**P1.1   EXAMINING PRECONVECTIVE HEAVY RAINFALL ENVIRONMENTS UTILIZING
OBSERVATIONAL AND MODEL ANALYSIS PROXIMITY SOUNDINGS**

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1.   INTRODUCTION

Extreme rainfall is just one type of treacherous weather event, but it has an enormous impact on all facets of transportation (WIST 2005). Two important societal impacts that arise from heavy rainfall include loss of visibility and flash flooding. As visibility decreases, the speed of traffic also decreases, especially when traffic flow is increasing (e.g., during local rush hours; WIST 2002). Flash flooding, just as with a loss of visibility, occurs quickly on small time scales and is potentially deadly. According to the National Oceanic and Atmospheric Administration (NOAA 2006), every year flooding costs an average of over 2 billion USD in damages and causes over 100 fatalities. In recent years the flash flood threat has risen due to increasing urbanization. As areas become more populated and are covered with impermeable structures and surfaces such as buildings and roads, the amount of storm-water runoff increases (Kelsch 2002). Consequently, modest rainfall episodes can become potentially dangerous flash flood situations.

Therefore, increased accuracy of forecasting the location and amount of precipitation is crucial in not only saving lives but also lessening property damage. However, quantitative precipitation forecasts (QPF) still lack the precision and confidence shown in other forecast products and remains one of the most difficult tasks in operational meteorology (Junker 2001). According to the United States Weather Research Program (USWRP 2001) and the National Weather Service (NWS), one of the top priorities is to increase the accuracy of QPF.

According to WIST (2002), the highway carrying capacity is expected to multiply, which will multiply the economic and safety impacts due to adverse weather and weather-related road conditions. These societal and economic concerns, associated with even moderate rainfall,

make the operational forecasting of these events paramount.

1.1   OBJECTIVE

This work is an attempt to apply several proximity-sounding techniques from previous researchers toward a different atmospheric phenomenon, heavy rainfall. To accomplish this, observed and Rapid Update Cycle Version II (RUC-2) analysis soundings were collected in the preconvective environments of heavy rainfall producing storms (rainfall event selection is illustrated in Section 3). Numerous sounding parameters were investigated to distinguish environmental differences between rainfall amounts (≥ four inches versus two inch rainfall days). This type of study has been conducted for severe weather events (e.g., tornadoes), but never for a large heavy rainfall dataset.

2   RELATED LITERATURE

2.1   OBSERVATIONAL SOUNDINGS

Darkow (1969), Houze et al. (1990), Brooks et al. (1994), and Rasmussen and Blanchard (1998) have studied the advantages of proximity soundings, using observed soundings, associated with warm season severe weather. Many obstacles present themselves when considering observed proximity soundings.

First, there are questions regarding the most relevant location for a severe weather proximity sounding. Second, severe weather such as supercells are essentially randomly distributed with respect to the observed soundings, making consistent data collection difficult at best. Beebe (1955) discovered soundings taken in a very close time and space proximity to tornadoes had noticeably different vertical structures compared to proximity soundings in the antecedent pre-convective environment several hours earlier. Supercells may exert influence on low-level shear and buoyancy profiles up to 30 km away from the storm, effectively altering what had been the pre-storm environment (Weisman et al. 1998). This

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illustrates that the proximity sounding should be chosen relatively close to the event, temporally and spatially. There are other concerns a researcher will most likely be presented with, such as sounding sample size and storm characteristics for their particular situations. The studies of Brooks et al. (1994) and Rasmussen and Blanchard (1998) illustrated that observed soundings are quite capable of serving as proximity soundings even when adjusting certain spatial and temporal allowances to increase the size of a dataset.

Brooks et al (1994) discovered that a spatial distance of 160 km and a temporal allowance of ±1 hour from the nominal sounding time allowed for more cases. Rasmussen and Blanchard (1998) defined their proximity soundings as inflow sector soundings based on the boundary layer mean wind vector. The sounding was assumed to be in the inflow sector of any meteorological event if it was within 400 km and the event fell within a 150° sector centered on the boundary layer mean wind vector.

2.2   MODEL ANALYSIS SOUNDINGS

A primary advantage to the use of model analysis grids is the collection of a much larger sample of storm cases in a shorter period of time. For example, RUC-2 model analyses contain asynoptic data from wind profilers, aircraft temperatures and winds, satellite-derived winds, surface observing networks, etc. However, model analysis grids must be consistent with observed data if they are to serve as a diagnostic tool, and the analysis grids must be available frequently in time so that changes in parameters can be observed over a mesoscale temporal domain (Thompson and Edwards 2000).

