22.2	7.8	21.3	8.0	21.2	8.7
CT	HARTFORD BRADLEY AP	21.2	7.1	21.4	5.5	22.2	7.5	22.6	6.1	20.4	3.1	19.4	2.3	18.1	2.1	16.4	0.9	17.5	1.9	18.7	2.7	20.2	4.9	20.5	6.6
CT	BRIDGEPORT SIKORSKY	N/A		N/A		23.9	9.2	N/A		N/A		20.1	4.1	18.6	2.3	N/A		20.8	4.5	N/A		N/A		N/A	
DE	WILMINGTN NEW CASTLE	22.1	8.1	21.7	6.4	23.4	8.3	23.7	7.4	20.7	3.9	19.8	3.2	18.9	2.6	17.3	1.5	18.0	2.1	19.1	3.1	20.8	5.2	21.3	6.5
FL	ORLANDO INTL ARPT	18.4	2.4	19.1	2.6	20.3	3.9	19.2	1.5	19.4	2.5	20.0	3.3	21.7	5.8	19.5	3.5	18.2	2.1	17.3	1.3	16.6	1.1	17.0	1.0
FL	DAYTONA BEACH REG AP	20.2	3.6	20.8	3.8	22.1	5.8	20.4	2.8	20.1	2.2	19.8	3.3	20.4	4.4	19.3	2.9	18.5	1.4	19.2	2.6	18.8	2.0	18.5	2.5
FL	KEY WEST INTL ARPT	20.5	3.8	20.3	3.5	21.3	4.5	20.9	3.1	19.3	2.0	19.0	2.9	19.3	3.3	20.3	4.1	20.9	4.3	20.1	3.1	20.5	2.7	20.3	3.5
FL	MIAMI INTL ARPT	19.7	2.6	20.5	2.5	22.0	4.5	21.3	3.1	20.9	2.5	20.6	3.0	20.8	3.5	20.5	3.1	20.3	2.9	19.7	2.6	19.6	2.1	19.2	2.1
FL	TAMPA INTL ARPT	18.2	2.1	19.1	2.3	20.0	3.3	19.4	2.2	19.4	1.8	19.7	2.8	20.1	3.0	20.0	3.7	18.9	2.4	17.4	1.2	17.1	1.0	17.2	1.4
FL	W PALM BEACH INTL AP	21.7	5.2	22.2	4.5	23.9	7.2	23.2	5.3	22.6	3.4	22.1	4.2	22.2	5.2	21.5	4.1	21.6	4.1	21.2	4.0	21.6	3.8	20.7	3.5
FL	JACKSONVILLE INTL AP	20.1	4.2	21.0	5.0	22.2	5.6	20.8	3.6	20.6	3.0	21.0	4.4	21.2	4.4	19.7	2.7	19.0	2.4	18.9	2.7	18.7	2.3	18.5	2.8
FL	TALLAHASSEE MUNI AP	17.5	1.3	19.1	1.9	20.6	3.0	19.9	1.6	19.3	1.7	19.4	2.8	20.0	2.7	18.4	2.4	17.3	1.3	17.0	0.3	16.9	0.7	16.7	0.9
GA	MACON LEWIS B WILSON	18.0	2.8	19.0	3.0	20.5	4.8	19.5	2.2	18.6	2.3	18.3	2.1	18.5	3.2	16.7	1.3	15.7	1.1	15.6	0.5	16.3	1.2	16.8	2.2
GA	AUGUSTA BUSH FIELD	18.1	3.2	19.1	3.0	20.2	4.0	19.6	2.7	18.6	2.2	18.4	2.3	19.2	3.3	17.0	1.7	15.4	0.8	15.7	0.7	16.1	1.1	16.7	2.4
GA	SAVANNAH INTL AP	18.6	3.9	19.6	3.6	20.9	5.0	19.7	2.3	18.5	2.2	18.7	2.5	19.1	3.0	17.6	2.1	16.5	1.0	16.6	1.3	16.6	1.5	16.8	2.0
GA	ATLANTA HARTSFIELD	22.0	5.9	22.8	6.5	23.8	8.1	23.1	5.9	21.1	3.4	20.4	3.2	20.8	4.4	18.9	2.4	18.2	1.5	18.7	1.4	19.5	3.0	20.8	4.3
GA	COLUMBUS METRO AP	17.4	1.8	18.4	2.0	20.1	3.5	19.3	2.4	18.1	2.5	17.1	1.3	18.0	2.2	16.1	1.1	15.8	0.4	16.2	0.5	16.5	1.5	16.8	1.8
IA	DES MOINES INTL AP	21.8	5.9	21.2	5.4	23.8	8.8	25.9	12.0	22.7	7.9	22.8	7.2	20.2	3.9	18.6	1.9	19.8	2.8	21.5	5.8	21.7	6.7	21.4	5.8
IA	SIOUX CITY MUNI AP	22.9	8.1	21.7	6.3	24.0	9.6	27.4	14.5	24.3	9.9	24.8	8.9	21.2	4.5	20.3	3.6	21.9	4.6	22.7	7.4	22.5	7.5	22.3	7.7
ID	BOISE AIR TERMINAL	16.2	2.9	17.9	2.1	20.6	4.6	21.6	5.5	21.8	6.1	21.1	4.1	19.9	3.3	19.4	3.1	18.1	1.9	17.3	1.6	17.9	2.8	17.0	2.5
ID	POCATELLO MUNICIPAL	20.7	7.1	21.7	7.5	23.2	8.7	26.3	12.8	25.3	10.4	23.8	7.5	22.8	7.6	23.1	7.4	21.0	5.5	21.4	6.8	22.4	8.5	21.3	8.6
IL	PEORIA GTR PEORIA AP	21.0	5.4	20.3	4.2	23.3	8.9	24.4	8.3	21.0	5.5	20.8	4.4	18.3	2.1	16.9	1.9	17.9	1.6	19.4	2.7	21.6	5.7	20.7	4.9
IL	MOLINE QUAD CITY AP	22.4	6.5	21.1	4.7	24.3	9.3	26.1	11.9	23.1	8.0	22.0	6.9	19.6	3.3	18.7	2.7	19.5	2.8	21.6	5.6	22.6	7.2	21.9	7.0

