DIURNAL AND SEASONAL VARIABILTY OF VARIOUS CLIMATOLOGICAL PARAMETERS FOR A SELECTION OF STATIONS IN ARIZONA AS ILLUSTRATED BY "HOUR BY MONTH" CLIMOGRAMS

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1. INTRODUCTION

The following presents, in an "atlas" creating demonstration, a collection of 49 "hour-by-month" climograms generated from observational data at four first-order weather station locations in Arizona. A visual analog to the topographic map, the climograms make use of a 2-D grid setup, with digitized calendar month coordinates comprising the y-axis, and digitized hour of the day coordinates the x-axis. Upon the grid, a parameter of interest's (z-coordinate) diurnal/seasonal variation is depicted in the form of contours, shadings, vector arrow icons, etc. Sunrise/sunset demarcation lines are overlain, and since calendar month and hour are circular variables, to eliminate wrap-around effects in the case of contour intersections with the x and y axes, data point values for certain month/hour combinations approaching the graph's boundaries are duplicated internally with new offset values assigned to their coordinates. The duplicated stats are part of the actual analysis, but they serve only the wrap-around elimination function, not being depicted in the actual 12-month by 24-hour extents of the graph. A given climogram will have 288 "points", but in reality, 612 are processed internally to create the finished product.

The concept for displaying seasonal and diurnal climatological variation on a 2-D grid is certainly not new, this particular adaptation initially presented by Fisk (2004). Succeeding demonstrations (Fisk, 2008, 2009, 2010, and 2014) focused on illustrating the applicableness on different parameter types, not so much with the stations identities. Outside of conference venues, however, the individual station focus has always been the primary aspect of their use operationally, as examples: a number of Naval Air Station commands, a U.S. Army Proving Grounds station, NOAA Buoys in the Southern California Bight area, and a National Weather Service Forecast office. Hundreds have been produced in all.

The list of parameter types that have been visualized is quite extensive, including elements such as percent frequencies of Fog, Haze/Smoke, High Winds, Blowing Dust, Thunderstorms, Calms, Prevailing Winds (16-point or 8-point compass directions, individual wind directions), various types of Flying Weather (VFR, HVFR, etc.,), and percents of time with cloud ceilings.

Also depicted have been mean hourly temperatures, average wind speeds, mean relative humidities, median ceilings' heights, and extremes (for example, upper 99th percentile thresholds of hour by month temperature, wind speed; or lower 1st percentile readings of hour-by-month relative humidities).

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Other adaptations have involved portrayals of the diurnal and seasonal variations in mean vector (or prevailing) wind orientations and speeds by hour, and median ceilings' heights.

In this study, the focus is changed from introducing and demonstrating various chart categories (already accomplished) to collective application of these on a series of climatological stations – a "mini-atlas" production of sorts. The Arizona stations chosen are four first-order ones with lengthy 40-year plus periods of record: Phoenix, Tucson, Yuma, and Flagstaff. An assortment of twelve meteorological parameters (in another case thirteen) are represented in the stations' climogram sets. This figure represents just a small sampling of different kinds that have been produced operationally.

The original raw data were downloaded from the NCDC Integrated Surface Hourly online site, the periods of record dating back to between 1973 and 1978, extending forward to 2017 or 2018. The layouts are intended to provide quick-study visual overviews of the stations' diurnal and seasonal character for the parameters concerned, the insights potentially useful for general planning and scheduling endeavors, or "purely" climatological – interpretations/comparisons for their own sake.

2. METHODS AND PROCEDURES

Most of the 12 chart types have simple straight-forward interpretations but two of these (both winds-related) probably require some advanced explanations.

All of the presentations cited in the Introduction have extended abstracts, and the References section at the close of this paper provides their online links.

2.1 - "Mean Vector Wind" and Vector Wind "Constancy" Climogram

The mean vector wind and vector wind "constancy" characterize overall wind direction and persistence. Calculation is performed by decomposing individual wind observations into their north/south and east/west components, adding the components, and then recombining their arithmetic averages into a single overall "mean vector wind" or "resultant wind". Since individual wind directions almost always show variability from observation to observation, resultant wind speeds will be somewhat less that the corresponding mean scalar wind speeds (mean wind speed irrespective of direction). The ratio of the former to the latter multiplied by 100 measures vector wind "constancy". Constancy values can range from 100 (individual wind observations unvarying in direction but not necessarily in speed) to 0 (individual wind observations canceling each other out exactly when added vectorially. As the charts illustrate, mean vector wind directions, speeds, and constancies for a given station can vary considerably on an hour-by-hour basis climatologically, owing to diurnal, seasonal, and local topographical influences.

Mean vector winds are depicted in their climogram as arrows, oriented in the direction of flow, the lengths proportional to speed. Constancy values are depicted by color shadings.

2.2 - "Prevailing Winds" Climogram

"Prevailing Winds" in this application are the most frequently observed 8-point compass wind directions. The climogram depicts for each hour, by calendar month, its direction and mean speed, the arrows also oriented in the direction of flow with their lengths proportional to mean speed. Occurrence frequencies are represented as superimposed color shadings.

Prevailing winds information, of course, is less inclusive than that of the mean vector wind, as information on just one direction is considered. However, its interpretation is somewhat more intuitive, and in this regard the two charts complement each other. Prevailing wind frequencies that are high in magnitude, say >30 percent, are generally associated with mean vector winds of a similar directional orientation accompanied by a high constancy value.

3. RESULTS

3.1 - Phoenix Sky Harbor Airport - 33.44° N, 112.01° W; Elev:1135 ft

Phoenix, as described from selected excerpts in its 2017 "Local Climatological Data Annual Summary" publication is located in the oval-shaped/ flat Salt River Valley at an elevation of about 1,100 feet ASL. It is surrounded by scattered mountains rising to as much as 1,500 feet above the valley floor. Temperatures range from very hot in summer to mild in winter. Usually, there is a rather abrupt break from the extreme early summer (June) dryness to the onset of Monsoonal thunderstorms in July. Fog is rare, occurring principally in winter. The valley is characterized by light winds.

The following twelve climograms depict Phoenix's diurnal and seasonal variation for a selected group of variables: 1.) Resultant or Mean Vector Winds, 2.) Prevailing 8-Point Compass Wind Direction/Speeds, 3.) Mean Scalar Wind Speeds, 4.) Extreme High (99th Percentile) Sustained Wind Speeds, 5.) Mean Hourly Temperatures, 6.) Extreme Low (1st Percentile) Hourly Temperatures, 7.) Extreme High (99th Percentile) Hourly Temperatures, 8.) Mean Relative Humidities, 9.) Hourly Percents with Cloud Ceilings and Hourly Median Ceilings' Heights,10.) Hourly Percents with Thunderstorms, 11.) Hourly Percents with Fog, and 12.) Hourly Percents with Blowing Sand/Dust.

Hourly data for the 1973-2018 period (nearly 417 K observations) were reduced and analyzed for this purpose.

3.1.1 – *Phoenix Winds*

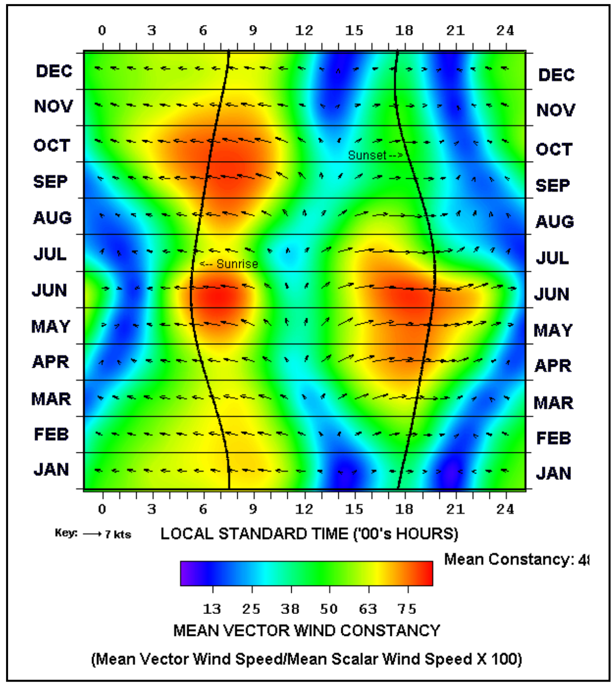

Figure 1. Mean Vector Wind/Constancy Chart for Phoenix Sky Harbor Airport, AZ.

Figure 1 shows the Mean Vector Wind/Constancy Climogram for Phoenix. In general, the vectors at the higher orange to red constancy magnitudes (70 and above) seem to alternate between light easterly for the pre-noon hours to light westerly for the afternoon and early evening, reflecting a sort of downslope (easterlies) vs. upslope (westerlies) back and forth flow regime. The maximum constancy easterlies are positioned over the first few hours just after sunrise for May-June and August-October; September and October also show high constancy vectors for a few hours prior to sunrise. High constancy westerlies are present for April to June over the mid-afternoon to sunset hours, and in some cases a few hours beyond. The blue arc-like bands, depicting low constancy (< 20) magnitudes, reflect several-hour duration transition periods, where the fesultants shift in orientation from easterlies to westerlies or vice-versa. The mid-to-early afternoon band (easterlies to westerlies) is not as prominent as the mid to late evening one (westerlies back to easterlies), but each are parallel in shape on a month-to-month basis to the sunrise and sunset demarcations, respectively, indicating that their characteristics are being driven by seasonal variations in insolation factors (length of daylight and solar elevation angle).

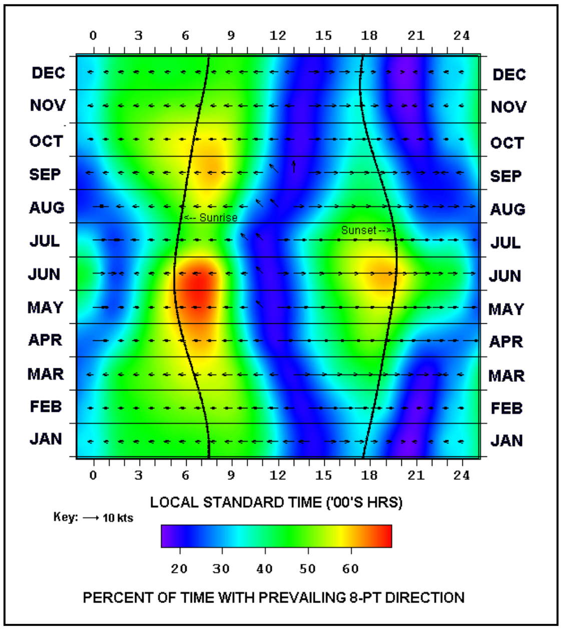

Figure 2. Prevailing Eight-Point Compass Winds' Chart for Phoenix

Figure 2 shows the Prevailing Eight-Point Compass Winds' Chart for Phoenix. The graph's features resemble very closely those of Figure 1, namely the month-by-hour placements of the easterlies vs. westerlies, and those of the changeover interval bands. A uniform eight-point compass distribution of wind directions (assuming no Calms) would have 12.5 % per direction, but in Figure 2, the green to red colored areas depict climatological percentages of 35 to nearly 70 percent, indicative of a very preferential prevailing wind climatology. On an individual case-basis, the most preferential example is that for June at 0700 LST, the prevailing direction easterly at a 69.1% incidence, and a mean speed from that direction of 6.3 knots. In contrast, the most extreme individual prevailing westerly case is that for June at 1900 LST: 62.2 % incidence associated with a mean speed of 10.1 knots.

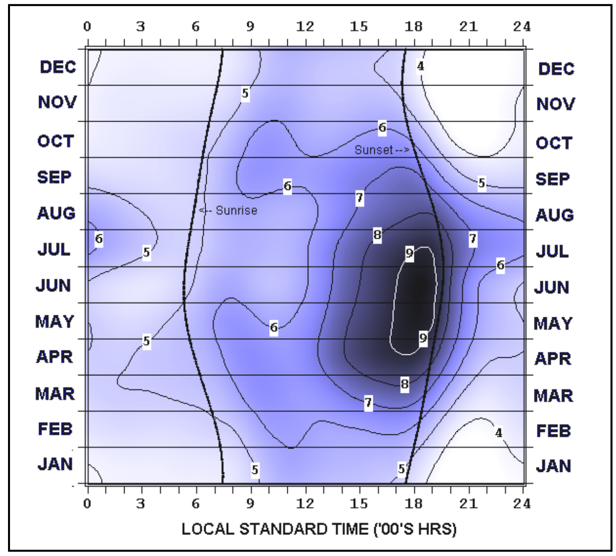

Figure 3. – Mean Scalar Wind Speeds (kts) for Phoeniz, AZ.