Thompson et al. (2003), Edwards and Thompson (2000), and Thompson and Edwards (2000) investigated RUC-2 model soundings as effective proximity soundings. Thompson and Edwards (2000) chose the nearest (i.e., to the supercell) available RUC-2 grid point data in the inflow sector of the supercell. They also normalized the RUC-2 soundings to the equilibrium level (EL) height by dividing each sounding into ten equal height layers from the surface to the EL. This allowed them to relate various types of supercell storms (e.g., light precipitation, heavy precipitation, classic, and mini-supercells) to one another based upon sounding-derived parameters within the ten equal height layers.

The results Thompson and Edwards (2000) found are critical and therefore must be explained in some detail to completely understand the biases of the RUC-2 model. The RUC-2 analysis soundings were found to be characteristically 1 to 2°C too dry at the surface and 850 hPa, as well as 1 to 2°C too cool at the surface and too warm at 850 hPa, when compared to observed soundings at the same time and location. This minor cool and dry bias of the RUC-2 soundings at the surface, combined with the warm bias at 850 hPa, contributed to a tendency for convective inhibition to be somewhat overestimated, and surface-based CAPE to be underestimated by approximately 500-1000 J kg^{-1}. Temperature errors in the middle and upper troposphere were substantially smaller than in the lower troposphere, therefore, the CAPE errors were basically the result of a cool and dry surface bias of the RUC-2 analyses. They discovered the potential for some of the surface errors to be the result of differences between the RUC-2 surface pressures and those of the co-located observations, as well as due to the interpolation differences in the RUC-2 soundings constructed from grids of 25 hPa vertical resolution.

As with surface temperatures and low-level dew points, Thompson and Edwards (2000) discovered that the majority of the vertical shear parameters were slightly underestimated in the RUC-2 analysis soundings. Parameters such as 0-3 km system-relative helicity (SRH) and the bulk Richardson number (BRN) shear term, which incorporate low-level details from the hodograph, were most sensitive to small variations in the compared wind profiles. The mean absolute analysis errors for the BRN shear term and 0-3 km SRH were substantial, though small negative mean errors suggested only a slight tendency for the RUC-2 analysis hodographs to consistently underestimate low-level vertical shear. The 0-6 km wind vector difference showed even less difference between the observations and RUC-2 analyses.

The errors in the RUC-2 model soundings, when compared to observed soundings at the same time and location, were found to be within instrumentation measurement errors (Thompson and Edwards 2000). Therefore, even given the errors of the model, unmodified RUC-2 model analysis soundings may be used as proximity soundings.

3.   DATA AND METHODOLOGY

The General Meteorological Package (GEMPAK; Koch et al. 1983), software and Saint Louis University's SLUbrew diagnostic analysis program were used to diagnose and display key parameters on surface and upper-air plots. Also, both sets of software use the Barnes (1973) objective analysis to objectively analyze the data being examined. To statistically analyze the significant difference between parameters for each sounding, the Statistical Package for the Social Sciences (SPSS) was used.

In GEMPAK, observational data as well as 3-hourly RUC-2 (Benjamin et al. 2004) initialization model data, acquired from the NWS observational network via Unidata's Internet Data Distribution (IDD) network, were used in the analysis of the synoptic setting, moisture, instability, and wind shear parameters. For the four and two inch rainfall cases in this study, GEMPAK surface analyses were created to diagnose the location of the extratropical cyclones (ETC) and their associated fronts and precipitation. The surface station plots were created from surface METAR observations using GEMPAK. The upper-air station plots and analyses were created from the NWS operational upper-air observations using GEMPAK. These plots were generated to help classify these rainfall events into various Maddox et al. (1979) atmospheric settings. The sounding parameters were then divided into the various atmospheric settings, where a statistical analysis (described below) was conducted between each Maddox et al. (1979) setting and between each rainfall category.

SLUbrew, created by Graves and Moore (2002), uses upper-air and surface data, from the NWS via IDD, to diagnose various basic and derived parameters. Upper-air data is collected twice daily (0000 UTC and 1200 UTC) for over 100 stations, spaced approximately 400 km apart, across North America. These data are archived at Saint Louis University in the form of soundings containing temperature, dewpoint, wind direction and speed information for all mandatory and significant pressure levels. Surface data are collected from over 600 observation stations for every hour. These datasets are also archived at Saint Louis University in METAR form, and contain temperature, sea level pressure, cloud cover, precipitation type and intensity, wind direction and speed, and hourly barometric tendency.