	Station	January		February		March		April		May		June		July		August		September		October		November		December	
IL	SPRINGFIELD CAPTL AP	21.7	5.4	20.7	4.4	23.2	8.0	24.8	8.9	21.8	7.0	20.4	4.9	18.1	2.8	16.3	1.4	18.0	2.4	20.1	3.9	22.0	6.5	21.7	5.7
IN	FORT WAYNE BAER FLD	21.3	5.7	19.7	3.4	21.8	6.1	23.1	7.1	20.7	4.3	20.5	4.3	18.1	2.3	16.5	1.3	17.8	2.1	19.5	3.4	20.9	5.5	20.3	5.1
IN	SOUTH BEND MICHIANA	22.2	6.2	20.9	4.2	22.8	7.3	24.1	8.4	21.3	5.0	20.5	4.3	18.7	2.7	16.8	1.2	18.0	1.9	19.7	3.7	21.1	4.7	21.1	5.3
IN	EVANSVILLE REG AP	19.4	4.0	18.9	3.1	21.4	6.9	22.5	6.6	19.5	3.7	18.9	2.7	16.9	2.1	15.5	1.1	16.1	1.0	17.6	2.7	19.3	3.6	18.7	3.5
IN	INDIANAPOLIS INTL AP	20.7	5.3	20.4	4.1	22.5	7.2	23.5	8.0	20.3	4.1	19.6	3.8	17.7	1.9	16.8	1.6	16.9	1.1	19.1	3.1	20.9	5.2	20.1	4.8
KS	WICHITA MID-CNTNT AP	23.3	9.1	23.5	8.4	26.3	12.8	27.2	13.6	24.7	10.8	26.0	12.5	24.0	8.8	23.8	7.6	23.7	8.7	23.6	9.1	23.5	9.3	24.0	10.1
KS	DODGE CITY MUNI AP	23.4	7.8	24.3	9.2	27.8	14.8	29.1	16.1	27.8	15.1	28.2	15.0	26.5	12.3	25.3	10.2	25.0	10.1	25.5	11.7	25.3	10.9	24.7	9.9
KS	TOPEKA MUNI ARPT	20.8	5.8	20.6	4.5	24.2	9.6	25.4	11.5	23.3	8.2	23.1	7.7	20.0	3.6	18.8	2.8	19.5	3.8	21.1	5.1	21.2	5.5	21.3	6.2
KS	GOODLAND RENNER FLD	24.9	9.9	23.9	7.5	28.8	15.8	30.9	17.9	28.7	14.8	28.7	14.9	27.3	13.9	25.7	10.7	25.2	10.1	25.3	9.7	24.5	9.5	24.9	9.9
KY	CINCI-NORTHERN KY AP	20.2	4.8	20.0	3.4	22.5	7.3	23.1	7.3	19.5	3.5	19.5	3.5	17.9	2.2	17.3	2.2	17.3	1.6	17.9	1.8	20.0	4.3	19.9	4.5
KY	LEXINGTON BLUEGRASS	19.8	3.9	19.6	3.6	21.3	6.4	21.6	5.9	18.7	2.3	18.6	3.2	17.3	2.6	16.1	1.4	15.9	1.1	17.1	1.8	19.4	3.3	19.4	4.0
KY	LOUISVILLE STANDIFRD	18.9	4.2	18.9	2.8	21.3	6.2	22.0	6.2	19.4	3.0	19.0	3.1	17.8	2.3	17.1	1.8	16.7	1.4	16.9	1.4	18.8	4.0	18.9	3.1
LA	NEW ORLEANS INTL AP	19.1	3.3	19.7	3.3	20.5	4.1	20.1	2.7	18.5	2.0	18.0	2.0	18.8	2.7	18.0	2.1	17.4	1.3	16.8	1.3	18.1	2.5	18.5	2.9
LA	SHREVEPORT REGIONAL	19.1	3.8	20.2	3.6	21.8	5.4	22.0	4.8	20.3	4.4	19.6	3.7	18.8	3.7	18.1	2.3	17.9	2.0	17.9	2.4	18.8	3.2	18.9	3.2
LA	BATON ROUGE RYAN AP	18.2	2.2	18.8	2.2	19.8	3.4	19.8	2.4	19.0	2.5	17.4	1.2	17.7	2.6	17.7	1.8	16.8	1.2	16.3	0.7	17.2	1.4	17.5	1.5
MA	BOSTON LOGAN INTL AP	26.4	12.0	26.0	10.5	26.4	12.6	26.4	11.4	23.6	7.5	22.6	5.2	21.4	3.9	20.5	2.8	21.5	4.3	23.0	6.8	24.9	10.1	26.0	12.0
MD	BALT-WASHGTN INTL AP	21.5	8.1	21.3	6.1	22.7	8.6	23.2	7.7	20.5	3.7	19.9	3.6	18.6	2.9	17.6	2.0	17.1	1.8	18.1	2.7	20.5	5.3	20.6	6.1
ME	PORTLAND INTL JETPRT	20.8	5.8	20.7	5.0	22.3	7.2	22.8	7.0	21.2	4.5	20.0	2.4	18.2	0.9	17.6	1.4	18.5	2.2	20.1	4.3	20.4	5.2	20.9	6.2
MI	FLINT BISHOP ARPT	22.1	6.3	20.5	4.8	22.1	6.9	23.8	7.8	21.1	4.9	20.6	4.1	18.5	2.2	18.0	2.9	19.2	3.2	19.9	4.2	22.0	7.0	21.5	7.3
MI	LANSING CAPITAL CITY	22.2	6.3	21.3	5.0	22.8	6.8	23.5	7.8	20.8	5.1	20.5	3.6	18.9	2.6	17.3	1.2	18.9	2.6	19.9	3.7	21.6	6.2	21.5	6.5
MI	MUSKEGON CO ARPT	24.1	9.7	23.0	6.2	24.0	9.1	24.1	9.0	21.0	4.8	20.6	5.2	19.4	3.2	18.9	3.1	20.5	4.6	23.1	8.5	24.5	9.8	23.9	9.5
MI	SAULT STE MARIE ARPT	20.8	6.7	18.9	3.5	20.1	4.9	22.0	6.0	20.2	2.8	18.9	2.4	18.3	1.6	17.3	1.5	18.9	2.9	20.3	5.3	21.0	5.9	20.1	5.1
MN	DULUTH INTL AP	21.8	5.6	20.0	3.4	21.9	6.3	23.8	8.0	22.7	6.5	22.5	7.1	20.4	4.1	20.0	3.5	21.5	4.6	22.2	6.6	21.2	5.4	20.6	4.5
MN	INTERNATL FALLS ARPT	17.5	2.7	17.3	1.1	19.5	3.5	21.0	4.9	20.7	4.0	21.1	4.5	19.9	2.8	19.4	2.9	20.4	3.3	20.6	4.7	18.8	2.6	17.2	1.5