Figure 3 depicts the diurnal/seasonal mean scalar winds speed pattern for Phoenix, the isopleths indicating a relatively light speed regime, ranging from 4 to 9 knots, the latter contour encompassing the area one to two hours prior to sunset over mid-April to mid-July. Overall mean hourly wind speed in Phoenix is 5.6 knots.

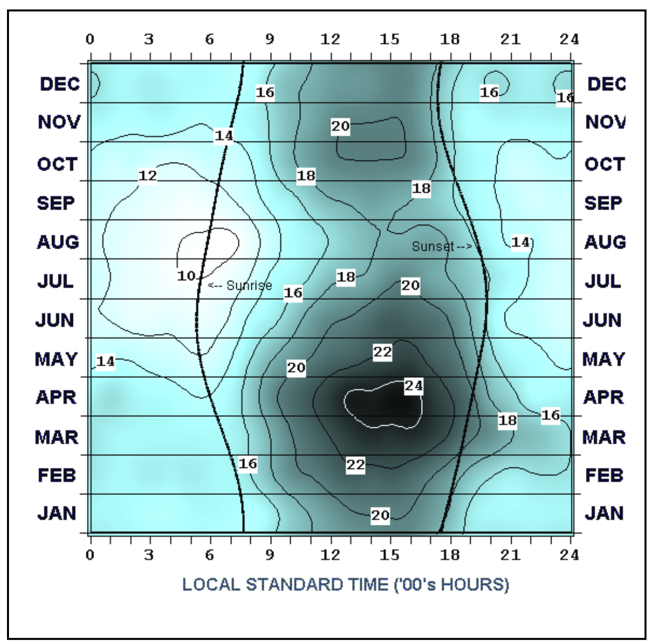

Figure 4- Upper 99th Percentile Sustained Wind Speeds for Phoenix, AZ

Figure 4 shows the hour by month climatological character of hourly-specific high end sustained wind speeds, in this case at the upper 99th percentile threshold level. In a departure from Figure 3's pattern, Figure 4's areal maximum feature is shifted to the earlier afternoon hours covering March to May. More specifically, the 24-knot maximum isopleth is a feature of late March/most of April, including the hours 1300 LST to 1700 LST.

***3.1.2 –** Phoenix Temperatures and Relative Humidities.*

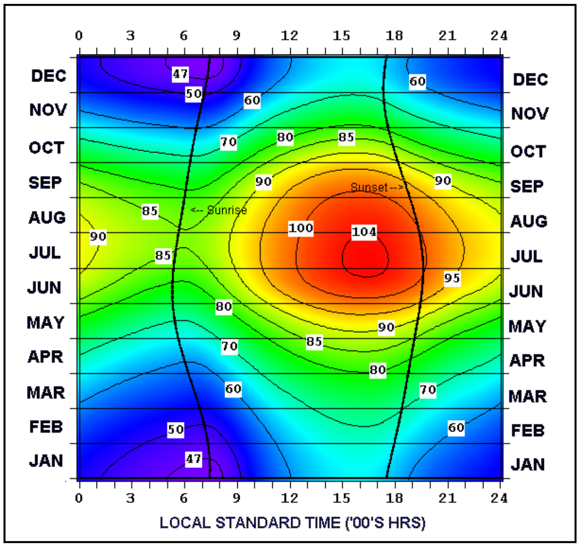

Figure 5. Mean Hourly Temperatures for Phoenix, AZ Sky Harbor Airport (Deg F)

Figure 5 displays the hourly mean hourly temperature configuration for Phoenix. Mean hourlies range from the high 40's to mid 60's in January, from the mid 80's to around 104 F in July. The July maximum isopleth is centered around1600 LST, and covers the whole month. The lead-season and lag-season 85 F isopleths intersecting sunrise exhibit a narrowing gap in late July, suggestive that mean morning minima in Phoenix are a bit higher late in the month than earlier. From the start of July through mid-August mean temperatures at midnight are at or in excess of 90 F.

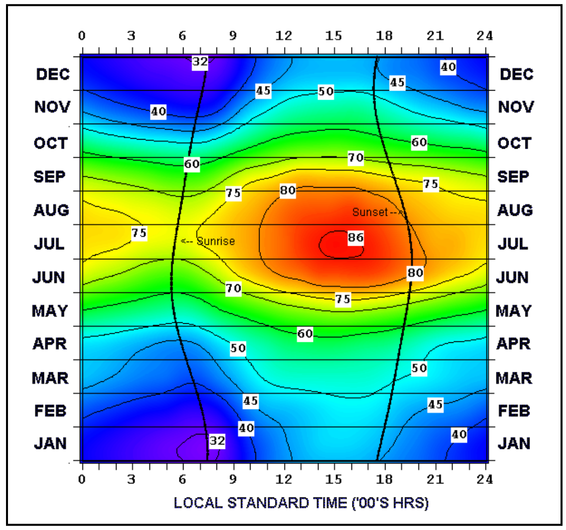

Figure 6. Lower 1st Percentile Threshold Temperatures for Phoenix by Hour

Next, Figure 6 graphs the Lower 1st Percentile Threshold Temperatures for Phoenix. Interpreting this statistic, since an individual day in a given month makes up about 3 percent of the total number of days, a 1 percent event could be regarded as occurring about once every three years on that specific calendar day for the given hour. This would be most accurate for the middle of a given calendar month as the actual monthly mean statistics utilized to generate the climograms are positioned at that midpoint (e.g., at 7.5 for the month of July), although for a station like Phoenix, in which the climatological gradients in temperatures between the beginning of the month to the end are not great, the discrepancies would thus be minor. The lower 1st percentile temperatures, of course, are not the *absolute* extremes that have been registered over history; those figures might be several degrees or more extreme for a given month/hour. For example, in a 40-year data base, an individual hour would have about 1200 cases, by calendar month, and 1% of these, or about 12 cases, would be even more extreme (colder) than the 1% threshold value.

The 1st percentile isopleths in Figure 6 range from 32 F in January, encompassing the interval 0600 LST to 0800 LST to 86 F in July covering 1400 LST to 1700 LST. Selectively interpreting some of the other isopleths' configurations, one might generalize that a typical coldest Phoenix day in January would range from about 32 F to the high 40's F; in July the range would be from the low 70's F to the mid to upper 80's F.

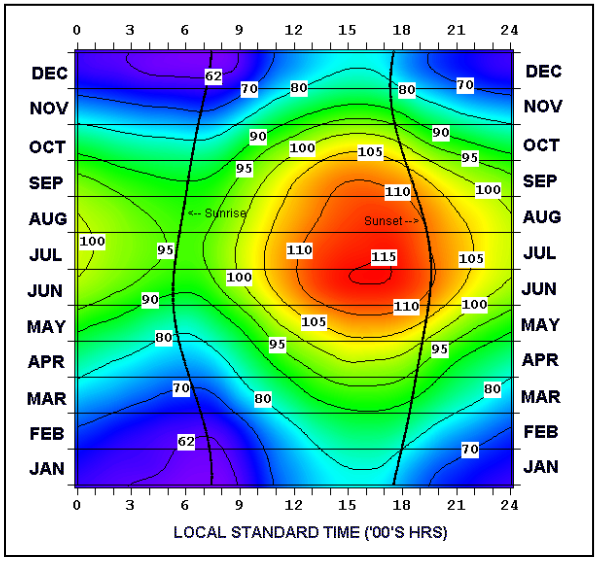

Figure 7- Upper 99th Percentile Threshold Temperatures for Phoenix, by Hour

Figure 7 depicts upper 99th Percentile Threshold Temperatures by hour for Phoenix. Two striking features are the presence of the 115 F and 100 F isopleths in summer, the latter crossing midnight from late June to mid- August. Indeed, inspecting the later pre-dawn hours for those periods, one can infer that on some relatively infrequent occasions, overnight minimum temperatures might not drop below 90 F. Also, the 115 F isopleth is noticeably "squeezed" shape at its top, confined it mostly to late-June . This likely reflects the monsoonal effect, whose onset commences in early July. The associated frequencies of higher humidities and high-level clouds from thunderstorms, both distant and local, would depress July and August extreme afternoon maximum temperatures somewhat, thus altering the hourly temperatures' statistical distributions and their 99th percentile thresholds.

January in Phoenix, conversely, can experience afternoon temperatures as warm as the low 80's F and overnight minima in the low 60's F.

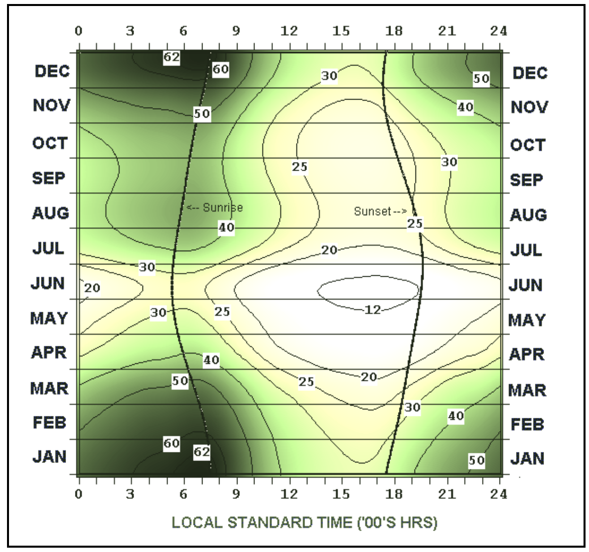

Figure 8 – Mean Hourly Relative Humidities for Phoenix

Figure 8 shows Phoenix's mean hour by month relative humidities. Average overall figure is 33.8%, the highest individual statistic 62.3%, for 0700 LST in January, the lowest 10.2% for June at 1700 LST. It will be noted that the minimum 12% isopleth is confined to the afternoon hours of late May to late June, during the "pre-monsoonal" period. In July, the afternoon means increase noticeably to 20 percent and higher from mid-month on, but still being quite low in the absolute sense.

***3.1.3 –** Phoenix Ceilings, Thunderstorms, and Visibility restricted conditions*

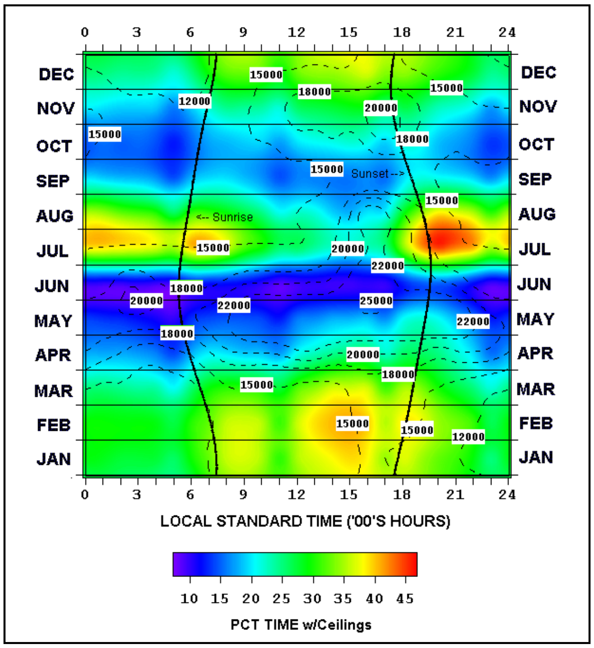

Figure 9: Percent of Times with Cloud Ceilings and Median Ceilings' Heights – Phoenix, AZ

Turning to the cloud ceilings genre, Figure 9 depicts in a color hierarchy: 1) the percents of times with Cloud Ceilings (sky covered 50 percent or more with clouds), and as dashed contours: 2.) the median heights of cloud ceilings (when they are observed).

Possessed of a dry climate, cloud ceilings in Phoenix are the exception rather than the rule, the overall percentage just 24.2 %. With some exceptions, the ceilings' frequencies appear as quasi-horizontal color bands, indicative of a more seasonal, less-diurnal variability. The first band (mostly green to yellow) covers roughly January to April, reflecting percent frequencies in the 20's to mid-30's range. In May and June, the "pre-monsoonal" period, the frequencies drop into the very low "blue" range (less than 20 percent), including the extreme minimum 7.9 % figure for June at 1100 LST. Then with the onset of the monsoon in July, they increase significantly into the green to orange and sometimes red range, this applicable as well for most of August. The monsoonal period includes the absolute maximum figure (46.7 %) for July at 2000 LST, part of the red oval isopleth feature covering roughly early July to early August for the hours 1800 LST to 2300 LST. The next mainly light blue band covers most of September and October, followed by principally green bands over November and December. Median ceiling heights, overall, range from 12000 to 25000 feet, the May-June pre-monsoonal period showing just an 18000 to 25000 feet spread. The Phoenix median heights' figures are so high because low and even moderate ceilings when they are observed are quite uncommon relative to the high ones.

