# DIRECTIONAL CLIMATOLOGY AND PRECIPITATION ON THE SOUTHERN HIGH PLAINS OF NORTH AMERICA

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**Abstract**.–There is a direct and observable connection between wind direction and atmospheric conditions; however, the exact relationship depends on location and the physical characteristics of surrounding geographic features. In this study, attempts have been made to better quantify relationships between wind direction and resulting atmospheric conditions on the Southern High Plains of North America. A 48-year record (1973-2020) of hourly observations of climate variables paired with observations of wind direction provided the raw data from which directional distributions of climate variables were computed. Results of these analyses suggest that north-northeast winds tend to be associated with the highest precipitation and the highest relative humidity; however, north-northeast winds were not associated with exceptionally high absolute humidity, as indicted by fairly moderate dew point values. South-southeast winds tended to have the highest absolute humidity or the highest dew point temperatures. Directional distributions of precipitation were found to vary only marginally with the seasons. Although one would assume that directional distributions of precipitation would vary with geographic location, a comparison of distributions computed from data collected at three meteorological stations on the Southern High Plains proved inconclusive. Results suggest that the Lubbock and Midland stations follow nearly identical patterns whereas the Amarillo distribution appears to deviate somewhat from the other two sites.

Keywords: wind direction, atmospheric conditions, Llano Estacado

Wind velocity is a vector quantity that is properly described by a scalar magnitude (wind speed) and direction. However, wind velocity is an unconventional vector. The direction of a more conventional vector is reported as the direction of movement whereas the wind velocity vector is reported as the direction winds are "blowing from" rather than the direction winds are "blowing to".

The reason for this unconventional reporting is rooted in human experience. It has long been recognized that there is a direct and

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observable connection between the direction winds are blowing from and climatic conditions. For example, winds blowing from sea to land are typically moist and can lead to increased humidity and a higher potential for rainfall. The opposite is true of winds blowing from dry desert regions. Of course, the exact relationship between wind direction and climate depends on location and the physical characteristics of surrounding geography and sources of moisture.

On the Southern High Plains of North America, the key source of moisture is the Gulf of Mexico and winds that convey moisture from the Gulf tend to be moist and associated with a higher probability of precipitation (Orton 1964). Winds with a westerly component are typically dry and tend to promote desiccation of the landscape. Northerly winds, often associated with cold fronts, convey cold and dry continental polar air to regions of relative warmth. Thus, the semi-arid Southern High Plains is a transitional region located between the arid conditions to the west and northwest and the humid climates to the east and southeast.

In the present study, attempts have been made to better quantify the relationship between wind direction and climatic conditions near Lubbock, Texas, the largest city in the Southern High Plains. The primary focus is on climate factors such as temperature, relative humidity, dew point, wind speed, and precipitation. The goal was to determine average or normal climatic conditions associated with a given wind direction. This was accomplished by conditionally averaging hourly data provided by the National Weather Service. Measured hourly values were sorted by wind direction and the climate variables of interest are averaged separately for each wind direction sector. The result of this process is a conditionally averaged climate variable associated with a given wind direction.

*Past Work*.–The subject of wind direction and rainfall was investigated by von Herrmann (1925) in a paper titled "The Rain-Bearing Winds at Atlanta, Ga." von Herrmann was attempting to answer the question: "From what direction does the wind mostly blow during rain?" von Herrmann focused on hourly records of precipitation and wind direction measured over a 20-year period in Atlanta. He found that the largest amount of rain occurred with east and southeast winds, as expected, since the primary source of moisture is the Atlantic Ocean to the east and southeast of Atlanta. But he was surprised to find that a substantial amount of rainfall occurs with northwest winds during the spring and summer months of May through August.

Following the publication of this paper, a number of similar papers were published for other locations in the United States (Reed 1927; Epperly 1933; Bunch 1937). A study of central Oklahoma by Epperly (1933) is perhaps the most pertinent to our study of the Southern High Plains since central Oklahoma is not far from the Texas High Plains. Epperly's study of rain-bearing winds found that the wind of rain periods had little relation to the prevailing direction of surface winds. Epperly found that the prevailing direction of the surface wind was from the south, yet winds during rain periods were from the north from September to March, equally divided between north and south in April and May, northeast during June and July, and equally divided between north and southeast in August. Epperly found that, during April and May, rain-bearing winds shifted from south to north and, during June and July, there was a shift from south to northeast. Since June and July were the months with the greatest frequency of thunderstorm development, Epperly suggested that this contributed to the shift of the rain-bearing winds to more northerly directions.