Daily rainfall accumulation plots were used to show the location(s) of the greatest rainfall accumulation. These data were obtained through the National Climatic Data Center (NCDC) River Forecast Center (RFC). Doppler radar (WSR-88D) data, also obtained from NCDC and the University Corporation for Atmospheric Research (UCAR), were used to determine the location, orientation, intensity, and movement of the precipitation field with units given in decibels (dBz).

SPSS is a statistical package which analyzed the data from various parameters for all soundings within the datasets. This included checking for statistically significant differences between four and two inch rainfall sounding parameters. Also, this software was used to compare four and two inch rainfall sounding parameters within their respective synoptic settings (i.e., synoptic, frontal, mesohigh) to determine which parameters would best distinguish between four and two inch rainfall days given a specific Maddox et al. (1979) atmospheric setting.

3.1   DETERMINING SIGNIFICANT DIFFERENCES

In order to determine whether a parameter or multiple parameters are significantly different from one rainfall category to the next, two statistical evaluations were conducted. The first statistical procedure was to generate boxplots (i.e., box-and-whisker plots). The second statistical procedure utilized the Mann-Whitney test statistic to determine whether the means of each distribution are significantly different between the rainfall categories.

Boxplots are a frequently used graphical tool that depicts five simple statistics. The minimum, lower quartile (25th percentile), median (50th percentile), upper quartile (75th percentile), and the maximum values are illustrated in boxplots. These five statistics, within the boxplot graphic, allow an individual to quickly examine the distribution of the data (Wilks 2006). When boxplots of a particular parameter for all rainfall categories are aligned side-by-side it shows how that particular parameter may vary from one category to the next. If the "box" portion of the boxplots overlaps from one category to the next, then there is potentially no statistically significant difference between the rainfall categories for that particular parameter. However, if the "box" portions do not overlap, then there is a higher probability of significant difference between the rainfall categories. To help discern differences, the Mann-Whitney test statistic is utilized.

While boxplots are extremely helpful and give a quick representation of the distribution, they lack additional insight. The Mann-Whitney test

statistic gives further detail of the data in question. The Mann-Whitney test is a nonparametric test for location (i.e., difference between the means) for two independent (i.e., both serially independent, and unpaired) samples. It is extremely useful as it does not require the user to assume a distribution (Wilks 2006). When the boxplots indicate an increase or decrease in parameter values from one category to the next, but the "box" portions still overlap, the Mann-Whitney test was used to determine if there is a statistically significant difference between the categories even though the boxplots do not indicate this statistical difference.

The combination of the boxplots and the Mann-Whitney test were used to determine which parameters illustrate a significant between rainfall categories. These significant parameters will be utilized to construct potential heavy precipitation formulas in the near future. These heavy precipitation formulas will allow forecasters to determine if there is a potential for a significant heavy rainfall episode for their area.

3.2 CASE SELECTION

Parameters and processes are examined using the software described in Section 3 for 33 case studies associated with rainfall accumulations equal to or greater than four inches and 47 case studies associated with rainfall accumulations between one and two inches. The 33 heavy rainfall cases were chosen on the following basis:
- Rainfall events occurred during the warm season (March through September) in the central United States for the years 2003 through 2005.
- Storm Data publication listed an event under the categories of heavy rainfall, flooding, and/or flash flooding.
- The Climate Prediction Center River Forecast Center 24 hour rainfall accumulation plots indicated rainfall accumulations greater than or equal to four inches with reports from more than one station. These plots were also compared to the Storm Data listing of an event for cross-referencing.
- Doppler radar depicted the rainfall was generated from one precipitation system and not waves of precipitation. Also used to determine the timing of the precipitation near observational sounding sites.
- Observed soundings were collected if they occurred within six hours prior to and 250 km of the event.

- Model analysis soundings were collected in close temporal and spatial proximity to an event.

The 47 light rainfall cases were chosen on the following basis:
- Rainfall events occurred during the warm season (March through September) in the central United States for the years 2003 through 2005.
- The Climate Prediction Center River Forecast Center 24 hour rainfall accumulation plots indicated rainfall accumulations between one and two inches with reports from more than one station.
- Doppler radar depicted the rainfall was generated from one precipitation system and not waves of precipitation. Also used to determine the timing of the precipitation near observational sounding sites.
- Observed soundings were collected if they occurred within six hours prior to and 250 km of the event.
- Model analysis soundings were collected in close temporal and spatial proximity to an event.

After dividing the four-inch and two-inch datasets into various synoptic settings, the results from comparing the four-inch dataset with the two-inch dataset and all the statistical analyses of the numerous parameters, associated with each comparison, are illustrated in Section 4. Section 5 provides a summarization of the results.