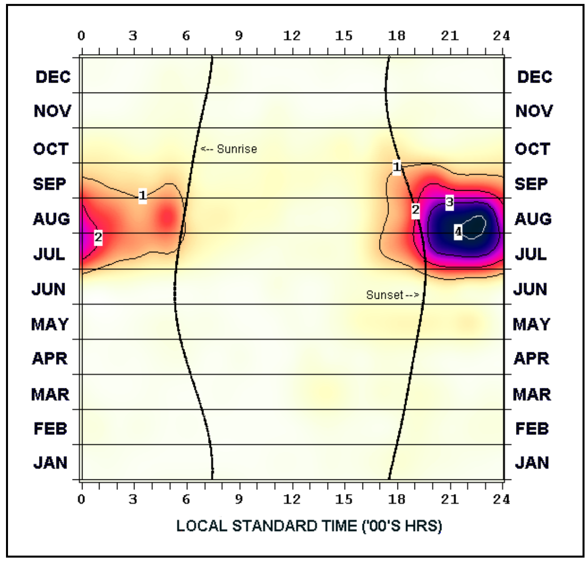

Figure 10 – Percent Frequencies of Thunderstorms at Phoenix

Next, moving into the thunderstorms and restricted visibilities realms, Figure 10 portrays the hourly percent frequencies of thunderstorm activity in Phoenix. While the isopleth percentages are no higher than 4 percent, they indicate that such activity is confined predominantly to the July to early September period just before or during the hours beyond sunset, carrying on at reduced frequencies sometimes to the following sunrise.

Lastly, Figures 11 and 12 depict the incidence percentages of Fog and Blowing Sand/Dust. While visibility restricted conditions are quite rare at Phoenix, the climogram creation objective here is to provide insights as to their diurnal/seasonal tendencies when they do occur.

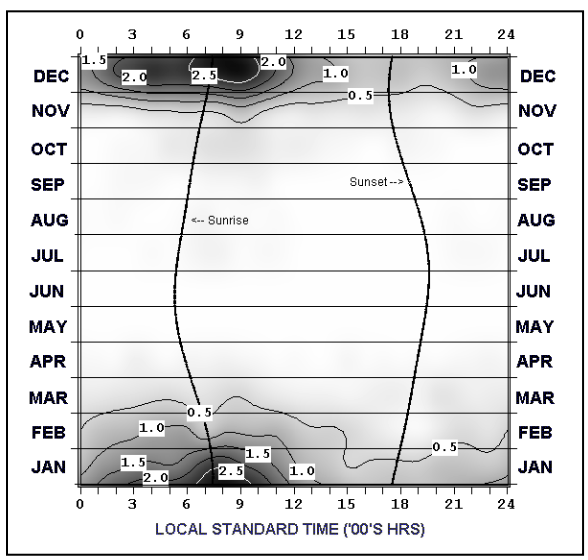

Figure 11: Percent Frequencies of Fog at Phoenix

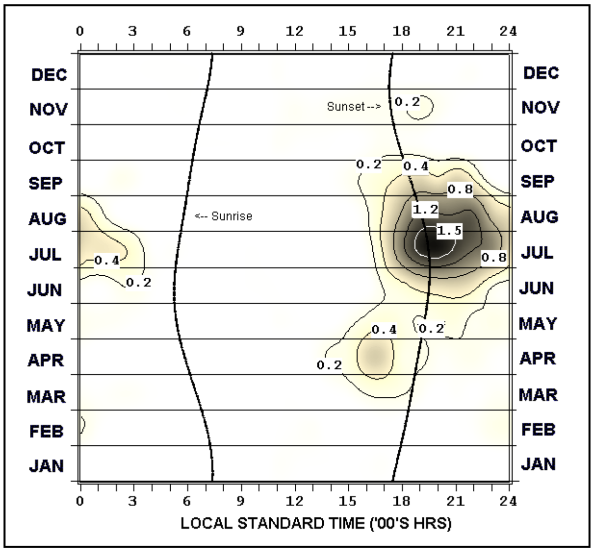

Figure 12 : Percent Frequencies of Blowing Sand/Dust at Phoenix

From Figure 11, Fog incidence (radiational) is confined almost exclusively to December-January during the overnight hours through sunrise, and in rare instances beyond Noon LST. Blowing Sand/and Dust incidence (Figure 12) appears mostly associated with downdrafts/outflows from Monsoonal thunderstorms, but also in rarer cases from high wind events during late Spring afternoons (principally April).

3.2 - Tucson International Airport - 32.12° N, 110.94° W; Elev: 2643 ft

Tucson, about 113 miles to the southeast of Phoenix, is described in its 2017 "Local Climatological Data Annual Summary" publication as more or less surrounded by mountains, including the Catalinas to the north, and other ranges located to the east and south, as high as 5000 feet or more above the airport weather station altitude. Hills ranging from 500 to 4000 feet higher are found to the west as well. The climate is characterized by "a long hot season from April to October", the hottest mid-summer temperatures moderated by low relative humidities. Average cloudiness is low, and surface winds are generally light. Wind velocities and directions are influenced by the surrounding mountains, and the general slope of the terrain. Usually, the local winds tend "to be southeasterly during the night and early morning hours, shifting to northwesterly during the day".

Period of record analyzed here was 1973-2018, comprising nearly 414 K hourly obs.

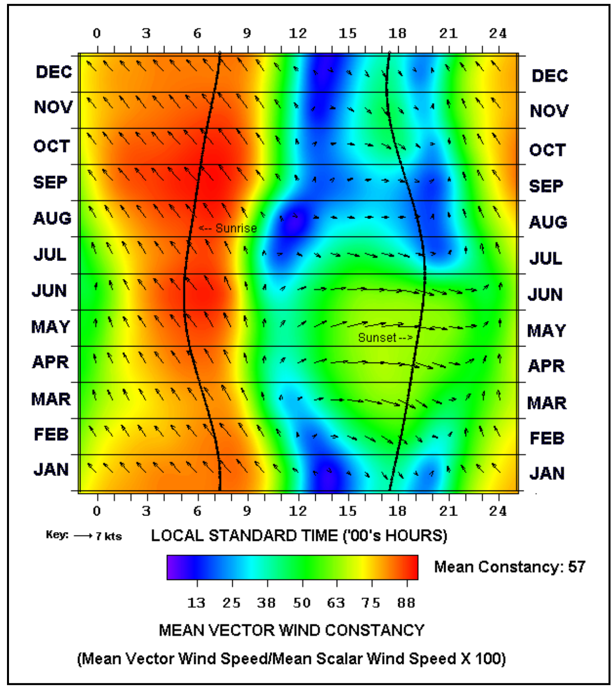

Figure 13. Mean Vector Wind/Constancy Chart for Tucson Int'l Airport, AZ.

3.2.1 – *Tucson Winds*

Figure 13 shows the Mean Vector Wind/Constancy Climogram for Tucson. Highest constancy mean vectors (75 and above magnitudes) are associated with the post-midnight southeasterlies mentioned in the preceding section, being relatively light in magnitude and persisting, over all months of the year, through sunrise, and several hours beyond. A blue transition zone, similar in shape on its leftmost margin to the sunrise demarcation line, commences a gradual several hour changeover period to light westerly to north-westerly orientations, these to persist from the early afternoon hours on. The orientations for the most part continue at green constancy levels until about 2100 LST, at which time as they switch back to south-easterlies again. .

Figure 14 displays the Prevailing Eight-Point Compass Winds' Climogram for Tucson. Like Phoenix, the graph's prevailing winds' features resemble rather closely those of its counterpart Mean Vector chart, namely, in the case of Tucson, the placements of the nocturnal to mid-morning southeasterlies, the afternoon to early evening westerlies (particularly over April-June), and the several hour wide blue changeover bands, the shape of the latter onset "front" strikingly similar to that of the sunrise line a few hours prior. Also indicative of a pronounced preferential directional wind climatology, the percent frequencies at "green" to "red" levels range from around 40 percent incidence to beyond 60 percent.

On an individual case-basis, the most preferential example is that for October at 0700 LST, the prevailing

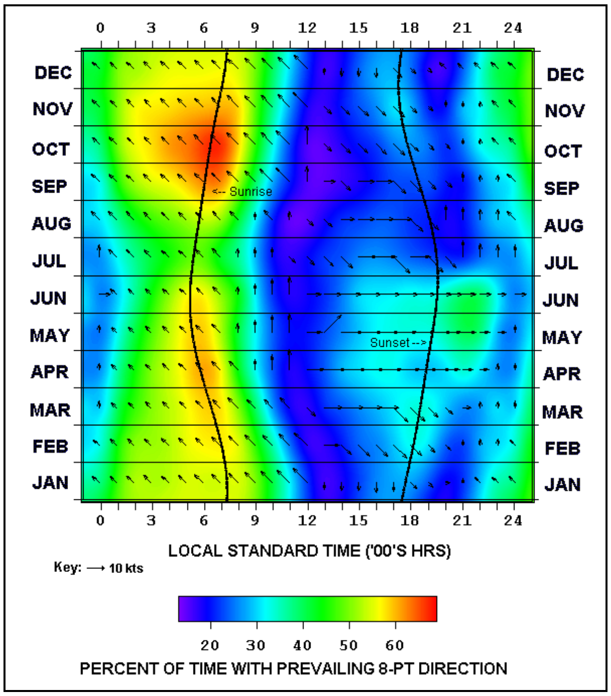

Figure 14. Prevailing Eight-Point Compass Winds' Chart for Tucson Int'l Airport

direction southeasterly at a 68.9% incidence with a mean speed from that direction of 8.0 knots. In contrast, the most extreme individual prevailing westerly case is that for June at 2200 LST: 41.8 % incidence associated with a mean speed of 7.2 knots.

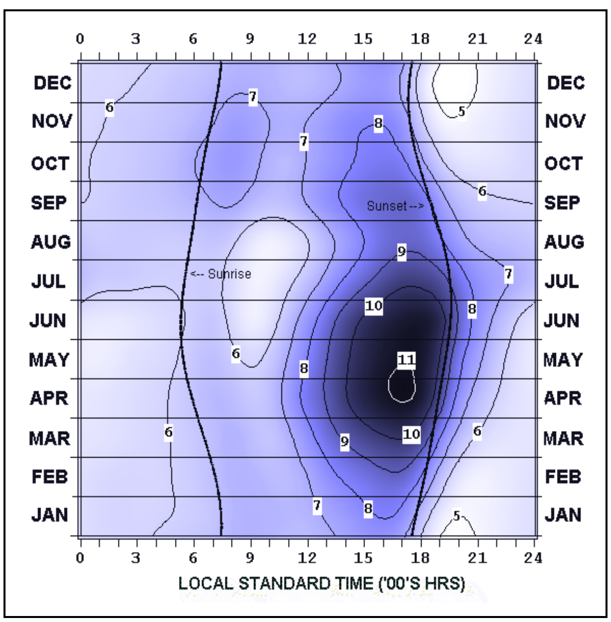

Figure 15 - Mean Scalar Wind Speeds (kts) for Tucson, AZ.

Figure 15 depicts the Mean Hourly Scalar winds speeds for Tucson, the overall mean speed (6.9 knots) a bit higher than Phoenix's 5.6 knot figure. The isopleths range from 6 to 11 knots, the extreme maximum contour positioned over late April covering the rather compact 1600 to 1700 LST space.

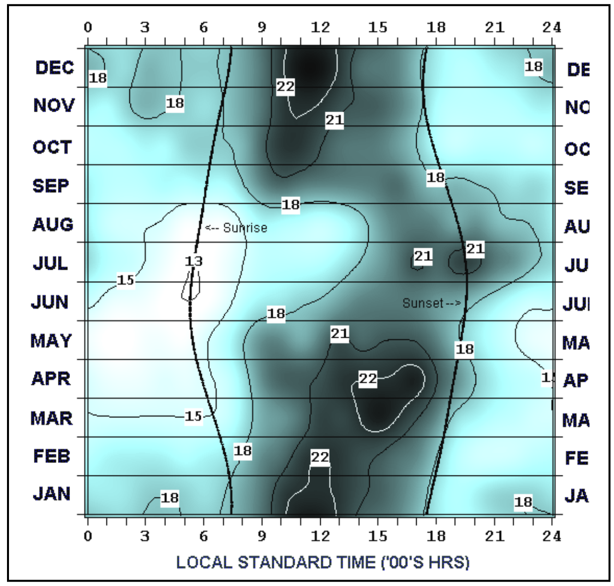

Figure 16 - Upper 99th Percentile Sustained Wind Speeds for Tucson, AZ

Figure 16 shows the diurnal/seasonal patterns for upper 99th percentile sustained wind speeds. Two expansive areas within the maximum isopleth contour (22 knots) are evident. The first encompasses the December to mid-January interval with the widest hourly coverage between 1000 LST to 1300 LST; the 22 knot isopleth extends backward into November and forward into February, but the hourly widths for those periods are narrower. The second encompasses March into mid-April, the hourly breadth at a maximum in early-April, spanning the hours 1400 LST to 1700 LST.