MN	MINNEAPOLIS INTL AP	21.1	5.1	19.9	3.2	23.1	7.2	25.3	10.9	23.5	7.4	23.9	8.1	22.1	5.6	21.5	4.4	22.4	5.9	22.6	7.3	21.5	5.7	20.6	4.9
MN	ROCHESTER MUNI AP	25.0	10.7	23.9	8.6	26.0	11.8	28.0	13.8	25.7	10.9	26.7	12.4	23.8	8.3	22.3	5.7	23.9	7.8	25.3	11.3	25.3	11.5	25.0	11.0
MN	ST CLOUD MUNI ARPT	17.2	2.3	16.0	1.1	18.0	2.3	21.6	5.0	19.4	3.0	18.4	2.0	16.3	1.0	16.2	0.7	17.4	1.3	17.6	1.7	17.2	1.6	16.3	1.5
MO	ST LOUIS LAMBERT AP	22.7	7.0	21.9	5.4	24.1	8.7	25.7	10.2	22.5	6.2	21.7	5.6	19.8	3.0	18.4	1.8	19.4	2.8	20.9	4.9	21.9	6.0	21.7	5.4
MO	SPRINGFIELD REG AP	20.9	5.6	20.5	4.1	22.9	7.9	23.3	8.1	19.7	3.9	19.5	3.8	18.0	1.9	17.4	1.5	17.8	1.6	19.2	2.8	20.6	4.8	20.5	4.4
MS	MERIDIAN KEY FLD	17.5	1.6	18.5	2.3	20.2	3.9	19.2	3.0	17.4	1.5	16.3	1.9	16.9	2.8	15.2	0.8	15.6	0.5	15.4	0.7	16.9	2.0	17.4	2.0
MT	BILLINGS LOGAN AP	23.0	8.6	21.8	5.8	21.5	5.5	23.3	7.8	23.1	7.8	23.7	8.1	23.3	8.2	22.4	7.1	20.3	3.6	21.1	5.5	23.1	7.1	24.2	10.1
MT	GREAT FALLS INTL AP	24.9	12.6	23.9	10.3	23.4	9.4	24.7	10.5	24.5	9.7	25.1	10.3	23.5	8.8	23.9	9.1	22.2	7.5	24.7	11.5	26.2	13.6	26.8	14.7
MT	HELENA ARPT	18.5	6.4	18.8	5.4	21.0	6.3	23.9	9.3	24.3	9.3	25.3	10.1	23.9	7.8	22.4	6.8	19.7	4.1	19.9	5.9	20.6	7.4	19.5	6.4
MT	KALISPELL GLACIER AP	13.7	2.4	15.6	3.1	17.3	2.5	20.6	3.4	20.2	3.4	20.0	2.9	19.1	2.1	18.9	2.6	17.9	2.6	15.4	2.0	15.0	2.2	14.6	3.0
MT	MISSOULA JOHNSN-BELL	15.0	2.9	16.6	3.8	19.2	4.4	22.6	6.7	22.5	6.7	23.0	7.7	23.0	6.8	22.8	7.0	19.0	3.1	16.4	3.0	16.1	3.3	14.8	3.0
MT	GLASGOW INTL AP	20.1	5.6	20.4	4.8	21.9	7.3	25.0	10.0	26.2	11.9	25.9	10.7	24.2	9.0	24.0	7.1	23.5	7.4	22.2	6.4	20.1	4.5	20.3	6.3
NC	RALEIGH DURHAM AP	18.7	3.3	19.4	3.3	20.7	4.1	20.6	4.6	17.7	1.2	16.9	1.6	16.8	1.9	15.7	1.6	14.9	0.4	16.2	0.9	17.3	1.6	17.4	2.4
NC	GRNSBR,HGH PT,W-S AP	17.5	2.6	18.3	2.5	19.7	3.6	19.8	3.9	17.3	1.5	16.5	1.1	16.9	2.5	14.8	0.5	14.3	0.4	15.4	1.1	16.4	1.6	16.4	2.0
NC	WILMINGTON NEW HANVR	20.3	5.1	20.7	4.7	22.6	6.6	22.2	5.6	20.1	2.5	19.6	2.2	19.6	2.4	17.5	1.6	17.2	1.2	18.1	2.3	18.3	2.2	19.4	4.1
NC	CHARLOTTE DOUGLAS AP	18.6	3.2	19.6	3.0	21.0	4.8	21.2	5.2	19.0	2.1	17.9	1.9	18.1	2.4	16.6	1.8	16.1	1.0	16.3	0.8	17.2	2.1	17.7	3.0
ND	FARGO HECTOR FIELD	22.7	7.7	22.0	6.2	23.3	9.2	25.1	10.6	24.5	10.5	24.1	10.0	21.9	5.2	21.8	5.6	22.2	6.8	24.0	9.5	22.4	6.7	21.8	7.4
NE	GRAND ISLAND ARPT	23.4	8.5	21.7	5.3	24.9	10.8	28.2	15.1	25.2	10.6	25.2	10.4	22.3	5.9	21.6	5.0	22.3	5.3	23.5	8.9	22.9	8.0	23.5	8.6
NE	NORFOLK STEFAN AP	24.4	9.4	23.1	6.8	25.4	10.8	28.3	15.3	25.3	11.0	25.6	10.9	23.1	7.3	22.6	6.5	23.9	8.1	24.5	9.5	24.3	9.2	24.4	10.1
NE	NORTH PLATTE BRD FLD	21.4	6.5	21.2	5.1	24.5	10.0	27.8	13.7	25.3	10.4	25.2	10.0	23.8	8.1	22.6	6.3	22.8	6.9	23.5	9.2	22.8	7.4	21.2	5.7
NH	CONCORD MUNI AP	19.6	5.5	20.1	5.2	21.0	6.5	21.5	5.6	19.8	2.9	19.4	2.6	18.0	1.3	16.6	1.3	17.3	1.4	17.8	3.1	19.1	5.0	19.4	5.8
NH	MOUNT WASHINGTON	76.3	30.3	72.8	27.2	68.9	29.7	63.5	27.7	54.3	28.6	52.1	26.7	47.6	26.5	44.0	25.1	51.7	26.0	59.9	28.9	68.6	29.2	73.0	30.6
NJ	NEWARK INTL ARPT	23.5	9.1	23.5	8.5	24.1	9.6	24.8	9.8	21.4	5.6	21.3	5.1	19.3	2.5	18.6	2.1	18.8	2.0	19.8	3.8	21.8	6.9	23.0	8.6
NM	ROSWELL INDSTRL ARPK	19.2	5.6	21.3	6.6	26.2	12.2	26.2	11.4	26.4	12.3	25.8	10.7	21.4	5.3	21.1	3.9	18.7	1.8	19.3	3.2	18.6	3.6	18.4	4.1