*Physical location*.–The Southern High Plains, also known as the Llano Estacado or Staked Plains, is a vast physiographic region located in western Texas and eastern New Mexico (Figure 1) (Shumard 1892, Johnson 1901). Renowned for its remarkably level surface and the towering escarpments along its outer margins, the elevated surface of the Southern High Plains forms an immense tableland that stands in high relief at the southern end of the Great Plains of North America (Cummins 1892; Fenneman 1931).

To the casual observer, most of the Southern High Plains appears absolutely flat but no natural surface can be completely flat and the Southern High Plains is no exception. Over a distance of 400 km, the surface elevation grades from a high of 1640 m at its northwestern edge to a low of 720 m along its southeastern edge. The general downward


Figure 1. Map showing the location of the meteorological stations in Amarillo, Lubbock, and Midland on the Southern High Plains.

slope of the plain is toward the east-southeast at a grade of 2.3 m/km or around 0.2%. Such a gradual slope is, for all practical purposes, imperceptible.

These elevated plains lie in a semi-arid zone between the arid deserts of the American Southwest and the more humid regions of central and eastern Texas. The Southern High Plains has a warm, temperate, subtropical climate characterized by mild and dry winters and warm and relatively wet summers (Blackstock 1979). In Lubbock County, average annual precipitation is 464 mm but annual rainfall amounts are extremely variable. In 1941, the wettest year on record, total precipitation was 1,030 mm whereas only 149 mm of rain fell in 2011, the driest year on record. Maximum precipitation usually occurs during the months of May and June, when warm and moist tropical air is carried far inland from the Gulf of Mexico. Warm season rainfall occurs most frequently in the form of intense afternoon and evening convective thunderstorms, often resulting in significant runoff (Joel 1937).

## MATERIALS & METHODS

In climatology, it is common practice to define average or mean values of climate variables such as wind speed, temperature and humidity. Here, similar climatic averages are obtained for specific wind direction sectors.

This analysis focuses exclusively on hourly observations since one can usually define a definitive wind direction each hour. This is not true of daily weather observations. During a typical 24-hour period, wind direction can shift significantly; therefore, it is often difficult to associate a daily-average climate variable with a single representative wind direction. For example, winds can be blowing from the south in the morning and from the north in the evening during a given 24-hour period and the resulting vectorially averaged wind direction may not faithfully represent the actual wind direction when precipitation was occurring.

The National Weather Service (NWS), formerly known as the United States Weather Bureau, has collected long-term records of hourly weather observations at various sites across the United States. The length of record depends upon the location and the climate factor of interest. In the Lubbock area, hourly observations have been recorded at two sites since the early 1940s. The longest and most continuous record was obtained at the Lubbock International Airport, formerly known by various names including the South Plains Army Airfield, West Texas Air Terminal, South Plains Airport or the Lubbock Municipal Airport (Abbe 2014).

Ideally, one would prefer a uniform data set with hourly observations for each hour of each day but this is rarely the case. Throughout the 1940s there are large data gaps in the Lubbock data, some random and some systematic. In 1946, hourly weather observations were obtained only during the day from 7:00 to 17:00 but not at night. From 1965-1972, weather observations were obtained every three hours instead of every hour. Starting in 1973, the NWS adopted a more rigorous schedule of hourly observations every day of the year. In this study, we limit our consideration to data collected from 1973-2020.

Of course, there are missing values that occur randomly throughout the data set for all variables. These missing values may result from instrument failure or human error and are often flagged by quality codes that indicate the reason for omission. Data continuity is desirable but not absolutely critical since each set of hourly observations can be treated as a separate entity.

With regard to this analysis, it is important that each climate variable be paired with an observed wind direction; however, during rare calm periods, wind direction is undefined. Thus, when wind speed is zero or below the start-up speed of the anemometer, climate variables cannot be paired with wind direction and therefore were not used in this analysis. Overall, approximately 2% of the hourly observations were obtained during calm periods where wind speed was recorded as 0 and the wind direction was therefore undefined.

The NWS reports wind direction in 10-degree increments. For example, an observed wind direction of 22 degrees is rounded off to 20 degrees and a value of 258 degrees will be reported as 260 degrees. This method of reporting can introduce observational bias as well as systematic bias when standard 8-point or 16-point compass formats are used (Ratner 1950; Lea 1971). In the case of a 16-point compass divided into sixteen 22.5-degree sectors, some wind direction sectors may contain more 10-degree increments than others (Applequist 2012). This type of systematic bias can be avoided by adopting a 12-point compass format with twelve 30-degree sectors, in which case, each sector contains an equal number of 10-degree increments.

The 12-point compass format is used in this study. For most hourly observations of a climate variable there is a corresponding wind direction. Each value of wind direction is assigned to one of the principal wind direction sectors. For example, if a measured hourly wind direction was 230 degrees, then the wind direction would be assigned to a wind direction sector of west-southwest (WSW) when using the 12-point compass format. The same process is repeated for each hour for the entire record and then all data pairs are sorted by wind direction sector, forming 12 separate directional subgroups. The climate variables are then averaged separately for each wind direction sector, resulting in a conditionally averaged climate variable associated with a specific wind direction.