4. RESULTS

4.1 SYNOPTIC-TYPE EVENTS

The comparison between four-inch and two-inch rainfall days associated with a synoptic-type heavy rainfall setting illustrated numerous parameters that showed significant variations between rainfall categories. These variations in moisture, instability, wind shear, and other parameters are shown below.

When investigating key moisture parameters, each parameter showed an increase (i.e., an increase in moisture) from the two-inch category to the four-inch category. These key parameters are K index, precipitable water (PW), subcloud layer relative humidity, surface-500 hPa relative humidity, and surface-500 hPa theta-e. An increase in these values was anticipated since there is an increase in rainfall amount.

The boxplots of these parameters illustrate the increasing values. Illustrated in Figure 1 are the K index values. Figure 2 depicts the increase in PW values. The others parameters (not shown) follow the same pattern. However, the boxplots still overlap, and therefore do not depict a significant difference between rainfall categories. Thus, the Mann-Whitney test statistic was generated to determine if the means from the two rainfall distributions were significantly different. All moisture parameters demonstrated a less than one percent chance that the two rainfall distributions are related, or could have come from the same population.

The 700-500 hPa lapse rates (Fig. 3), 850-500 convective instability (Fig. 4), and lid strength (not shown) values decrease from the two-inch to four-inch rainfall categories. Coinciding with this decrease in stability, most unstable parcel convective available potential energy (MUCAPE; Fig. 5) increases across the rainfall categories. It is evident that the atmosphere is less stable for the four-inch rainfall days when compared to the two-inch days.

The boxplots show similar results as the moisture parameters, therefore, the Mann-Whitney test was utilized once more. Nearly all instability parameters illustrated a less than one percent chance of the two rainfall categories being from the same distribution. Two parameters (most unstable parcel convective inhibition and convective temperature) demonstrated higher percentages, 2.385 and 20.327 respectively.

Wind shear (speed and directional) parameters were investigated to decipher the potential impact of wind shear on the local environments associated with these rainfall events. 0-2, 0-3, 0-6, and 3-6 km speed and directional bulk shear were compared. Looking for differences between the boxplots (i.e., distributions), only two parameters depicted a difference. 0-3 km (Fig. 6) and 3-6 km (Fig. 7) speed shear illustrate a decrease (i.e., a decrease in wind speed) from the two-inch to four-inch category. When compiling the Mann-Whitney statistic for these two parameters, only the 3-6 km speed shear demonstrated a less than one percent chance of the two categories being from the same distribution. The 0-3 km speed shear showed a greater than 20% chance the two rainfall categories are related. Otherwise, the atmospheres associated with the two rainfall categories are very similar with typically northerly low-level winds at roughly 25 ms^{-1}.

Other parameters investigated include the equilibrium temperature, the distance between the level of free convection (LFC) and the equilibrium level (EL), the pressure level of the LFC, the pressure level of the lifted condensation level (LCP), and the warm cloud depth. All of which use the most unstable parcel, except the LCP. The equilibrium temperatures (Fig. 8) show colder temperatures for the four-inch category than the two-inch. Also, the distance between the LFC and EL (Fig. 9) increases from the two-inch to four-inch category. The last two parameters that appeared interesting are the LCP (Fig. 10) and warm cloud depth (Fig. 11). LCP values increased (i.e., lower LCL heights), while the warm cloud depth values also increased, indicating higher freezing levels in the atmosphere. The Mann-Whitney statistics identified the top three parameters in this category to be the warm cloud depth, distance between the LFC and EL, and the LCP with percentages of 0.013, 0.357, and 1.578, respectively. Once again, this test statistic illustrates a strong difference between the two rainfall categories.

These last few parameters combined with several instability and moisture parameters illustrate a different four-inch sounding profile than the two-inch profile. With steeper lapse rates, lower LCL heights, colder equilibrium temperatures, a greater distance between the LFC and EL, and an increase in MUCAPE values indicates a longer (taller), more moist, and less stable profile than the two-inch rainfall events. Also, the increase in warm cloud depth values illustrates that heavier rainfall events rely on warm cloud precipitation processes to produce greater rainfall accumulations.

4.2   FRONTAL-TYPE EVENTS

The comparison between four-inch and two-inch rainfall days associated with a frontal-type heavy rainfall setting illustrated some surprising results. Numerous parameters that showed significant variations in the synoptic-type setting did not show the same results here.

When investigating key moisture parameters, only three parameters showed an increase (i.e., an increase in moisture) from the two-inch category to the four-inch category. These key parameters are PW, subcloud layer relative humidity, and surface-500 hPa relative humidity. Once again, an increase in these values was expected since there is an increase in rainfall amount, but for only three parameters to show a difference between rainfall categories was surprising.