Curiously, while Tucson's mean speeds are about 20 percent higher than Phoenix's, the latter has a sizeable higher 24 knot isopleth in its upper 99th percentile sustained winds chart (see Figure 4).

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3.2.2 – Tucson Temperature and Relative Humidity

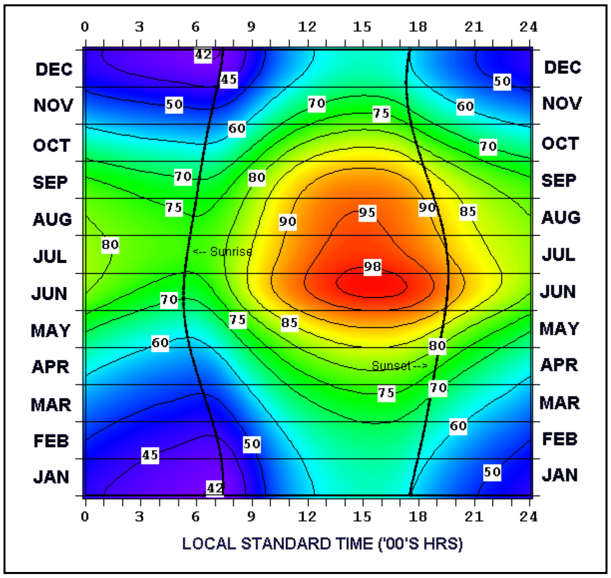

Figure 17. Mean Hourly Temperatures for Tucson, AZ

Turning to mean temperatures, Figure 17 presents average hourlies for Tucson. Compared to Phoenix, owing to Tucson's higher elevation, topographical setting, and perhaps its somewhat less urbanization, the hourly temperatures average 5.3 F cooler in aggregate.. The differences vary significantly by hour of the day and season, the mean figures being 7.6 F cooler at midnight, 6.5 F cooler at 0600 LST, 2.5 F cooler at 1200 LST, and 5.4 F cooler at 1800 LST. On a monthly basis, the mean differences are 3.4 F cooler for December and 8.5 F so for August.

From the climogram, Tucson mean temperatures in January range from the low 40's to perhaps the upper 50's, and from the upper 70's F to high 90's F in July. The 98 F maximum early to late afternoon isopleth is centered in late June, in the pre-monsoonal period.

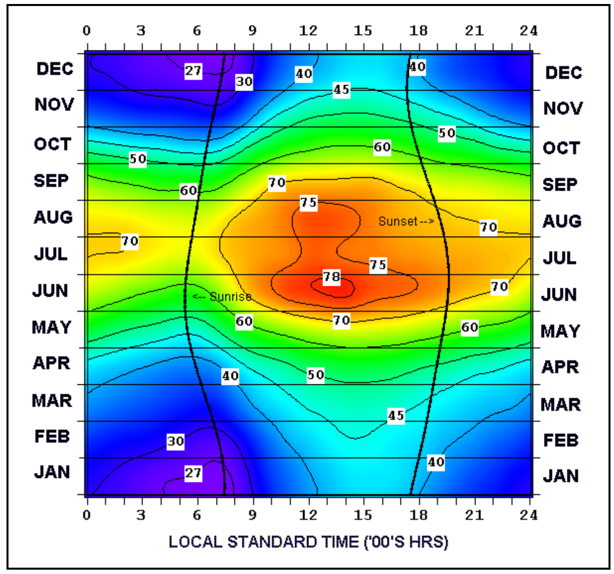

Figure 18 - Lower 1st Percentile Threshold Hourly Temperatures for Tucson.

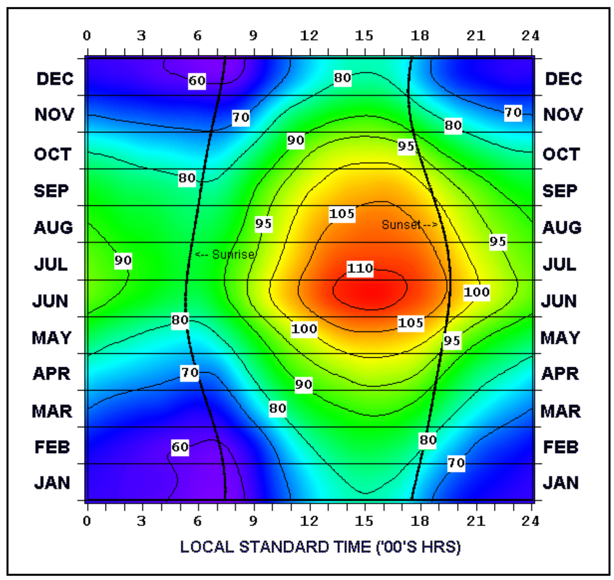

Figure 19 – Upper 99th Percentile Threshold Hourly Temperatures for Tucson

Figures 18 and 19 show the Lower 1st Percentile and Upper 99th Percentile Temperature Threshold patterns, respectively, for Tucson. Similar to the mean hourly temperature data comparisons, the Tucson Lower 1st percentile statistics average about 6.1 F cooler than those of Phoenix, and again there are diurnal/seasonal contrasts within, the mean midnight difference being 7.1 F cooler, the 0600 LST contrast 6.6 F cooler, that for 1200 LST 4.6 F cooler, and for 1800 LST, 6.5 F cooler. On a monthly basis, the figure is 5.3 F lower for January and 7.9 F so for July, The same holds true for the upper 99th percentile data sets, the statistics averaging about 4.5 F cooler than those of Phoenix. The mean midnight difference is 6.2 F, the 0600 LST gap 5.4 F, that for 1200 LST 1.6 F, and for 1800 LST, 4.8 F. On a monthly basis, the mean discrepancy is 1.5 F for January and 7.7 F for August, these also the individual extremes.

For each chart, the "pre-Monsoonal" feature is present, namely the placement of the extreme highest isopleths (78 F and 110 F, respectively) "set back" into June.

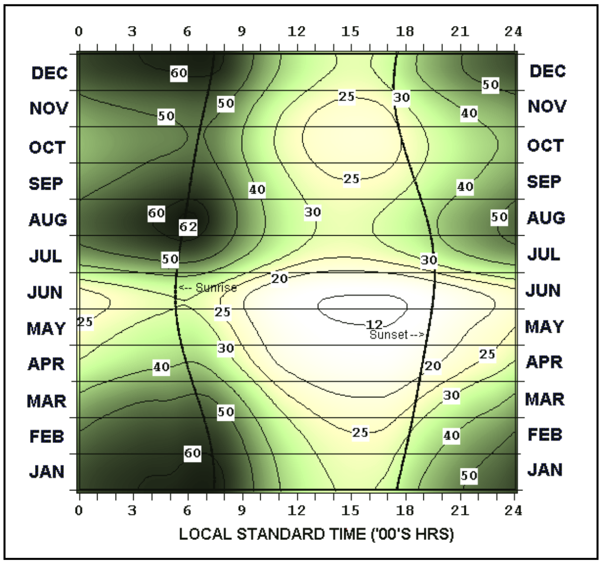

Figure 20 – Mean Relative Humidities for Tucson.

Concerning relative humidities, Figure 20 represents Tucson's mean hourly figures of this parameter. Average overall relative humidity is 36.6%, compared to Phoenix's 33.7%. Highest individual hourly statistic, 63.3%, is for 0600 LST in August, the lowest 12.0% for both May & June at 1700 LST, during the "pre-monsoonal" period.

Like that for Phoenix, as the monsoonal period sets in, the Tucson relative humidity afternoon means increase significantly over July and August. The Tucson individual hour 63.3 % maximum for August at 0600 LST, represents a major contrast with that for Phoenix, the latter's corresponding statistic at that hour in August just 47.5 %.

Repeating the more comprehensive diurnal/seasonal comparisons that were done for the hourly tempera-tures, Tucson relative humidities average 5.3 percent higher on a straight arithmetic basis than Phoenix's at 0000 LST, 4.1 % higher at 0600 LST, 0.5 % *lower* at 1200 LST, but 3.0 % higher again at 1800 LST. On a monthly basis, the figure is 0.9 % lower for March, but 10.2 % higher in July and 11.2 % higher in August, these being the extremes.

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***3.2.3 –** Tucson Ceilings, Thunderstorms, and Visibility restricted conditions*

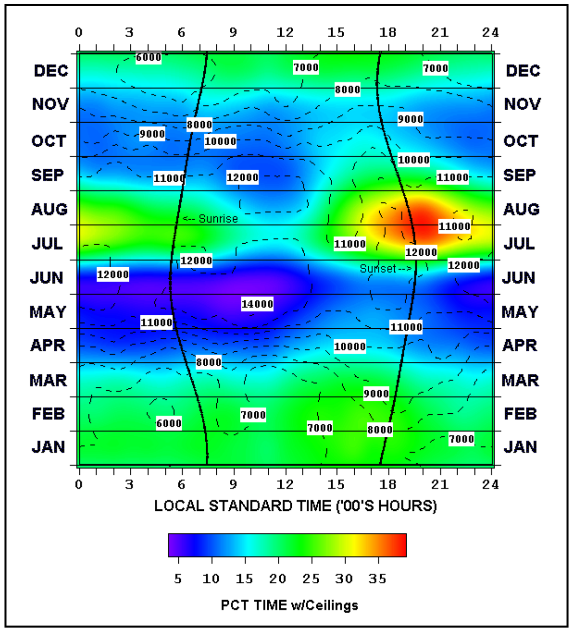

Figure 21: Percent of Times with Cloud Ceilings and Median Ceilings' Heights – Tucson, AZ

Moving on to Thunderstorms and Visibility restricted scenarios, Figure 21 is the Percent of Time with Ceilings/Median Ceilings climogram for Tucson. Cloud ceilings are even less frequent than those at Phoenix, the overall percentage just 16.5 %, but because of the higher station elevation the median heights are reduced (recall that ceilings are the vertical distance from *ground level*). However, the relative color band pattern is much like that of Phoenix's, the correlation coefficient between the 288 ceilings' percent frequencies: +.841. The May/June "pre-monsoonal" period frequencies are again in the very low blue to violet range, including the extreme minimum 4.3 % figure for June at 1100 LST; this is the exact same hour that produced the absolute minimum statistic (7.9%) for Phoenix. With the onset of the monsoon in July, the frequencies, like those for Phoenix, also increase significantly into the green to orange and sometimes red range (note that the hierarchy of colors in the Tucson color bar is tailored to its particular range of ceilings frequencies, thus being somewhat different compared to Phoenix's bar in Figure 9). The monsoonal period includes the absolute maximum Tucson figure (38.0 %) for August at 2000 LST, portion of another red oval isopleth feature covering roughly early July into August for the evening hours. Median ceiling heights, overall, range from 6000 to 14000 feet, the May-June pre-monsoonal period showing a 11000 to 14000 foot spread. Overall average is about 9400 feet, compared to Phoenix's 16100 feet. As the difference in elevation between Phoenix and Tucson is only about 1500 ft, Tucson's typically lower