With regard to precipitation, the terms “rainfall” and “precipitation” are often used interchangeably out of convenience; however, it is important to emphasize that both terms refer to the liquid equivalent of both rain and occasional frozen precipitation. Each hour with measurable precipitation was associated with a wind direction sector based upon the observed wind direction during the hour of active precipitation. Values were then sorted by wind direction and conditionally summed to obtain the total amount of precipitation for each wind direction sector. Each direction-specific total was then divided by the total amount of precipitation recorded over the entire sampling period for all wind direction sectors to form a “rainfall fraction”, which represents the fraction of total precipitation associated with a given wind direction.

## Results & Discussion

*Wind*.– On the Southern High Plains, wind can be both a blessing and a curse, depending on one’s perspective. For those engaged in the burgeoning wind energy industry, strong winds are a blessing. For those residents who have to endure the destructive effects of windstorms and sandstorms that frequent the region, strong winds are held in somewhat lower esteem (Stout 2014).

In this analysis, Lubbock surface wind observations were analyzed from 1 January 1973 to 31 December 2020. Overall, there were a total of 418,724 hourly observations of wind speed during this 48-year period of which 405,610 (97%) could be paired with a measured wind direction.

To compute the fraction of time that winds were blowing from a certain direction, each hourly observation of wind direction was assigned to one of 12 wind direction sectors and the total number of wind-direction observations within each wind direction sector was counted and divided by the total number of hourly observations summed across all wind direction sectors. The resulting dimensionless values represent the fraction of wind-direction observations associated with each wind direction sector. A wind-rose diagram for a 12-point compass is shown in Figure 2.

By definition, a prevailing wind is "a wind blowing most frequently from a specific direction in a particular area" (Kotlyakov & Komarova 2007). The results of this analysis suggest that the prevailing wind on the Southern High Plains blows from the south or a wind direction of 180 degrees.

To compute the prevailing wind direction, wind strength was ignored; thus, an analysis of directional frequency provided little information regarding the average wind speed associated with a given wind direction. To compute the average wind speed associated with each wind direction sector, each hourly wind speed was paired with the observed wind direction for each hour, then all data pairs were sorted by wind direction forming separate directional subgroups, which could be averaged separately. The results of this process produced conditionally averaged wind speeds for each of the wind direction sectors, plotted as a 12-point wind rose (Figure 2). Note that the highest average wind speed for the Lubbock station was associated with winds blowing out of the north (N) and north-northeast (NNE) and there were other peaks associated with winds blowing out of the south (S) and south-southwest (SSW). The lowest average wind speed was associated with winds blowing from the east (E).

*Air temperature and humidity.*–When considering atmospheric moisture content, it is important to consider both relative and absolute

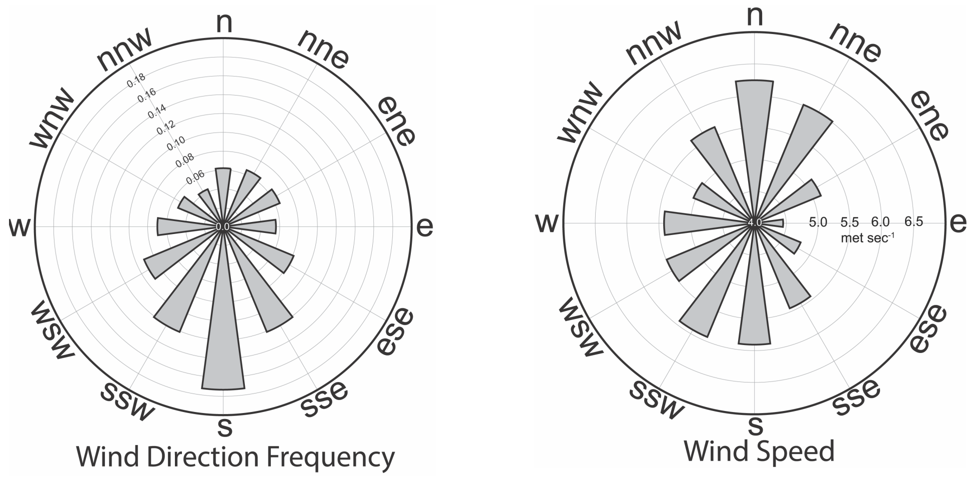


Figure 2. Plots of wind direction frequency (left) and average wind speed (right) plotted as a function of wind direction for Lubbock, Texas. Wind direction frequency represents the fraction of time that winds were blowing from a specific wind direction. The results suggest that the prevailing wind direction at Lubbock is from the south and all winds with a southerly component tend to have high wind direction frequencies. At the opposite extreme, winds with a northerly component tend to have low wind direction frequencies. The wind speed plot shows the average wind speed associated with a specific wind direction sector. Results suggest that the strongest winds tend to blow out of the north and northeast whereas the lowest average wind speed was associated with winds blowing out of the east.

humidity. The NWS does not routinely measure absolute humidity. Rather, air temperature and dew point temperature are measured and relative humidity is calculated from these values. For the 48-year period from 1973-2021, there were a total of 419,588 hourly observations of air temperature, 419,497 hourly observations of dew point temperature and 419,476 hourly values of relative humidity.