The boxplots of these parameters illustrate the increasing values. Illustrated in Figures 12, 13,

and 14 are PW, subcloud layer relative humidity, and surface-500 hPa relative humidity, respectively. The boxplot values for the K index are shown in Figure 15 to illustrate a lack of separation between the two rainfall categories. Looking at the median values for each category, they are equal (32) demonstrating that the values in both distributions are distributed nearly equally. Others parameters (not shown) follow the same pattern as the K index values.

The Mann-Whitney test statistic was generated to determine if the means from the two rainfall distributions were significantly different for the three parameters that indicate a potential difference (i.e., an increase in moisture). Of the three moisture parameters, only one demonstrated a less than one percent chance that the two rainfall distributions are related, or could have come from the same population. This parameter was the surface-500 hPa relative humidity with a percentage of 0.038. The other two, PW and subcloud layer relative humidity, have percentages of 12.714 and 3.438, respectively.

The 700-500 hPa lapse rates (Fig. 16), 850-500 hPa convective instability (Fig. 17), and convective temperature (not shown) illustrate differences from the two-inch to four-inch rainfall categories. These are the only instability parameters that depict a difference between rainfall categories. This was a surprise as well. The Mann-Whitney test was utilized once more. Of the three instability parameters that showed a difference, utilizing boxplots, only one illustrated a less than one percent chance of the two rainfall categories being from the same distribution. Surface-500 lapse rates have a percentage of 0.199. The other two parameters (850-500 hPa convective instability and convective temperature) have demonstrated higher percentages that just happen to be identical (10.383%). Therefore, it is not as evident as the synoptic-type heavy rainfall events that the atmosphere is less stable for the four-inch rainfall days when compared to the two-inch days. It appears that the instability of the atmosphere is nearly identical for both rainfall categories.

Just as with the synoptic-type heavy rainfall events, wind shear (speed and directional) parameters were investigated. Looking for differences between the boxplots (i.e., distributions), only one parameter depicted a difference, 3-6 km directional shear (not shown), illustrates a decrease (i.e., a change in wind from a northerly to a northwesterly direction) from the two-inch to four-inch category. Otherwise, just as with the instability parameters, the atmospheres

associated with the two rainfall categories are very similar with typically northerly low-level winds at roughly 18-20 ms^{-1}.

Other parameters investigated also show little change between rainfall categories. These include the equilibrium temperature, the distance between the level of free convection (LFC) and the equilibrium level (EL), the pressure level of the LFC, the pressure level of the lifted condensation level (LCP), and the warm cloud depth. Of these parameters, only three showed slight differences between categories. The distance between the LFC and EL (Fig. 18), LCP (Fig. 19), and the pressure level of the LFC (Fig. 20) depict an increase in values from the two-inch to four-inch categories. Therefore, there are lower LFC and LCL heights in the four-inch rainfall category than the two-inch and this allows for a greater distance between the LFC and EL. The Mann-Whitney statistics depicted the top three parameters in this category to be the distance between the LFC and EL, LCP, and the pressure level of the LFC with percentages of 4.363, 4.846, and 7.353, respectively. Once again, given these percentages, this does not illustrate a tremendously strong difference between the two rainfall categories, but it does indicate a 95% confidence that the two rainfall categories are different with respect to the distance between the LFC to the EL and the LCP.

These last few parameters combined with instability, moisture, and wind shear parameters illustrate that there are minor differences between the four-inch sounding profile than the two-inch profile. With only two parameters illustrating a less than one percent chance of the two rainfall categories being from the same distribution; and another four parameters illustrating a less than five percent chance. It becomes evident that a forecaster will have a more difficult time discerning whether a frontal-type heavy rainfall event will produce rainfall accumulations of two inches or greater than four inches just by utilizing proximity soundings. Perhaps strength and overall movement of the system should be considered.

5. SUMMARY

This work is an attempt to apply several proximity-sounding techniques from previous researchers toward a different atmospheric phenomenon, heavy rainfall. Observed and RUC-2 analysis soundings were collected in the preconvective environments of heavy rainfall producing storms. Numerous sounding parameters were investigated to distinguish

environmental differences between rainfall accumulations of greater than or equal to four inches versus rainfall days where only two inches had accumulated. Similar studies have been conducted for severe weather events (e.g., tornadoes), but never for a large heavy rainfall dataset.