	Station	January		February		March		April		May		June		July		August		September		October		November		December	
NM	ALBUQUERQUE INTL AP	20.1	5.4	21.8	6.8	26.2	13.5	28.7	16.4	28.8	17.1	28.2	15.8	27.3	14.0	24.6	9.6	22.3	6.9	20.6	6.9	19.7	5.9	18.8	5.4
NV	ELY YELLAND FIELD	19.2	4.0	20.9	5.2	22.8	7.5	24.8	9.4	26.1	12.2	26.2	12.0	26.4	13.3	25.6	10.6	23.0	6.9	19.8	3.6	20.3	4.7	19.9	4.0
NV	LAS VEGAS MCCRN INTL	16.8	4.9	19.3	6.0	23.7	10.2	25.0	11.4	25.8	12.8	25.4	11.4	24.4	8.9	23.7	7.9	21.3	5.6	18.4	4.5	18.2	5.4	16.0	3.6
NV	RENO CANNON INTL AP	15.8	4.5	19.7	5.6	23.1	8.5	24.8	8.9	24.7	9.1	25.3	10.4	24.5	8.1	23.6	6.2	20.3	3.8	17.6	3.1	18.4	5.9	17.0	5.6
NV	WINNEMUCCA MUNI AP	16.6	2.4	18.9	3.3	20.7	4.8	23.0	6.3	23.2	7.0	24.0	7.8	22.8	5.6	22.7	5.3	20.2	3.2	17.4	1.7	17.6	2.8	16.6	2.8
NY	BINGHAMTON LINK FLD	22.8	7.7	22.2	6.7	23.5	8.7	24.3	8.7	21.4	4.2	20.8	3.4	19.3	2.1	18.4	1.6	19.1	1.8	20.7	4.6	22.8	7.1	22.8	7.4
NY	NEW YORK LAGUARDIA	26.5	12.7	26.1	10.8	26.3	11.1	26.5	11.7	23.8	8.1	22.8	5.2	21.4	3.5	21.6	3.7	21.7	4.2	22.1	6.0	24.8	9.6	26.0	11.5
NY	BUFFALO GR BUFFLO AP	27.1	12.6	24.6	9.4	24.2	9.0	24.9	9.0	22.8	7.3	21.2	5.7	20.0	4.2	19.2	3.1	20.0	4.4	22.1	7.3	24.6	10.8	25.0	11.7
NY	ALBANY COUNTY AP	23.4	8.8	23.3	8.2	24.7	10.8	24.6	9.3	22.2	6.3	21.6	5.4	20.0	3.2	18.6	2.5	19.5	3.0	20.7	5.8	22.6	7.9	23.1	8.6
NY	ROCHESTER INTL AP	23.5	8.6	22.0	5.8	22.6	7.2	23.9	8.2	20.7	4.7	20.1	4.0	18.3	1.9	17.9	2.1	18.6	2.6	20.2	5.3	22.1	6.6	21.8	7.1
NY	SYRACUSE HANCOCK AP	22.5	8.3	21.3	5.8	22.7	8.1	22.8	7.1	20.5	4.3	20.2	3.7	19.0	2.5	17.6	2.5	18.6	3.1	19.3	4.8	21.3	5.9	22.3	8.3
OH	CLEVELAND HOPKINS AP	23.8	8.6	21.9	6.1	23.9	8.7	24.4	8.6	21.1	5.1	20.9	4.7	19.3	2.4	18.5	2.0	19.6	3.9	21.0	5.9	23.4	8.7	23.0	8.6
OH	COLUMBUS INTL AP	20.3	4.7	19.0	3.0	21.3	6.0	22.3	7.0	19.2	3.3	18.9	3.5	17.4	2.5	16.7	2.0	16.6	1.1	18.0	2.6	19.9	4.7	20.1	5.2
OH	YOUNGSTOWN MUNI AP	22.3	7.2	20.9	5.1	22.5	6.7	23.9	7.5	20.5	3.8	19.5	3.1	18.5	1.9	17.6	1.9	18.6	2.7	19.3	3.1	21.8	6.2	21.9	7.0
OH	AKRON-CANTON REG AP	22.2	6.4	20.7	4.8	22.8	7.3	23.3	7.2	20.2	3.9	19.9	3.6	18.4	1.9	17.7	1.9	18.2	2.6	19.3	3.5	21.6	6.3	21.7	6.7