Air temperature, conditionally averaged for each of 12 wind-direction sectors, is presented in the left plot of Figure 3. Not surprisingly, the peak average air temperature was associated with winds blowing out of the south (S) and the lowest average air temperature was associated with winds blowing from the north (N) and north-northwest (NNW). Residents of the Southern High Plains are well-aware that cold continental polar air masses frequently sweep

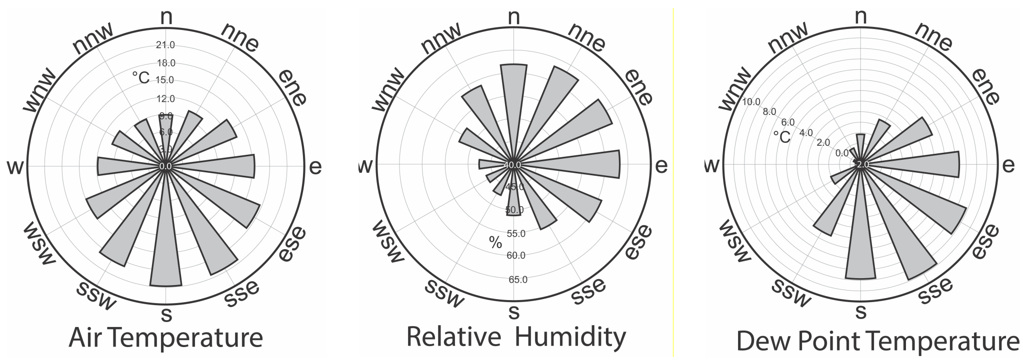


Figure 3. Average air temperature, relative humidity, and dew point plotted as a function of wind direction for Lubbock, Texas. Results suggest that the peak average air temperature was associated with winds blowing out of the south and the lowest average air temperature was associated with winds blowing from the north and north-northwest. The highest average relative humidity values for the Lubbock station were associated with winds blowing out of the north-northeast whereas the highest dew point temperature (a measure of absolute humidity) was associated with south-southeast winds.

southward across the Southern High Plains, especially during the winter.

There is a well-defined relationship between wind direction and atmospheric moisture content (Figure 3). Winds with a westerly component transport dry air from the desert regions of the American Southwest and are typically dry with low relative humidity and exceptionally low dew point temperatures. South-southeasterly winds convey tropical maritime moisture from the Gulf of Mexico and tend to be associated with high absolute humidity indicated by high dew point temperatures. The highest average relative humidity values for the Lubbock station were associated with winds blowing out of the north-northeast (NNE), east-northeast (ENE) and east (E) whereas the lowest average relative humidity was associated with winds blowing from the west-southwest (WSW). Continental polar air masses, transported from the north, tend to be cool with high relative humidity but low absolute humidity, as indicated by low dew point temperatures.

When comparing the angular distribution of relative humidity and absolute humidity (dew point) one finds that peaks do not match. The highest relative humidity was associated with east-northeast (ENE) winds whereas the highest absolute humidity was associated with south-southeast (SSE) winds.

*Precipitation.*–At the Lubbock station, there were a total of 412,058 hourly observations of precipitation collected from 1973-2020. Of these, 96.4% could be paired with a measured wind direction.

As with other climate variables, each hour with measurable precipitation was associated with a wind direction sector based upon the observed direction of the wind at the time of the precipitation observation. Precipitation values were then sorted by wind direction and conditionally summed to obtain the total amount of precipitation for each given wind direction sector. Each direction-specific total was then divided by the total amount of precipitation recorded over the entire sampling period for all wind direction sectors to form a "rainfall fraction", which represents the fraction of total precipitation associated with a specific wind direction.

The results based upon the 12-point compass format are presented in the upper plot of Figure 4, which suggests that the highest rainfall fraction for the Lubbock station was associated with winds blowing out of the east-northeast (ENE) and the lowest rainfall fraction was associated with winds blowing from the west-southwest (WSW). Rainfall for the top two wind-direction sectors – north-northeast (NNE) and east-northeast (ENE) – account for nearly a third of the total precipitation at the Lubbock station.