The results for the synoptic-type heavy rainfall setting demonstrate the typical results the researchers anticipated. As the rainfall accumulation increases, the moisture parameters indicate an increase in moisture and the stability of the atmosphere decreases. Also, there are steeper lapse rates, lower LCL heights, colder equilibrium temperatures, a greater distance between the LFC and EL, and an increase in MUCAPE values, which indicates a longer (taller), more moist, and less stable profile than the two-inch rainfall events. The increase in warm cloud depth values illustrates that heavier rainfall events rely on warm cloud precipitation processes to produce greater rainfall accumulations. While the majority of the wind shear parameters did not depicted noticeable differences between the rainfall categories, the 3-6 km speed shear parameter was the only outlier. This potentially indicates that the wind, in this layer, is not as strong in the four-inch cases, and therefore, the heavy rainfall producing cells are not advected as quickly as they are in the two-inch cases.

On the other hand, the comparison between four-inch and two-inch rainfall days associated with a frontal-type heavy rainfall setting illustrated some surprising results. Numerous parameters that showed significant variations in the synoptic-type setting did not show the same results here. Overall, the moisture, instability, wind shear, and additional parameters illustrate that there are minor differences between the four-inch sounding profile than the two-inch profile. With only two parameters (700-500 hPa lapse rates and surface-500 hPa relative humidity) illustrating a less than one percent chance of the two rainfall categories being from the same distribution. Also, only another four parameters illustrated a less than five percent chance that the two rainfall categories are related. It becomes evident that a forecaster will have a more difficult time discerning whether a frontal-type heavy rainfall event will produce rainfall accumulations of two inches or greater than four inches just by utilizing proximity soundings.