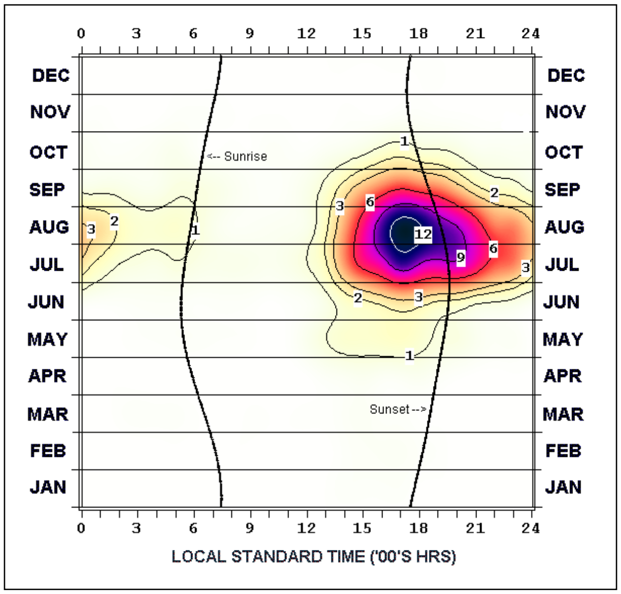

Figure 22: Percent of Time with Thunderstorms-Tucson , AZ

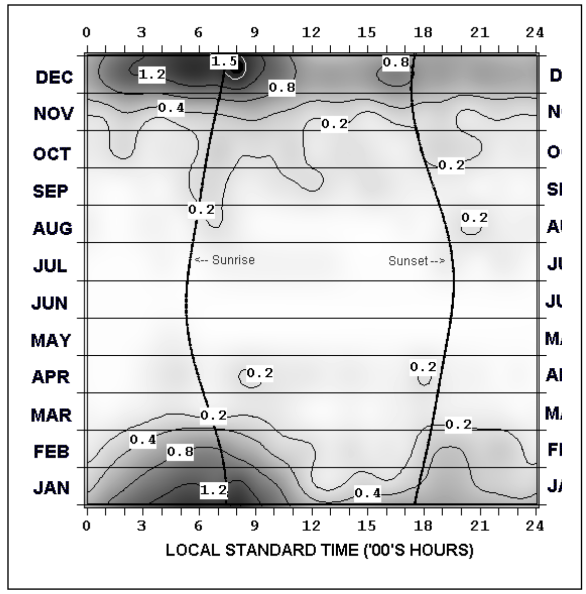

Figure 23 - Percent Frequencies of Fog at Tucson

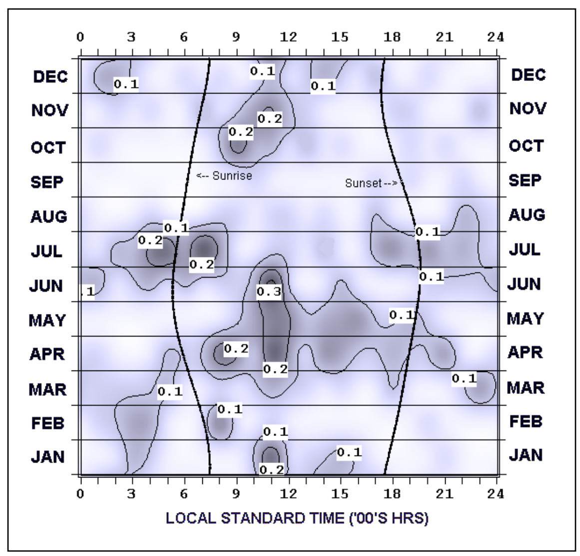

Figure 24 – Percent Frequencies of Haze/Smoke at Tucson

medians are at a level exceeding mere altitude, so other factors must be in play like, for example, orographic effects**.**

Figure 22 depicts the percent frequencies of thunderstorm activity in Tucson. Monsoonal moisture influx again plays the almost exclusive role in producing these occurrences, although compared to Phoenix, the incidence is roughly triple that at the most favored hours, a 12 % isopleth noted. Also, the pole of maximum frequency is shifted to the late afternoon hours; that for Phoenix was in the late evening. This might be attributable to topographical factors peculiar to Tucson: higher elevation, greater local scale orographic effects, and a somewhat greater proximity to the monsoonal moisture source regions.

Lastly, Figures 23 and 24 below depict the incidence percentages of Fog and Haze/Smoke, respectively. As the latter condition is more frequent than Blowing Sand and Dust on an overall basis in Tucson, it is chosen for climogram presentation.

From Figure 23, Fog incidence (1.5 percent or less), like that for Phoenix. is confined predominantly to December-January, during the overnight hours to sunrise and a few hours after. In even rarer cases, it's observed in March and April, again generally over the few hours either side of sunrise. Haze/Smoke incidence (Figure 24) is even rarer (maximum isopleth 0.3 %). It seems to be randomly generated over the grid except for a very slight relative proclivity in April and May (most of the daytime isopleths at or greater than 0.1 percent).

3.3 - Yuma MCAS Airport - 32.64° N, 114.61° W; Elev: 216 ft

Yuma MCAS Airport, about 200 miles southwest of Phoenix, is located in the Colorado River Valley Plain about 2 miles outside the city. Hourly data for the period 1977-2017, some 352 K obs, were utilized to produce the twelve climograms.

3.3.1 – *Yuma MCAS Winds*

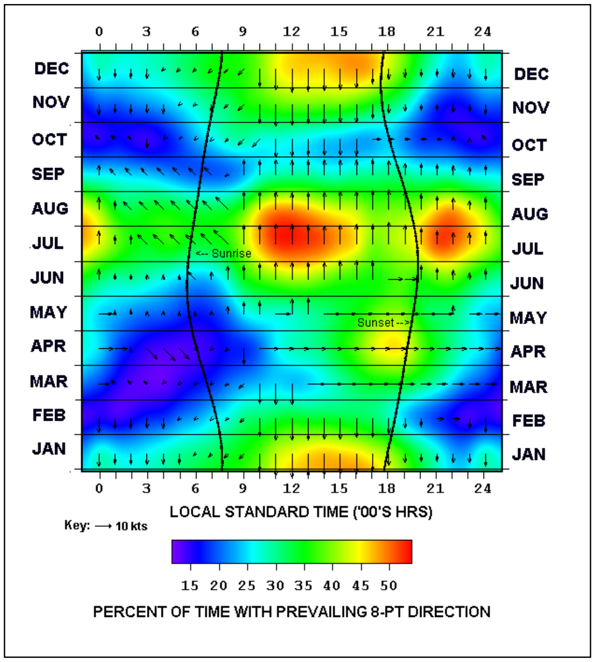

Figure 25 - Mean Vector Wind/Constancy Chart for Yuma, AZ

In Yuma's Figure 25 Mean Vector Wind/Constancy Climogram,. most of the vector orientations of significant relative magnitudes are quite northerly or southerly, most likely influenced by the Colorado River Valley topography. Mean vectors at orange to red (high) constancy values (>70 magnitudes) are concentrated in two seasons. The first (winter group) are the north-north-easterlies encompassing November, December and January over the 0300 LST to Noon LST hourly interval. The second (summer group) are the south-southeasterlies to south-southwesterlies covering the entire midnight-to-midnight period. The latter especially applies for July and August, less so for June, where the red-orange constancy south-southwesterlies are limited roughly to the afternoon/early evening. There does not seem to be any clear-cut, widespread blue transition zones, as were seen for Phoenix and Tucson. .

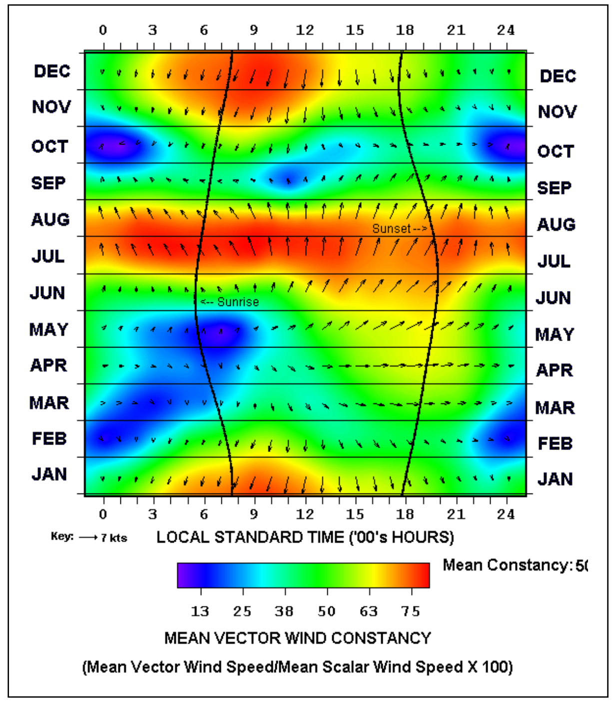

Figure 26 - Prevailing Eight-Point Compass Winds' Chart for Yuma MCAS Airport

Like those analogous charts for Phoenix and Tucson, the Yuma Prevailing Eight-Point Compass Winds' Climogram in Figure 26 exhibits a recognizable feature resemblance to its counterpart Mean Vector Chart.

Concentrating on the sunrise to sunset periods, prevailing directions are generally straight northerly or southerly, the former pertaining to the months October through March, the latter from June through September. An exception to this has the months March to May exhibiting mostly westerly prevailing directions during the daylight hours. The prevailings' frequencies are almost exclusively in the green to red color band areas, indicative of roughly 30 percent to greater than 50 percent climatological incidence.

On an individual basis, the most preferential case is that for July at 2100 LST, the prevailing direction southerly at a 53.5 % incidence – mean speed 7.8 kts. Ranking closely behind, also in July, is the prevailing southerly at 1100 LST (53.4 % incidence with a mean speed of 9.6 kts). In contrast, the most extreme individual prevailing northerly case is that for December at 1600 LST: 48.7 % incidence and associated with a mean speed of 9.1 knots.

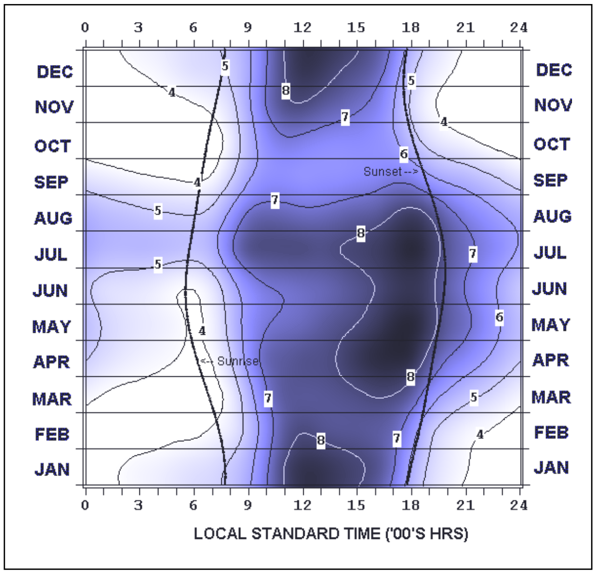

Figure 27 - Mean Scalar Wind Speeds (kts) for Yuma MCAS Airport, AZ.

Figure 27 depicts the Mean Scalar winds speeds for Yuma MCAS, the overall mean speed (5.8 knots) a shade higher than Phoenix's 5.6 knot figure. The isopleths range from 4 to 8 knots, the maximum contour situated over two areas. The first covers essentially December and January for the late morning to mid-afternoon hours, the second late-March to mid-August, including the late-afternoon hours through sunset.

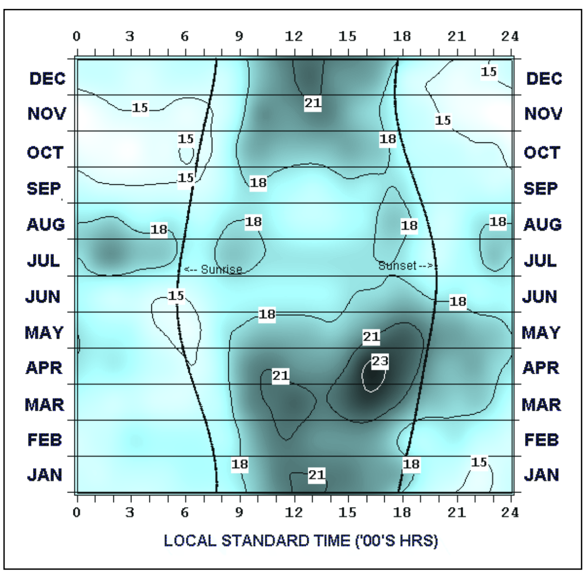

Figure 28 - Upper 99th Percentile Sustained Wind Speeds for Yuma MCAS, AZ

Figure 28 shows the diurnal/seasonal patterns for upper 99th percentile sustained wind speed observations. For Yuma, the maximum magnitude contour (23 knots) resides over late-March thru April, restricted to the narrow 1600 LST to 1800 LST interval.