On the Southern High Plains, rainfall is highly intermittent with highly variable intensity. A single intense precipitation event can produce more rain in a few hours than may normally occur in a few months. Thus, a few heavy rain events could possibly skew the angular distribution of rainfall.

An attempt was made to remove the effect of rainfall magnitude by simply considering the number of hours of active precipitation for a given wind direction sector. In other words, suppose we replace each hourly precipitation observation with a binary value of either 0 for no rain or 1 if rain was detected during the hour. Then the binary values were sorted by wind direction and conditionally summed to obtain the number of hours with active precipitation for each given wind direction sector. Each direction-specific total was then divided by the total number of hours with active precipitation across all wind direction sectors to form a dimensionless value of "rainfall activity", which represents the fraction of hours with precipitation associated with a specific wind direction.

Computed values of rainfall activity associated with each wind-direction sector is presented in Figure 4. The overall distribution of rainfall activity appears to follow a pattern that is similar to that of the distribution of the rainfall fraction.

*Comparison of precipitation patterns at other locations.–*Amarillo and Midland have long records of hourly meteorological data comparable to that of the Lubbock station. In addition, all three cities are located on the Southern High Plains with Amarillo near the northern edge, Lubbock more centrally located, and Midland near the southern end (Figure 1). Here directional patterns of precipitation were computed for all three locations for the same 48-year period 1973-2020.

The Amarillo and Midland data were analyzed in the same fashion as the Lubbock data set. Each hour with measurable precipitation was associated with a wind direction sector based upon the measured wind direction during the hour of the observation. Then the hourly precipitation and wind direction pairs were sorted by wind direction and conditionally summed to obtain the total amount of precipitation for each of the twelve wind direction sectors. These totals were then divided by the total amount of precipitation recorded for all wind directions to form rainfall fractions.

A comparison of the rainfall distributions suggests that all three stations follow similar but not identical patterns (Figure 5). Both Lubbock and Midland had peak rainfall values associated with either north-northeast (NNE) or east-northeast (ENE) winds and a minimum

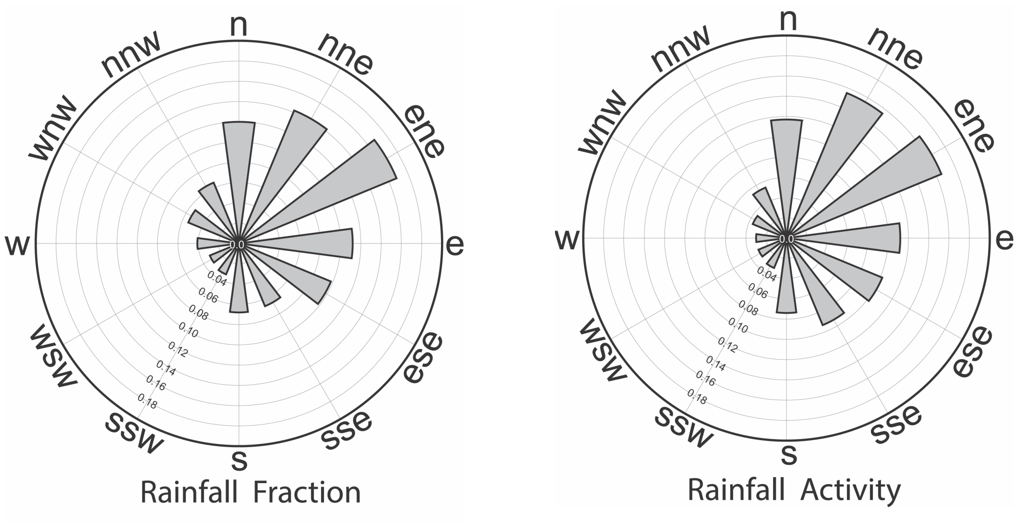


Figure 4. Rainfall fraction and rainfall activity plotted as a function of wind direction for Lubbock, Texas. Rainfall fraction represents the ratio of the amount of rain associated with a specific wind direction sector divided by the total amount of rain for all wind directions. Rainfall activity denotes the number of hours with measurable precipitation associated with a specific wind direction sector divided by the total number of hours with measurable precipitation for all wind directions. The results suggest that the angular distribution of rainfall activity appears to follow a pattern that is similar to that of the distribution of the rainfall fraction.

value associated with west (W) or west-southwest winds (WSW). A close inspection reveals that peak rainfall for the Amarillo station was shifted to the north (N) while the minimum value for Amarillo was associated with winds blowing from the west (W). The contribution of east-southeast (ESE) winds was also more pronounced in the Amarillo distribution compared to the other two.