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6.   ILLUSTRATIONS
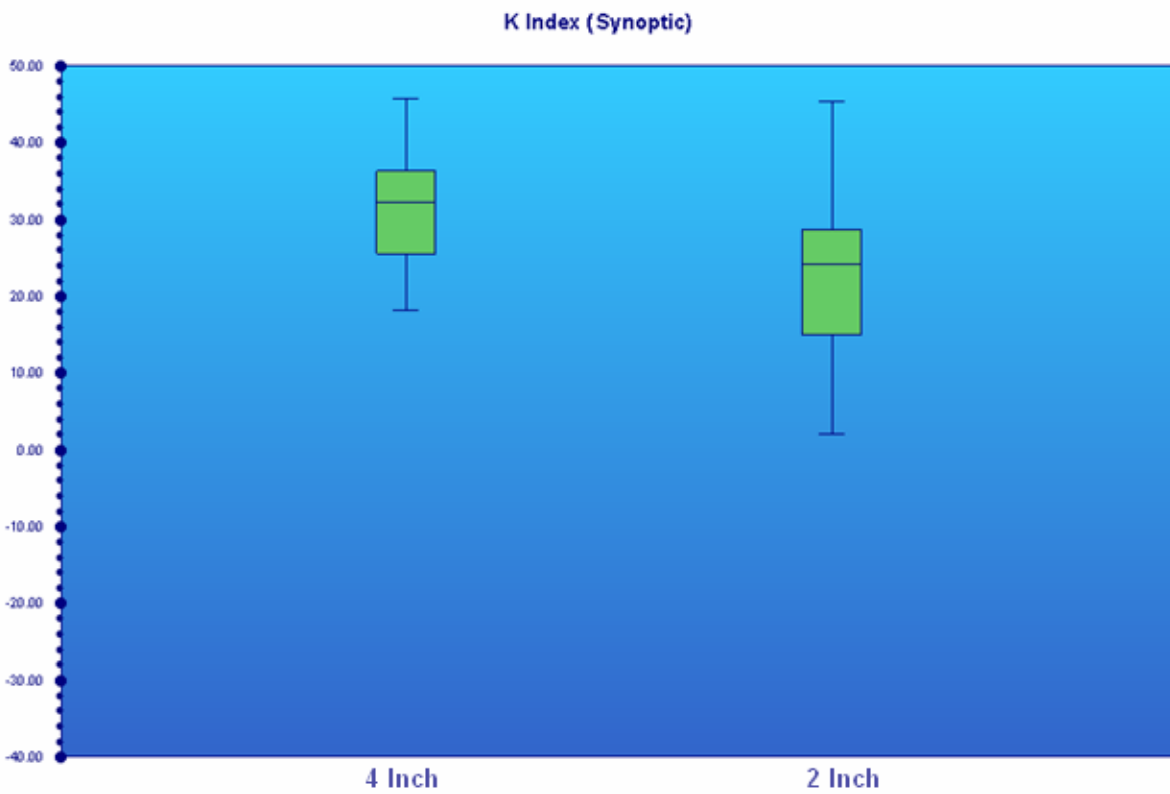
Figure 1.   Boxplots of K index for 4-inch (left) and 2-inch (right) rainfall days associated with a synoptic-type heavy rainfall setting. There is a noticeable difference in K index values from the 2-inch to 4-inch categories.