3.3.2 – *Yuma MCAS Hourly Temperatures and Relative Humidities*

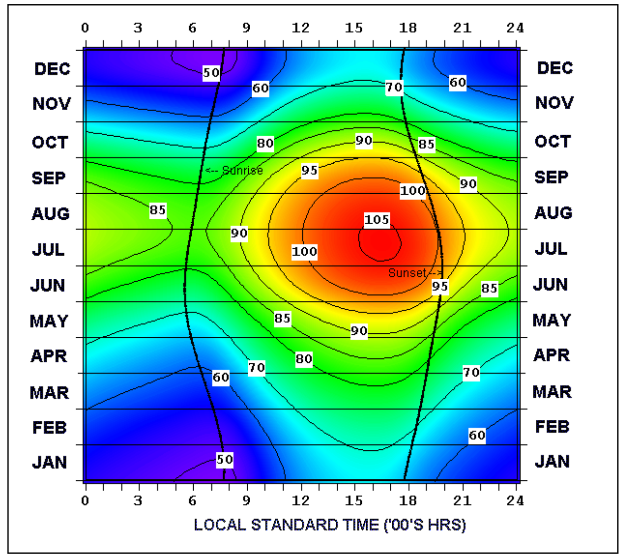

Figure 29 – Mean Hourly Temperatures for Yuma MCAS Airport

Moving on to temperatures, Figure 29 shows Yuma's mean hourly temperatures configurations. At first glance the contour magnitudes appear quite similar to those of Phoenix, but as Yuma is about 900 feet lower in elevation a detailed grid-point comparison of the two stations should reveal net positive discrepancies in favor of Yuma, assuming Phoenix heat-island influences are not much greater than Yuma's.

In aggregate, the hourly Yuma temperatures average about 0.8 F warmer than Phoenix's, but the differences do vary significantly by hour of the day and season, Diurnally, Yuma's mean figures are 0.6 F *cooler* at midnight, 0.9 F warmer at 0600 LST, 1.7 F warmer at 1200 LST, and 1.6 F warmer at 1800 LST. On a monthly basis, the mean differences are 2.5 F and 2.4 F warmer for January and February, respectively, compared to 2.4 F cooler for June.

In the mean, early morning wintertime Yuma temperatures appear to fall just below 50 F in December and January, recovering to the mid-60's F in the afternoons. In July, typical daily ranges are from the low 80's F to around 105 F.

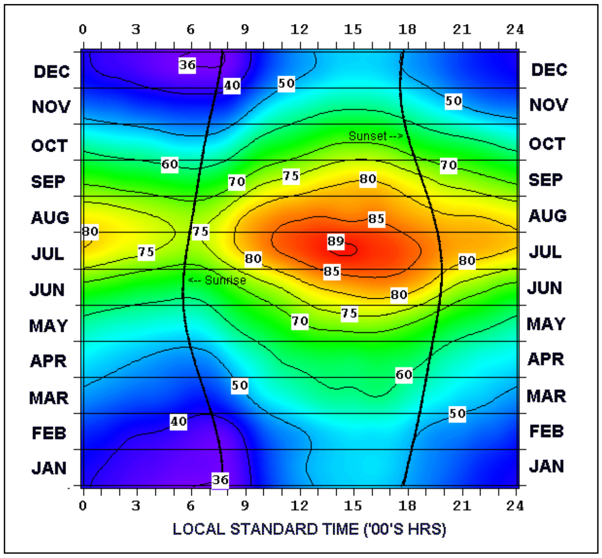

Figure 30 – Lower 1st Percentile Threshold Temperatures for Yuma MCAS Airport

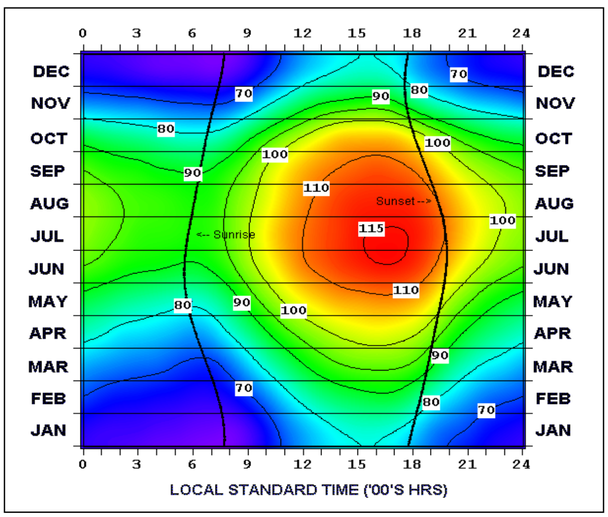

Figure 31 – Upper 99th Percentile Threshold Temperatures for Yuma MCAS Airport

Figures 30 and 31 show the Lower 1st\ Percentile and Upper 99th Percentile hourly temperature threshold patterns, respectively, for Yuma MCAS Airport. For the 1% extreme coolest hourlt statistics, Yuma's figures average about 2.5 F warmer than Phoenix's compared to 0.2 F higher for the 99% extreme warmest thresholds..

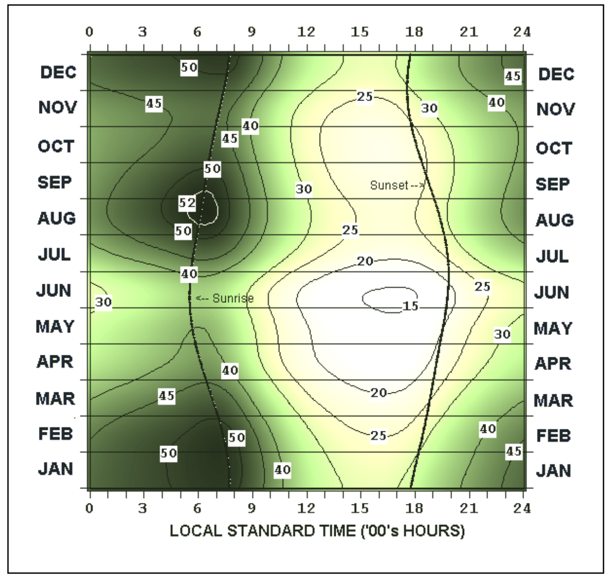

Figure 32 – Mean Hourly Relative Humidities for Yuma MCAS Airport

Figure 32 shows Yuma's hour by month relative humidities. Average overall figure is 34.5 %, a shade higher than Phoenix's 33.7% figure. Highest individual hour statistic 52.8%, is for 0600 LST in August, the lowest 14.3% for June at 1700 LST.

On a monthly overall basis, Yuma relative humidities are typically lower in winter than Phoenix's, but higher in summer, the differences more evident for the nocturnal hours.

3.3.3 – *Yuma Ceilings, Thunderstorms, and Visibility restricted conditions*

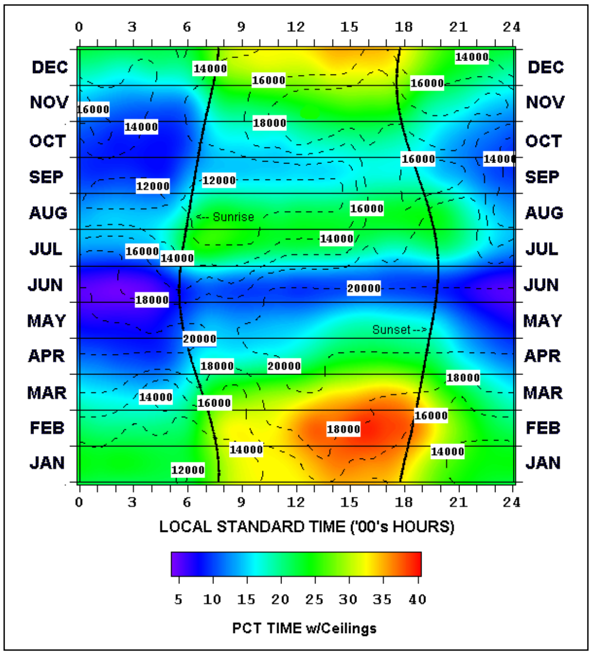

Figure 33: Percent of Times with Cloud Ceilings and Median Ceilings' Heights – Yuma, AZ

Proceeding to the Ceilings, Thunderstorms, and Visibility restricted conditions group, Figure 33 is the Percent of Time with Ceilings/ Median Ceilings Heights climogram for Yuma. Overall climatological frequency (19.5%) is somewhat less than Phoenix's (24.2%), the median heights' average (16400 feet) about 300 feet higher. On an overall seasonal/diurnal basis, Yuma's percent frequency pattern is highly correlated with Phoenix's (correlation coefficient: +.788), the pre-monsoon low frequency dark blue band feature evident again for June, but the red, smaller scale oval-shaped contour maximum present for Phoenix and Tucson in July and August evenings is not. Instead, Yuma's highest relative frequency area is set over January to mid-March for the afternoon hours through an hour or two beyond sunset. This feature includes the absolute highest percentage (40.4 %) for February at 1600 LST. In contrast, the absolute minimum statistic (3.9 %) is noted for June at 0200 LST.

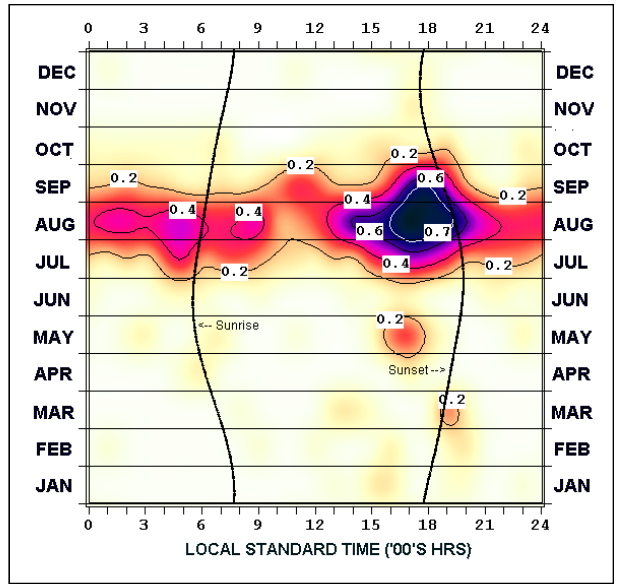

Figure 34 – Thunderstorm Frequencies at Yuma

Figure 34 shows the Percent Incidence of Thunderstorm Activity at Yuma. On an individual hourly basis, absolute frequencies are very low (less than 1 percent), but seasonally, they are confined almost exclusively to July-September with a slight diurnal relative preference for the late afternoon through sunset hours. There is also a subtle tendency for activity, not seen in the Phoenix and Tucson charts, to occur over the pre-noon to early afternoon hours.

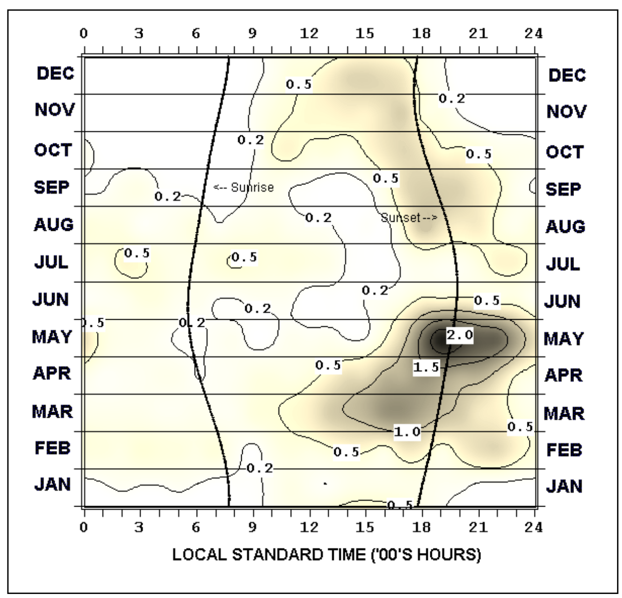

Figure 35 – Percent of Time with Blowing Sand and Dust at Yuma MCAS

The Figure 35 Blowing Sand and Dust Climogram identifies preferred times for such events at Yuma. Evident is a slight proclivity for the late afternoon to early evening hours during the Spring months (March to May). More specifically, a 2 percent maximum contour in May is situated over the approximate hourly interval 1700 LST to 2000 LST A lesser 1.5 percent contour in May extends almost to midnight.

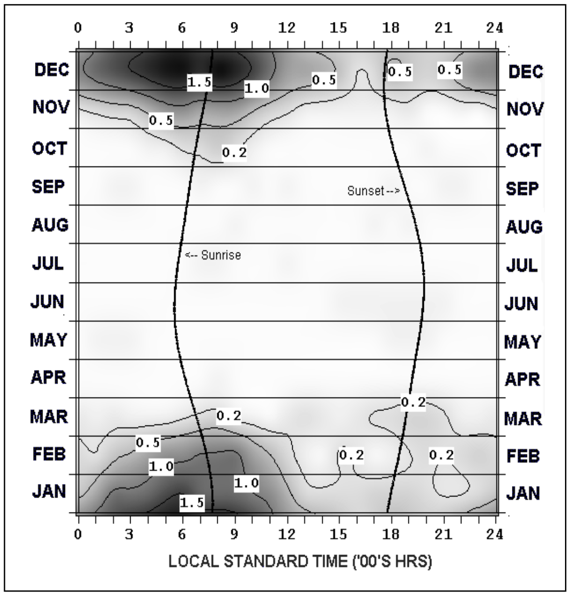

Figure 36 – Percent of Time with Fog at Yuma MCAS

Not unlike that shown in the Fog charts for Phoenix and Tucson (Figures 11 and 23, respectively), Yuma's variations depicted in Figure 36, are concentrated principally to the winter months, particularly December, covering the overnight hours through sunrise and a few hours beyond. Maximum contour a modest 1.5%, the same as Tucson's, but less than Phoenix's 2.5%.