It is not surprising to find that the directional distribution of precipitation varies with geographic location. One expects that moving the point of measurement influences the directional distribution of precipitation. However, it appears that moving the sampling site from the southern end to the northern edge of the Southern High Plains, a distance of 358 km, produces only minor variations in the overall distribution.

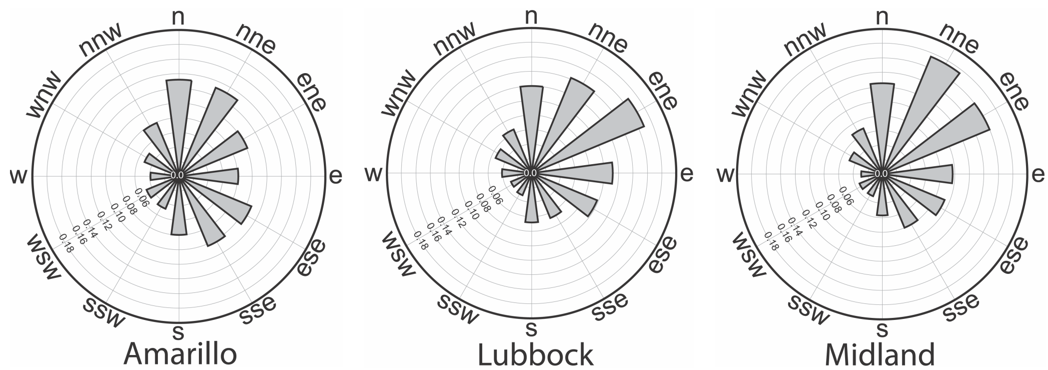


Figure 5. Directional distributions of rainfall fractions plotted for three locations on the Southern High Plains with Amarillo near the northern edge, Lubbock more centrally located, and Midland near the southern end (see Figure 1). A comparison of the rainfall distributions reveals that precipitation patterns at all three stations follow similar but not identical patterns.

*Seasonal variations of precipitation patterns.*– It is well known that the wind regime on the Southern High Plains varies with the seasons (Carlisle & Marrs 1982; Bomar 1983). For much of the year, south winds, or some component of south winds, are most frequently observed whereas during the winter, north winds are more common due to the passage of cold fronts (Ward 1916). One naturally wonders if there are similar seasonal shifts in the directional distribution of precipitation.

An attempt was made to quantify seasonal patterns of Lubbock rainfall through a multi-step process. First, each hourly precipitation observation was associated with one of the four seasons. The data set was sorted by season to form four seasonal subgroups to analyze separately. Using meteorological seasons, the directional distribution of rainfall was computed separately for each of the four seasonal subgroups by summing the precipitation amount for each of the twelve wind direction sectors and dividing by the total amount of precipitation associated with each season. The results provide data on seasonal variations of the directional distribution of precipitation (Figure 6).