OH	DAYTON INTL ARPT	21.1	5.8	19.6	3.7	21.8	6.5	23.1	8.2	20.0	3.8	19.6	3.9	18.2	2.6	17.1	1.6	17.5	2.4	18.7	2.6	20.6	4.9	21.1	5.9
OH	TOLEDO EXPRESS AP	22.4	6.6	21.0	4.7	23.1	7.3	24.5	9.1	22.0	5.6	20.4	4.5	18.0	1.9	17.2	1.2	18.9	2.9	20.8	4.4	22.3	7.1	21.1	5.3
OK	OKLAHOMA CITY ROGERS	22.9	7.9	24.1	8.8	26.4	13.0	26.8	13.0	24.1	8.2	23.1	7.2	20.7	3.3	20.4	2.9	20.5	4.6	22.7	7.6	23.1	8.2	23.5	8.5
OK	TULSA INTL AP	21.0	5.5	21.4	4.6	23.8	9.7	25.0	10.6	22.8	6.6	21.6	6.4	19.5	1.7	19.4	2.7	19.2	2.8	20.0	3.9	20.6	4.9	20.8	5.0
OR	PENDLETON MUNICPL AP	17.0	5.4	17.8	4.5	20.4	7.1	23.5	9.6	22.4	7.9	22.6	6.9	21.7	5.5	20.8	4.3	18.6	3.3	17.7	3.9	19.0	6.4	18.3	6.8
OR	EUGENE MAHLON SWEET	15.4	1.9	17.3	2.6	17.4	2.0	18.2	1.6	17.4	1.3	17.6	0.5	18.6	0.4	18.0	0.5	17.5	0.5	15.9	1.0	16.7	2.2	16.5	2.6
OR	MEDFORD JACKSON CO	12.5	2.8	13.6	2.2	15.6	1.8	16.8	1.5	17.3	1.2	17.3	0.5	16.9	0.2	16.1	0.4	14.2	0.4	11.5	0.6	11.5	1.7	11.8	2.4
OR	PORTLAND INTL ARPT	20.8	6.6	20.3	4.9	19.1	4.0	18.5	2.4	17.0	0.8	16.6	0.3	16.3	0.0	15.7	0.0	15.6	0.8	15.7	1.8	19.4	4.5	20.6	6.4
OR	SALEM MCNARY FIELD	16.3	3.3	18.2	4.1	17.4	2.6	17.9	2.3	16.9	0.6	16.4	0.1	16.4	0.2	16.0	0.1	15.6	0.4	14.9	1.6	17.7	3.6	18.0	5.1
OR	ASTORIA CLATSOP ARPT	22.0	7.9	22.9	7.7	21.2	5.2	22.3	6.2	20.5	3.2	19.3	1.5	18.5	0.8	18.0	0.9	18.3	1.4	18.7	4.1	23.3	9.5	23.3	9.5
PA	PHILADELPHIA INTL AP	20.9	6.1	20.9	5.1	22.2	6.6	22.1	5.5	19.7	2.9	18.8	3.0	17.8	2.1	16.6	1.1	17.1	1.6	17.9	2.3	19.5	3.9	20.3	5.6
PA	ALLENTOWN A-B-E INTL	22.2	8.2	22.2	6.8	23.5	8.6	24.5	8.7	21.9	5.6	20.7	3.4	18.8	2.4	17.6	1.8	18.2	2.2	19.2	4.4	21.5	6.5	21.8	8.2
PA	WILKES-BARRE SCRANTN	22.0	6.5	21.5	5.4	22.7	8.1	24.3	8.3	21.4	5.2	20.4	3.4	19.0	2.4	17.9	1.6	18.2	1.8	19.6	3.7	21.3	5.6	21.4	6.5
PA	WILLIAMSPRT-LYCOMING	22.5	8.0	21.6	6.3	23.6	9.7	24.6	9.8	21.6	6.3	20.6	4.1	18.1	1.9	17.3	2.2	17.7	2.3	18.8	4.1	21.7	6.4	22.1	7.9
PA	PITTSBURGH GR P'BURG	21.4	6.6	21.0	5.1	22.4	6.8	23.6	8.1	20.3	4.4	19.0	3.2	17.9	2.4	17.1	1.8	17.3	1.6	18.7	3.0	20.7	5.9	20.6	5.5
RI	PROVIDENCE GREEN ST	23.5	8.9	23.5	7.5	24.5	9.9	25.3	9.1	22.6	5.3	21.2	3.4	19.5	1.2	19.0	1.6	19.5	2.5	20.8	4.8	22.6	7.6	23.0	8.5
SC	CHARLESTON INTL ARPT	19.4	3.6	20.7	4.2	22.3	6.0	21.6	4.1	20.1	2.4	19.4	2.6	19.4	2.7	18.1	1.8	17.7	1.0	17.6	1.7	17.9	2.1	18.5	3.2