3.4 - Flagstaff Pulliam Airport - 35.19° N,111.65° W Elev:7014 ft

Using excerpts from its 2017 "Local Climatological Data Annual Summary" publication, Flagstaff is described as situated on a volcanic plateau, elevation 7000 feet. It has cold winters, pleasantly cool summers, moderate humidities, and large diurnal temperature changes, the latter a characteristic of high altitude climates. Freezing temperatures on average can occur as late as mid-June, but summer maxima are frequently above 80 F and occurrences into the 90's F are not unknown. The station is located about 150 miles north of Phoenix, and hourly data from the1978-2018 period d were utilized for analyses, some 350 K cases.

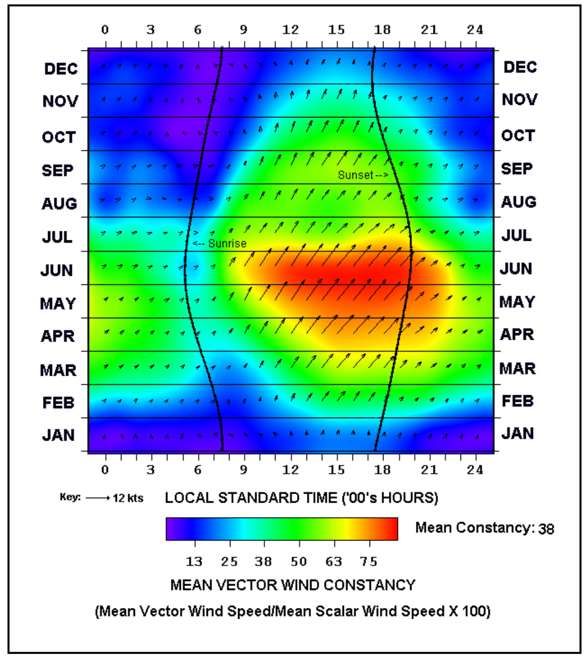

Figure 37 - Mean Vector Wind/Constancy Chart for Flagstaff Pulliam Airport, AZ

Figure 37 is the Mean Vector Wind/Constancy Chart for Flagstaff. The vectors are mostly southwesterly in orientation, both seasonally and diurnally, from very light but still southwesterly over the nocturnal hours generally, to appreciably higher southwesterlies (12 knots or greater) during daytime, particularly over the afternoons of April to June. The area of maximum constancy magnitudes (>75) is evident for the mid-morning to early evening hours of May and June, but in contrast, large areas of very low constancy indices (depicted in violet) are visible for virtually all the non-daylight hours of January, along with those hours over October to December that just precede sunrise.

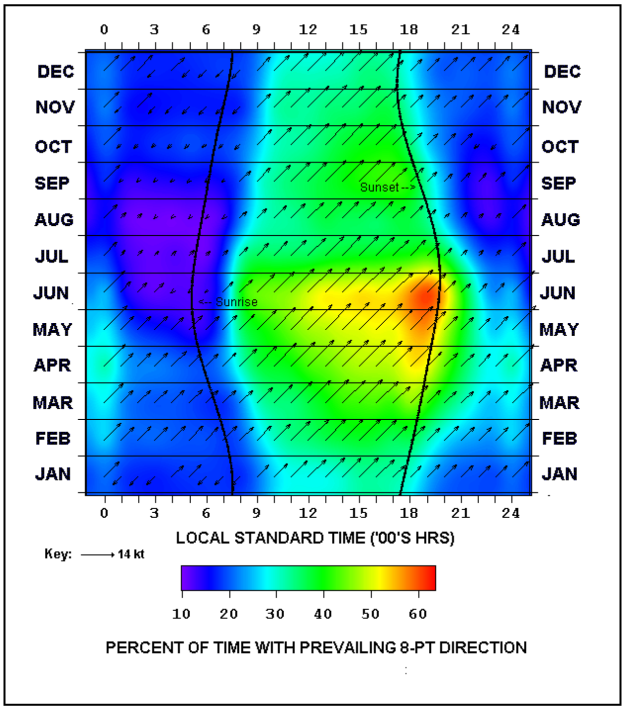

Figure 38 - Prevailing Eight-Point Compass Winds' Chart for Flagstaff Pulliam Airport, AZ

From the Prevailing 8-Point Compass Winds Chart (Figure 38), the predominance of the southwesterlies generally, especially for daytime, and the night vs. day contrast of their relative frequencies is quite striking. Some 85.1% of the total 288 data points that make up the climogram have prevailing southwesterlies at some frequency level. Most of the daytime cases are in the green to red frequency range (35% to greater than 60% incidence).

On an individual case-basis, the most predominant case is that for June at 1900 LST, the prevailing direction southwesterly at a 63.4% incidence with a mean speed from that direction of 9.8 knots.

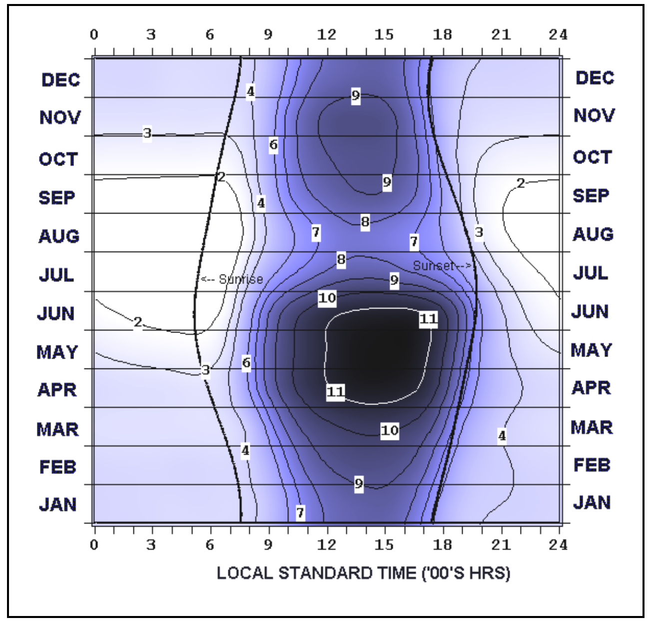

Figure 39 - Mean Scalar Wind Speeds (knots) for Flagstaff Pulliam Airport

Figure 39 depicts the Mean Scalar winds speeds for Flagstaff. Overall mean speed (5.4 knots) is relatively light, but there is a wide range of isopleth magnitudes, from 2 to 11 knots. The latter contour comprises the afternoon hours Noon LST to about 1700 LST, for the monthly periods April to mid-June. Individual maximum hourly mean speed is 11.7 knots for May at 1600 LST.

Areas within the 2 knot minimum isopleth undoubtedly include a lot of Calms, which would show up as high frequency isopleths on a climogram dedicated to them as a category.

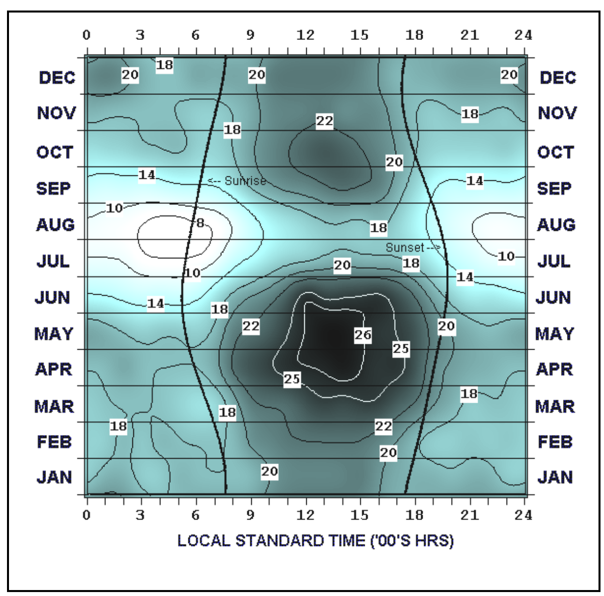

Figure 40 - Upper 99th Percentile Sustained Wind Speeds for Flagstaff Pulliam Airport, AZ

Figure 40 is the Upper 99th Percentile Sustained Winds Threshold chart for Flagstaff. The 26 knot maximum isopleth placement indicates that such relatively high wind events are a Springtime afternoon phenomenon, the identified interval being Noon LST to 1500 LST over roughly mid-April to early June.

3.4.2 – *Flagstaff Pulliam Hourly Temperatures and Relative Humidities*

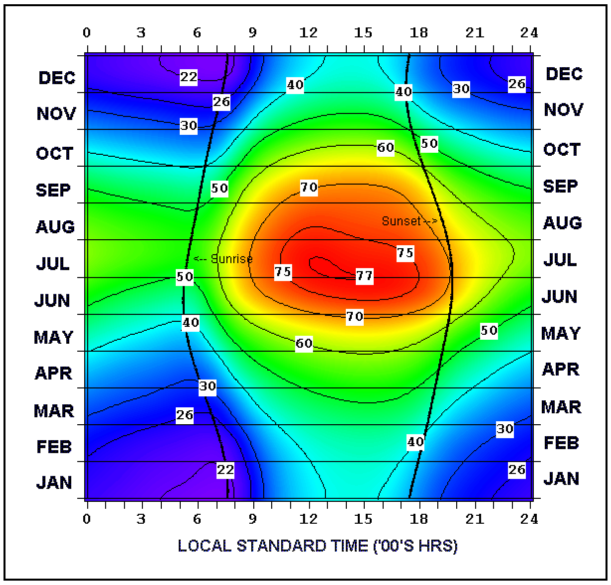

Figure 41 -– Mean Hourly Temperatures for Flagstaff Pulliam Airport

Temperature-wise, Figure 41 shows the mean hourlies at Flagstaff, the contours denoting mean readings considerably cooler than those for Phoenix, Tucson and Yuma. Mean hourly January temperatures range from the low 20's F to perhaps the low 40's F, and based on the positioning of the 30 F isopleth, sub-freezing readings are likely a routine occurrence into early April at least. July mean hourlies vary from perhaps the low 50's F to the high 70's F.

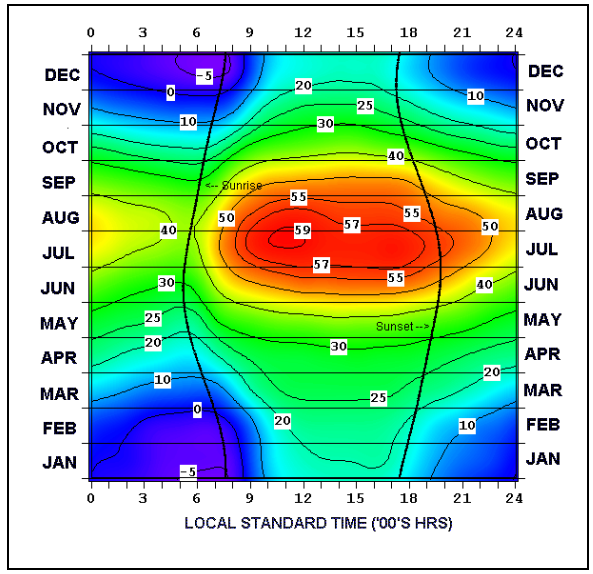

Figure 42 – Lower 1st Percentile Threshold Temperatures for Flagstaff Pulliam Airport

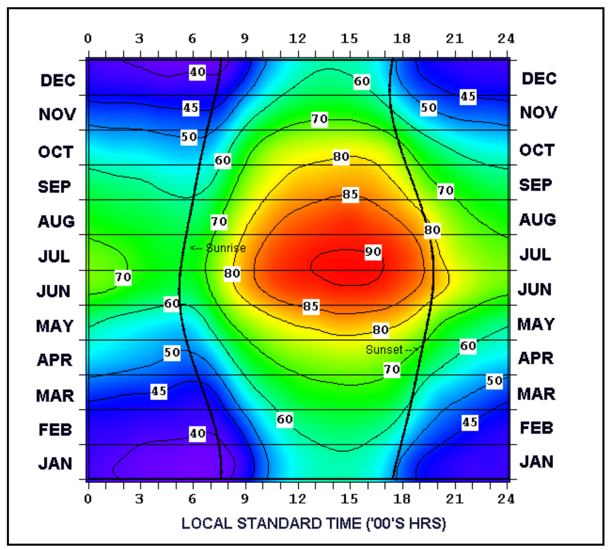

Figure 43 – Upper 99th Percentile Threshold Temperatures for Flagstaff Pulliam Airport

Figures 42 and 43 exhibit the Lower 1st Percentile and Upper 99th Percentile Temperature patterns, respectively, for Flagstaff. Interestingly, the unusually cool temperature regime cases for Flagstaff, depicted in Figure 42 generate no isopleths as warm as 60 F, the very localized maximum 59 F contour not even situated past mid-day, confined instead for the 1000 LST to Noon LST period over mid-July to early August. A subzero isopleth (-5 F) is also present, covering several pre-sunrise hours over early December to early January. Further noted, the 30 F contour extends all the way into mid-June (at sunrise).