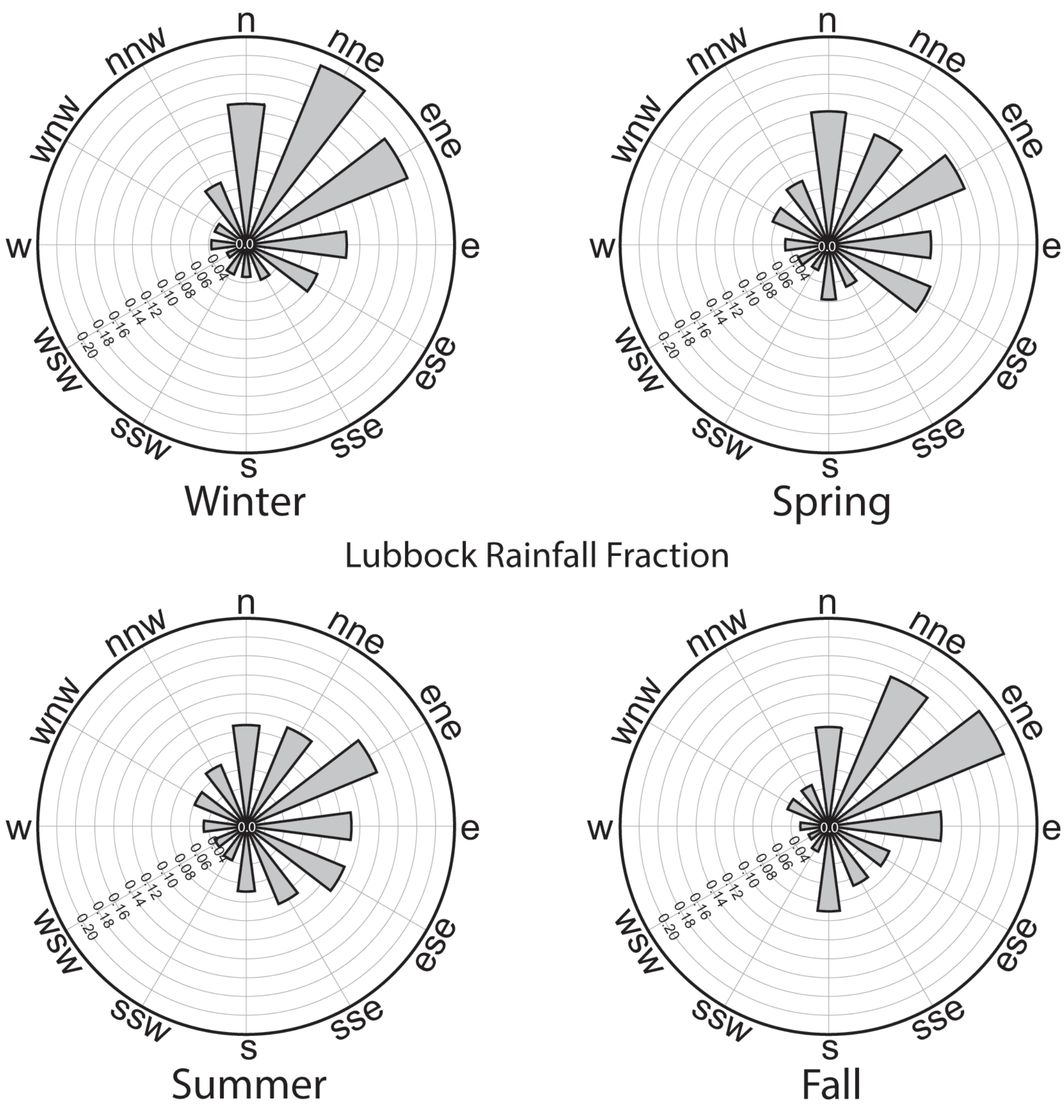


Figure 6. Season-specific angular distributions of rainfall fractions for Lubbock, Texas. A comparison of the rainfall distributions reveals that precipitation patterns for the four seasons follow similar but not identical patterns since the geographic location of sources of moisture and aridity do not vary significantly with the seasons.

Overall, most of the seasonal distributions follow similar but not identical patterns. Peak rainfall fractions for spring, summer and fall were associated with east-northeast (ENE) winds whereas the peak for winter was shifted slightly to the north-northeast (NNE). The minimum rain fractions for winter, summer and fall were associated with winds blowing out of the west-southwest (WSW) whereas the minimum for spring was shifted slightly to the south-southwest (SSW).

Considering the overall patterns, one finds that seasonal distributions were not substantially different. They all had a core cluster of high values associated with winds blowing from the north (N), north-northeast (NNE) and east-northeast (ENE) and all four seasonal distributions had a core cluster of low values associated with west-southwest (WSW) and south-southwest winds (SSW). One must conclude that the directional distributions of precipitation were not modified appreciably by seasonal shifts of the wind regime; rather, the seasonal distributions appear to be governed primarily by geography. Clearly, the relative location of sources of moisture and aridity do not vary significantly with the seasons.

## CONCLUSIONS

There is a direct connection between the direction winds are "blowing from" and climatic conditions at any location on Earth; however, the relationship between atmospheric conditions and wind direction depends on the specific location and surrounding geography. In this study, attempts have been made to better quantify the relationship between wind direction and associated atmospheric conditions on the Southern High Plains of North America. A long-term record of hourly observations of climate variables paired with observations of wind direction provided the raw data from which directional distributions of climate variables were computed.

Results of these analyses suggest that winds with a southerly component occur with the highest frequency and tend to be well above average with regard to air temperature, wind speed, and absolute humidity. The highest conditionally-averaged wind speed for the Lubbock station was associated with winds blowing out of the north (N) whereas the lowest average wind speed was associated with winds blowing from the east (E). The highest average relative humidity was associated with winds blowing out of the north-northeast (NNE), east-northeast (ENE) and east (E) and the lowest average relative humidity was associated with winds blowing from the west-southwest (WSW). The highest average dew point for the Lubbock station was associated with winds blowing out of the south-southeast (SSE) and the lowest average dew point was associated with winds blowing from the west (W) or west-northwest (WNW).

North-northeast (NNE) winds were found to be associated with the highest rainfall activity (frequency) and the highest amount of precipitation. This result was somewhat surprising as one would expect that peak rainfall would be associated with more southerly winds drawing moisture up from the Gulf of Mexico. However, this result is consistent with a low-pressure system moving from the west to east while the center of low pressure passes to the south of the point of measurement. Initially as the center of low-pressure approaches from the west, counter-clockwise circulation will draw moisture up from the Gulf. As the center of low pressure moves east of the point of measurement, winds will shift to a more northeasterly direction causing a collision of air masses. As relatively cool air from the north collides with the warm and moist air mass to the south the warm moist air will lift and override the cooler airmass, increasing condensation, and triggering precipitation.