SD	HURON REGIONAL AP	21.8	6.7	21.7	5.8	23.3	8.6	25.9	11.0	24.1	9.3	24.5	9.1	23.0	7.8	22.8	6.7	22.9	7.0	23.7	9.4	22.6	6.9	21.5	7.1
SD	SIOUX FALLS FOSS FLD	22.5	6.7	22.1	6.3	24.4	9.9	27.1	13.7	24.5	10.3	24.7	9.4	23.5	7.6	22.3	5.9	22.9	6.7	23.4	8.7	22.6	7.1	22.1	7.1
TN	BRISTOL TRI CITY AP	17.3	4.1	17.3	3.0	19.3	4.4	20.7	4.9	17.4	2.6	17.0	1.9	16.0	1.9	14.1	1.0	13.4	0.5	14.1	0.8	15.7	2.5	16.2	2.7
TN	CHATTANOOGA LOVELL	16.8	1.7	17.5	1.8	19.4	3.2	19.3	2.9	17.5	1.8	17.2	1.7	16.7	2.2	15.3	1.2	14.3	0.4	14.4	0.4	15.1	0.9	15.7	1.3
TN	KNOXVILLE MCG TYSON	15.9	2.5	16.7	2.5	18.4	4.2	18.6	3.6	16.4	2.1	16.6	2.2	15.3	1.7	14.0	0.9	13.3	0.4	13.9	0.6	15.1	2.1	15.4	2.0
TN	MEMPHIS INTL ARPT	19.8	4.2	19.9	4.4	22.4	7.3	22.9	7.1	20.8	4.5	19.5	3.2	18.5	2.7	16.9	1.6	16.7	1.2	17.1	1.2	19.0	3.4	19.3	3.6
TN	NASHVILLE METRO AP	19.6	4.7	19.8	4.1	21.6	6.7	21.2	5.3	18.6	2.9	18.6	2.9	18.4	2.9	17.0	1.7	16.5	1.0	17.2	1.5	19.1	3.8	19.6	4.2
TX	DALLAS/FT WORTH AP	22.5	7.9	23.0	7.7	25.4	11.5	25.9	11.2	24.4	9.9	22.6	6.3	21.3	4.3	19.9	2.5	20.3	4.0	20.5	5.2	21.8	6.7	21.4	6.0
TX	VICTORIA REGIONAL AP	21.7	7.2	22.4	6.2	23.5	6.8	24.0	6.9	22.7	5.3	21.6	3.0	21.7	2.8	21.3	2.8	19.7	2.2	19.8	3.1	21.2	5.1	20.8	5.0
TX	PORT ARTHUR JEFFERSN	21.2	5.0	21.4	3.9	22.5	6.4	22.6	5.2	21.4	4.5	20.4	2.7	19.2	2.7	18.6	2.6	18.6	1.3	19.1	2.7	20.3	4.3	20.4	3.5
TX	BROWNSVILLE INTL AP	21.8	6.1	23.4	7.6	24.9	10.2	25.9	10.9	24.3	8.3	23.5	5.6	23.4	4.9	22.5	3.7	20.9	2.4	20.8	3.6	21.7	6.0	21.5	6.0
TX	SAN ANTONIO INTL AP	19.0	3.7	19.3	3.4	21.4	4.8	20.8	3.5	20.4	3.5	20.0	2.1	19.8	1.8	19.3	1.8	18.7	1.7	18.0	2.6	18.4	3.0	18.1	2.6
TX	AUSTIN MUNICIPAL AP	20.9	5.4	21.2	4.8	22.8	6.1	22.0	4.7	21.5	4.7	20.5	3.1	19.8	1.6	19.6	2.1	18.7	2.2	18.7	3.2	20.4	4.6	20.4	4.9
TX	WACO MADISN COOPR AP	20.1	4.8	21.6	5.8	23.9	8.6	23.1	6.8	22.5	6.3	21.3	4.2	20.1	2.4	20.6	3.5	20.2	4.0	20.0	4.5	20.8	5.8	20.6	4.8
TX	ABILENE MUNI AP	22.8	8.2	23.7	8.1	26.5	13.7	26.6	13.3	26.1	12.0	24.2	8.1	21.8	3.4	20.4	2.6	20.5	3.6	21.6	6.1	22.5	6.9	22.5	7.4
TX	WICHITA FALLS MUN AP	21.1	5.9	22.7	6.7	25.0	10.4	25.6	10.2	25.1	9.7	23.6	6.7	21.1	3.0	20.8	3.7	20.8	4.1	20.8	5.2	21.2	6.0	20.6	4.9