From the Figure 43 Upper 99th Percentile Threshold climogram, Flagstaff can have a warm side climatologically as well, the 90 F isopleth seen to encompass most of the afternoon hours from mid-June to mid-July.

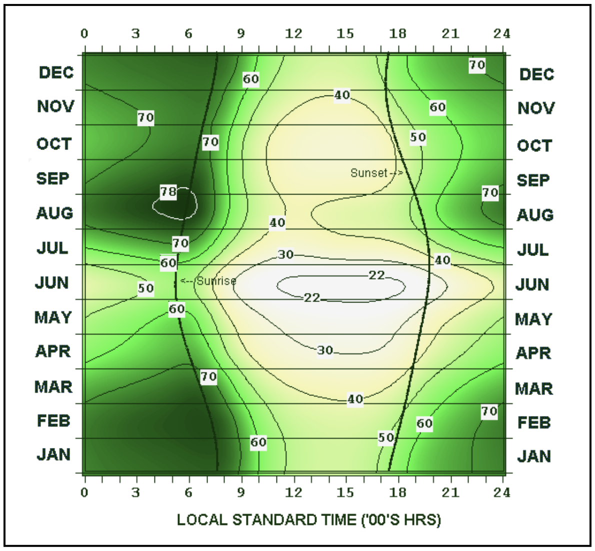

Figure 44 - Mean Hourly Relative Humidities for Flagstaff Pulliman Airport, AZ

Figure 44 shows Flagstaff's mean hour by month relative humidities. Average overall figure is 53.2%, significantly higher than that a Phoenix, Tucson, and Yuma, theirs in the 30's % range. Highest individual hour Flagstaff statistic, 78.8 %, is for 0600 LST in August, the lowest 19.2 % for June at 0600 LST, during the early summer "pre-monsoonal" period.

***3.4.3 –** Flagstaff Ceilings, Thunderstorms, and Visibility restricted conditions*

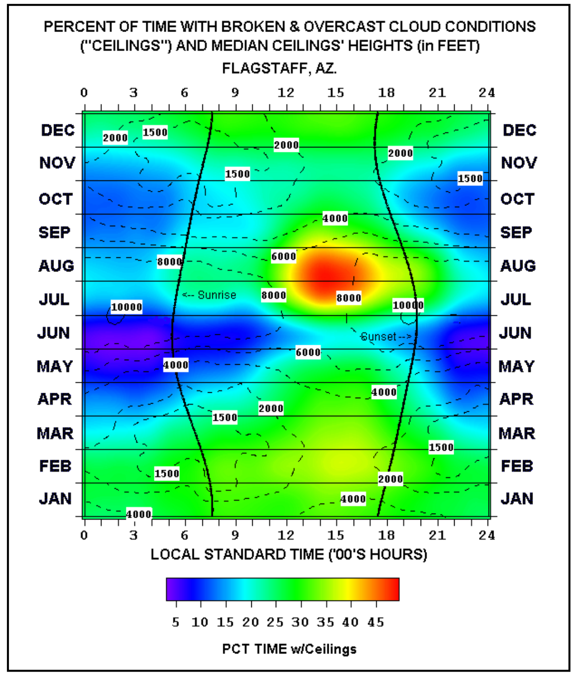

Figure 45: Percent of Times with Cloud Ceilings and Median Ceilings' Heights – Flagstaff, AZ

Figure 45 is the Percent of Time with Ceilings/ Median Ceilings heights climogram for Flagstaff Overall climatological frequency (22.8%) is a little less than Phoenix's (24.2%), but higher than either Tucson (16.5 %) or Yuma (19.5 %). Thanks to Flagstaff's 7000 foot plus station altitude, median ceilings heights' average just 4900 feet. A semblance of the low ceiling dark violet to blue "pre-monsoonal" feature is present over the May to June pre-sunrise and morning hours through about Noon LST, but it is not evident thereafter until after sunset. Also, another red oval high ceilings feature appears over mid-July through August, but it is shifted diurnally to the afternoon (1300 LST to 1700 LST) hours. As the next Climogram for Thunderstorm frequencies will hint, the latter feature is probably related to local Flagstaff thunderstorm occurrences, which are relatively frequent over those hours. Overall, Flagstaff's ceilings frequency pattern is correlated with Phoenix's at a magnitude r=+.595. Highest individual Flagstaff frequency is 49.0 % for August at 1400 LST, July's figure at that same time being 46.8%. Minimum figure is 3.1% for June at 0400 LST.

Inspecting the Thunderstorm incidence climogram for Flagstaff, the maximum incidence isopleth (16%) is quadruple that of Phoenix's, and about one-fourth higher in magnitude than that for Tucson. Seasonally, it similarly covers July and August, but diurnally, compared to the latter two stations, it has shifted to the earlier afternoon hours, the maximum "pole" situated at about 1400 LST. Monsoonal flow undoubtedly affects Flagstaff in July and and August, but other factors not present to same degree in Phoenix and Tucson must be involved to produce this phase shift.

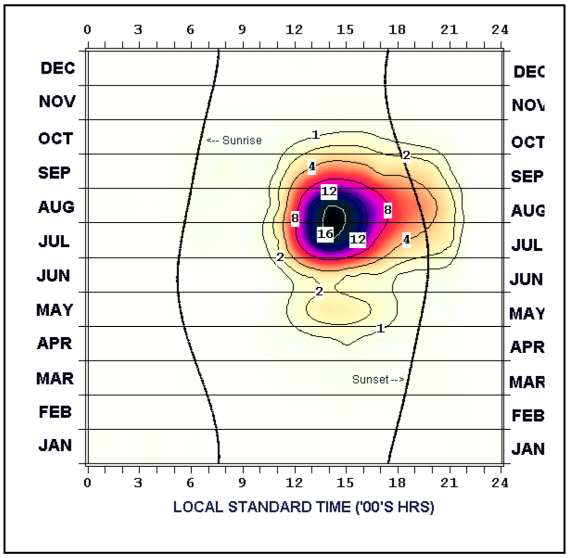

Figure 46: Percent of Time with Thunderstorm Activity in Flagstaff

As was done for Phoenix, Tucson, and Yuma, the remaining charts for Flagstaff depict the percent occurrences of various visibility restricted parameters. The possible selections being Blowing Sand and Dust, Fog, and Haze/Smoke

Since these three were all represented rather interestingly for Flagstaff, charts appear below each one (making 13 total climograms for Flagstaff).

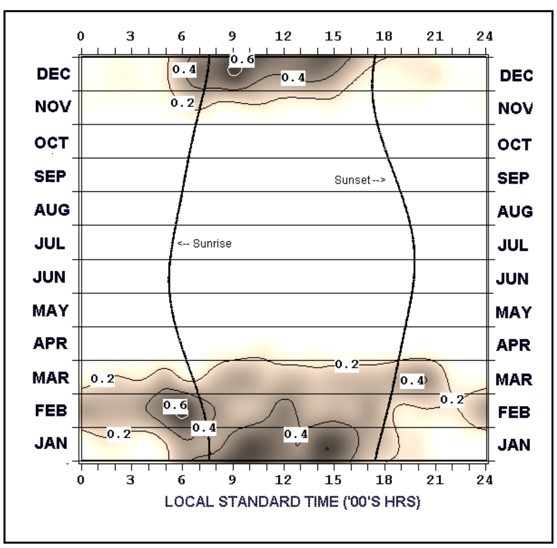

Figure 47: Percent of Time with Blowing Sand/Dust in Flagstaff

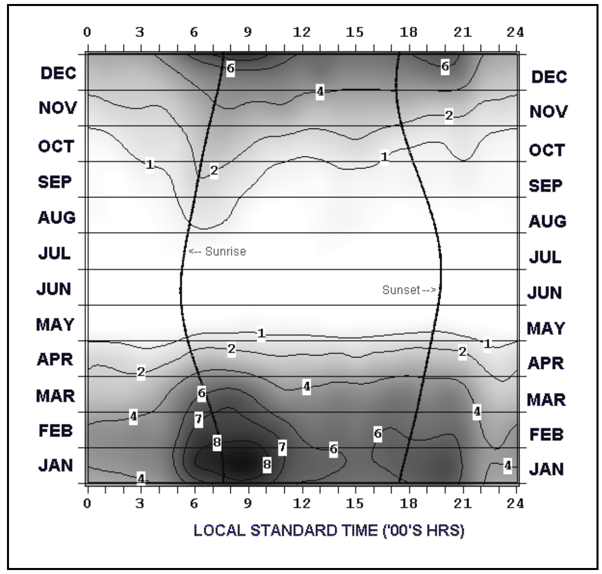

Figure 48: Percent of Time with Fog in Flagstaff

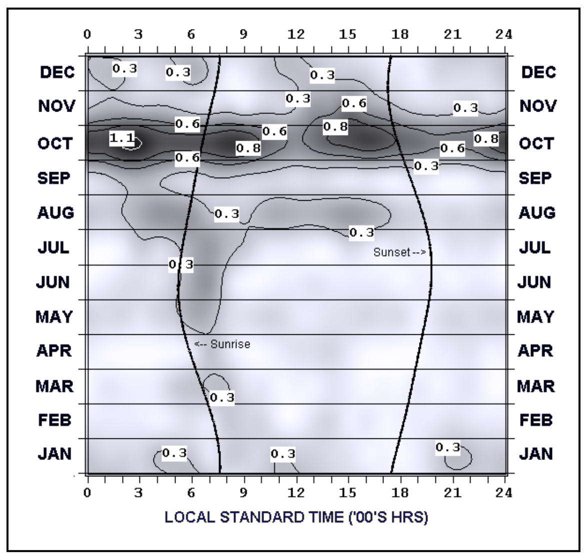

Figure 49: Percent of Time with Haze/Smoke in Flagstaff

Figure 47's Blowing Sand/Dust chart reveals a wintertime/early Spring relative maximum , the 0.2% or greater isopleths covering December and January principally for the daylight hours, but extending into some of the pre-sunrise and post-sunset ones in February and March. Maximum isopleth (0.6%) is positioned just prior to sunrise in February.

Fog in Flagstaff (Figure 48) is similar in seasonal and diurnal bent to that of Phoenix, Tucson, and Yuma, showing a cold season maximum, but the absolute magnitudes are higher, the 8 percent maximum contour indicated for January, covering the rough hourly interval 0600 LST to 1000 LST.

Finally, Haze and Smoke incidence (Figure 49), shows a conspicuous relative October tendency, although the absolute climatological frequencies across the chart are no higher than 1.1%. This particular seasonal maximum likely reflects transport of airborne pollutants (wildfire origins?) from distant sources to the west. Local Flagstaff winds are mostly southwesterly in October, especially during the day.

4. SUMMARY

The purpose of the foregoing study was to produce a series of hour-by-month climogram "atlases" for four first order Arizona weather stations, incorporating twelve and in one case thirteen different climogram types for each station. The first-order stations, all large population centers with meteorological periods of record longer than 40 years were Phoenix, Tucson, Yuma, and Flagstaff. Features of the charts were described in some detail, one climogram after the other, for each station, with inter-station comparisons occasionally made between those of the same type; Phoenix was frequently the baseline reference in this regard.

Other first order Arizona stations with lengthy histories and observations that would lend themselves to the same treatment, not written up here, are Prescott and Winslow. The Kingman and Bisbee Municipal airports also have hourly temperature and wind observations for appreciable periods of record but the availability of other parameters such as thunderstorm incidence and visibility restricted frequencies are not complete.

The advantage and motivation of the climogram methodology is that insights as to the character of diurnal/seasonal variation of selected parameters can be conveyed visually, concisely and rather compre-hensively on single-page layouts, without having to resort to voluminous tabular summaries or lengthy narratives, but in the context of presenting results in an extended abstract here, it was more or less necessary and obligatory to provide detailed written descriptions, explanations and interpretations in support of the graphs' results.

5. REFERENCES

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