Directional distributions of precipitation exhibited only minor seasonal variations. For spring, summer, and fall, peak precipitation was associated with east-northeast (ENE) winds and the least amount of precipitation was associated with west-southwest (WSW) winds. One must conclude that the directional distribution of precipitation is not modified appreciably by seasonal shifts of the weather; rather, they appear to be governed more by geography, especially with regard to the location of sources of moisture and aridity. The primary source of moisture for the Southern High Plains region is the Gulf of Mexico and the location of this source does not change with the seasons.

If geography is a key factor that influences the directional distribution of precipitation then one would expect the rainfall distributions to change as the location of a meteorological tower is moved, especially if such a move changes the relative location of surrounding sources of moisture and aridity. Clearly, moving a meteorological tower 358 km from the southern end to the northern edge of the Southern High Plains shifts the sampling location farther from the Gulf of Mexico and one would expect the directional distribution of precipitation to change somewhat. A comparison of directional distributions of precipitation for Midland, Lubbock, and Amarillo revealed minor differences that were due to a change of geographic location.

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## LITERATURE CITED

Abbe, D. R. 2014. South Plains Army Airfield. Arcadia Publishing, Charleston, SC, 127 pp.

Applequist, S. 2012. Wind rose bias correction. J. Appl. Meteorol. Climatol. 51(7):1305–1309.

Blackstock, D. A. 1979. Soil Survey of Lubbock County Texas. United States Department of Agriculture Soil Conservation Service in cooperation with the Texas Agricultural Experiment Station, Washington, DC, 105 pp.

Bomar, G. 1983. Texas Weather. University of Texas Press, Austin, viii+265 pp.

Bunch, S. 1937. The rain-bearing winds at Knoxville, Tennessee. Mon. Weather Rev. 65(7):269–270.

Carlisle, W. J. & R. W. Marrs. 1982. Eolian features of the Southern High Plains and their relationship to windflow patterns. Pp. 89–105 in Special Paper 192, Interpretation of windflow characteristics from eolian landforms (Marrs, R. W. & K. E. Kolm, eds.), Geological Society of America, Boulder, C), 109 pp.

Cummins, W. F. 1892. Report on the geography, topography, and geology of the Llano Estacado or Staked Plains with notes on the geology of the country west of the plains. Pp. 127–223 in Third Annual Report of the Geological Survey of Texas 1891 (E. T. Dumble, ed.), Henry Hutchings, State Printer, Austin, xi+711 pp.

Epperly, P. O. 1933. Rain-bearing winds of central Oklahoma. Mon. Weather Rev. 61(9):269–271.

Fenneman, N. 1931. Physiography of Western United States. McGraw-Hill, New York, NY, xiii+534 pp.

Joel, A. H. 1937. Soil conservation reconnaissance survey of the southern Great Plains wind-erosion area. Technical Bulletin 556, United States Department of Agriculture, Washington DC, 68 pp.

Johnson, W. D. 1901. The High Plains and their utilization. Pp. 601–768 in Twenty-First Annual Report of the United States Geological Survey, 1899–1900. Part IV - Hydrography. United States Department of the Interior, U.S. Geological Survey, Washington DC.

Kotlyakov, V. M. & A. I. Komarova. 2007. Elsevier's Dictionary of Geography, 1st Edition. Elsevier, Amsterdam, The Netherlands, xxiv+1048 pp.

Lea, D. A. & R. A. Helvey. 1971. A directional bias in wind roses due to mixed compass formats. J. Appl. Meteorol. 10(5):1037–1039.

Orton, R. B. 1964. The climate of Texas and the adjacent Gulf waters. Technical report, United States Department of Commerce, Weather Bureau, Washington DC, xviii+195 pp.

Ratner, B. 1950. A method for eliminating directional bias in wind roses. Mon. Weather Rev. 78(10):185–188.

Reed, T. R. 1927. Rain-bearing winds in the far western states. Mon. Weather Rev. 55(5):228–233.

Shumard, G. G. 1892. Artesian water on the Llano Estacado. Bulletin no. 1, Geological Survey of Texas, Department of Agriculture, Insurance, Statistics and History, Austin, 19 pp.

Stout, J. 2014. Detecting aeolian transport direction. J. Arid Environ. 107:18–25 https://doi.org/10.1016/j.jaridenv.2014.04.001

von Herrmann, C. F. 1925. The rain-bearing winds at Atlanta, GA. Mon. Weather Rev. 53(11):494–497.

Ward, R. de C. 1916. The prevailing winds of the United States. Ann. Assoc. Am. Geogr. 6(1):99–119.