	Station	January		February		March		April		May		June		July		August		September		October		November		December	
TX	MIDLAND REGIONAL TER	23.1	7.4	24.1	8.0	27.6	13.5	28.8	15.5	27.8	14.6	27.2	12.2	24.7	7.4	23.5	6.2	22.2	4.1	22.8	6.8	23.1	6.5	22.9	7.4
TX	SAN ANGELO MATHIS FD	21.4	5.1	22.3	6.1	24.8	10.6	25.4	10.4	25.3	8.4	24.6	8.5	22.0	3.8	21.2	2.7	20.4	2.8	20.3	4.1	21.6	5.5	20.6	4.4
TX	LUBBOCK REGIONAL AP	22.5	7.7	24.1	8.5	27.6	13.9	28.8	14.9	27.9	14.8	26.8	11.6	22.7	6.1	21.1	3.2	20.6	3.5	21.8	6.0	22.2	6.9	21.5	5.1
TX	EL PASO INTL ARPT	18.3	4.5	20.6	6.1	24.4	9.9	25.4	10.6	24.8	10.1	23.5	7.2	22.7	6.2	20.1	4.0	17.6	2.3	17.8	3.1	17.9	3.6	17.1	3.4
TX	AMARILLO INTL ARPT	25.2	11.0	26.3	11.6	29.7	17.0	31.0	19.6	28.8	16.7	28.2	15.6	25.7	9.6	24.7	8.5	23.9	6.5	25.2	10.0	25.0	9.6	25.0	10.7
UT	SALT LK CITY INTL AP	17.3	4.1	18.7	4.6	21.9	7.5	23.3	8.5	23.2	8.3	23.4	8.1	23.3	8.8	23.4	8.5	20.9	6.2	18.3	4.4	18.7	5.3	17.2	4.4
VA	LYNCHBURG MUNI AP	19.6	4.5	19.5	3.4	21.2	4.7	22.5	6.4	18.8	2.3	18.4	2.2	17.3	1.9	16.3	1.2	15.6	0.3	17.5	1.6	18.4	2.4	18.3	2.9
VA	NORFOLK INTL ARPT	23.1	9.0	24.2	9.1	25.2	10.9	24.6	8.8	22.3	5.9	21.7	4.6	20.9	4.0	20.2	3.8	20.2	3.5	20.6	3.8	22.2	7.0	22.5	7.3
VA	RICHMOND BYRD AP	19.1	3.6	19.3	3.6	20.9	5.5	21.3	4.9	19.1	2.7	18.3	2.2	17.9	2.4	16.6	2.1	16.1	1.3	17.1	1.7	18.1	2.9	18.1	3.2
VA	ROANOKE WOODRUM AP	22.2	9.7	21.4	7.3	22.5	8.7	23.6	8.9	19.3	3.8	18.6	2.4	17.7	2.6	16.2	1.0	15.2	0.7	17.1	3.4	18.8	5.6	20.2	6.7
VA	WASHINGTN DC NATL AP	21.8	7.6	22.1	7.3	23.4	8.4	24.1	9.0	21.0	4.5	20.1	3.9	19.7	3.4	18.1	2.3	17.7	2.3	18.8	3.5	21.1	6.3	21.3	6.6
WA	SPOKANE INTL ARPT	17.2	4.1	18.3	4.3	19.1	3.5	21.6	5.1	20.6	3.5	20.9	3.8	19.9	2.9	19.4	2.6	18.0	1.9	17.3	3.1	18.4	4.7	18.1	5.6
WA	OLYMPIA AP	15.2	2.7	17.2	2.6	17.8	2.6	18.8	2.1	17.6	1.1	16.7	0.6	15.2	0.1	15.3	0.3	14.9	0.6	15.6	1.6	18.0	3.5	17.0	3.5
WA	SEATTLE-TACOMA AP	18.8	3.6	19.1	2.9	18.4	2.2	18.1	1.8	16.9	0.9	16.2	0.3	15.1	0.1	15.2	0.3	15.2	0.4	16.4	2.1	20.0	4.4	19.9	5.1
WA	YAKIMA AIR TERMINAL	13.4	2.6	15.7	3.6	19.0	5.7	22.7	8.6	22.2	7.6	21.7	6.6	20.9	4.5	18.9	3.2	17.6	3.1	16.7	3.9	16.7	5.3	14.2	3.8
WI	MADISON DANE CNTY AP	20.6	4.8	20.0	3.2	21.9	6.6	23.9	8.2	21.7	5.6	22.1	6.1	19.6	3.2	18.5	2.5	19.4	2.7	20.8	4.9	21.1	5.6	20.1	4.3
WI	MILWAUKEE MTCHLL FLD	23.0	8.1	22.2	5.4	23.4	7.9	25.4	10.2	22.2	7.1	21.7	6.2	21.2	4.6	20.0	3.5	20.9	3.8	22.7	7.2	23.7	9.0	22.7	7.9
WI	GREEN BAY AUSTIN STR	19.8	3.9	19.1	2.4	20.4	5.0	22.8	6.7	20.7	4.4	19.7	3.5	18.5	2.4	17.8	2.1	18.9	2.0	19.7	3.9	20.5	4.2	19.2	3.4
WV	CHARLESTON KNWA AP	18.7	4.2	17.8	2.9	20.2	6.0	20.9	5.8	17.3	2.7	16.8	2.3	15.3	2.2	14.0	1.2	13.9	0.7	14.3	1.2	16.6	2.7	18.3	4.3
WY	CHEYENNE MUNI AP	30.8	18.2	29.8	15.9	29.9	16.5	30.4	16.6	27.5	13.6	27.7	13.5	26.3	11.6	25.8	10.6	25.3	10.3	26.3	13.1	28.2	14.6	31.3	18.4
WY	LANDER HUNT FIELD	15.8	3.5	16.3	3.3	19.5	5.3	23.2	9.1	23.9	9.7	25.3	11.2	25.3	10.9	23.9	10.5	20.2	5.7	18.1	4.4	17.2	4.0	17.8	4.6
WY	SHERIDAN COUNTY AP	20.0	7.3	19.1	5.7	21.7	7.8	25.3	11.6	24.1	9.3	22.8	7.5	22.9	8.2	22.2	7.2	20.6	6.0	21.0	6.7	20.0	6.6	20.1	7.2

APPENDIX B

Kolmogorov-Smirnov Test – A distribution-free test for general differences in two populations (Hollander and Wolfe 1999).

Given two independent samples, $X_1,\ldots,X_m$ and $Y_1,\ldots,Y_m$, the null hypothesis $H_0 =$ the two distributions are equal is tested against the alternative $H_1 =$ they are different. Let $Z_1,\ldots,Z_N$ (where $N = m+n$) be the ordered values for the combined samples of $X_1,\ldots,X_m$ and $Y_1,\ldots,Y_m$. From this we obtain the empirical distribution functions A and B,

$$A_i = \frac{number\ of\ sample\ X's\ \leq\ Z_i}{m} \qquad \textbf{(1a)}$$

and

$$B_i = \frac{number\ of\ sample\ Y's\ \leq\ Z_i}{n} \qquad \textbf{(1b)}$$

where $1 \leq i \leq N$. We now compute the two-sided two-sample Kolmogorov-Smirnov test statistic J,

$$J = \left(\frac{mn}{N}\right)^{\frac{1}{2}} \max_{1 \leq i \leq N} \left|A_i - B_i\right| \qquad \textbf{(2)}$$

Reject H_0 if the observed significance level, $F(J) < \alpha$ (this study uses the level of significance, $\alpha = 0.05$), where

$$F(J) = 1 - \sum_{k=-\infty}^{\infty} (-1)^k e^{-2k^2 J^2}. \qquad \textbf{(3)}$$

From **(3)**, if $J \geq \textit{the critical value} = 1.3581$, there is a probability of less than 5% that $X_1,\ldots,X_m$ and $Y_1,\ldots,Y_n$ have equal distributions, and H_0 is rejected in favor of H_1.

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