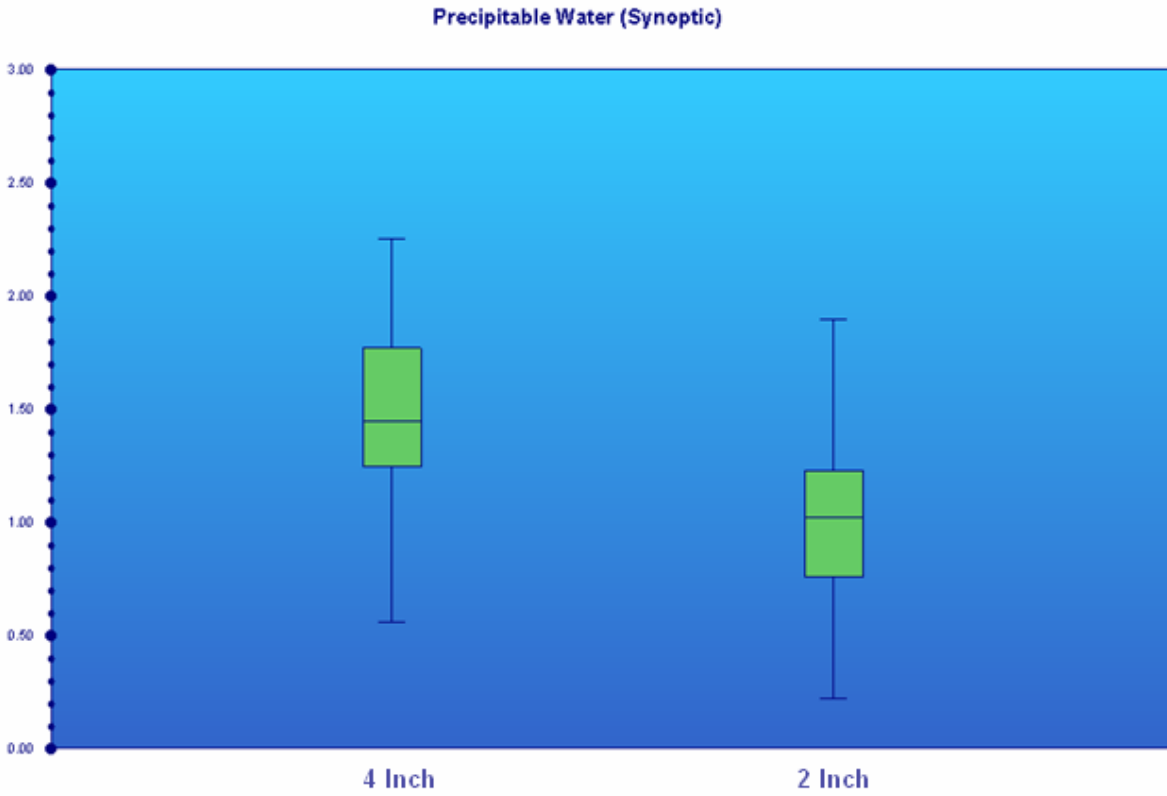
Figure 2. Same as Figure 1, except for PW (values in inches).
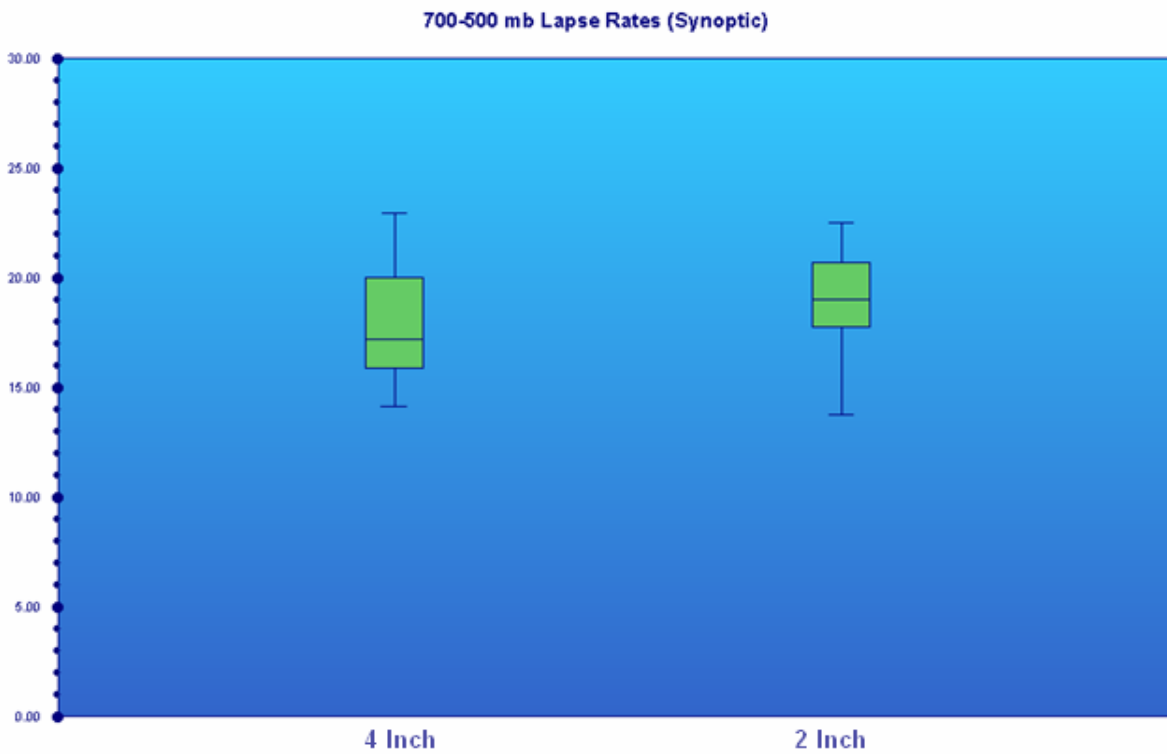
Figure 3. Same as Figure 1, except for 700-500 hPa Lapse Rates (values in °C).
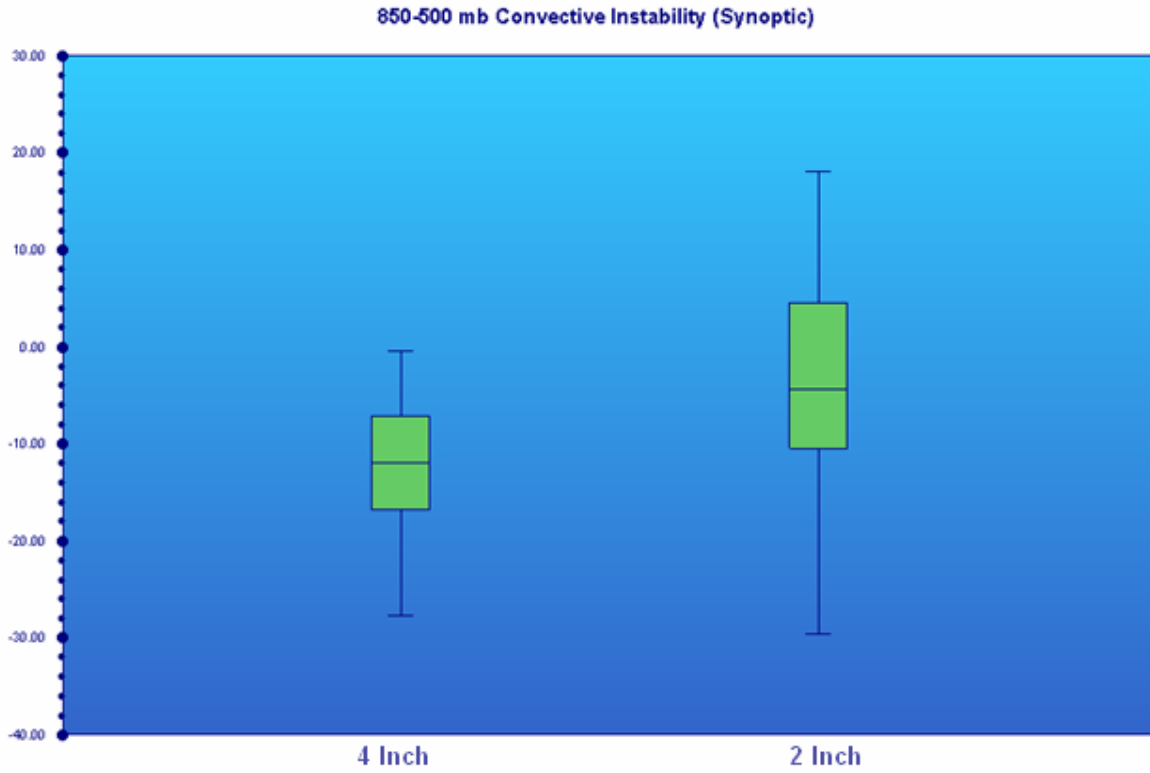
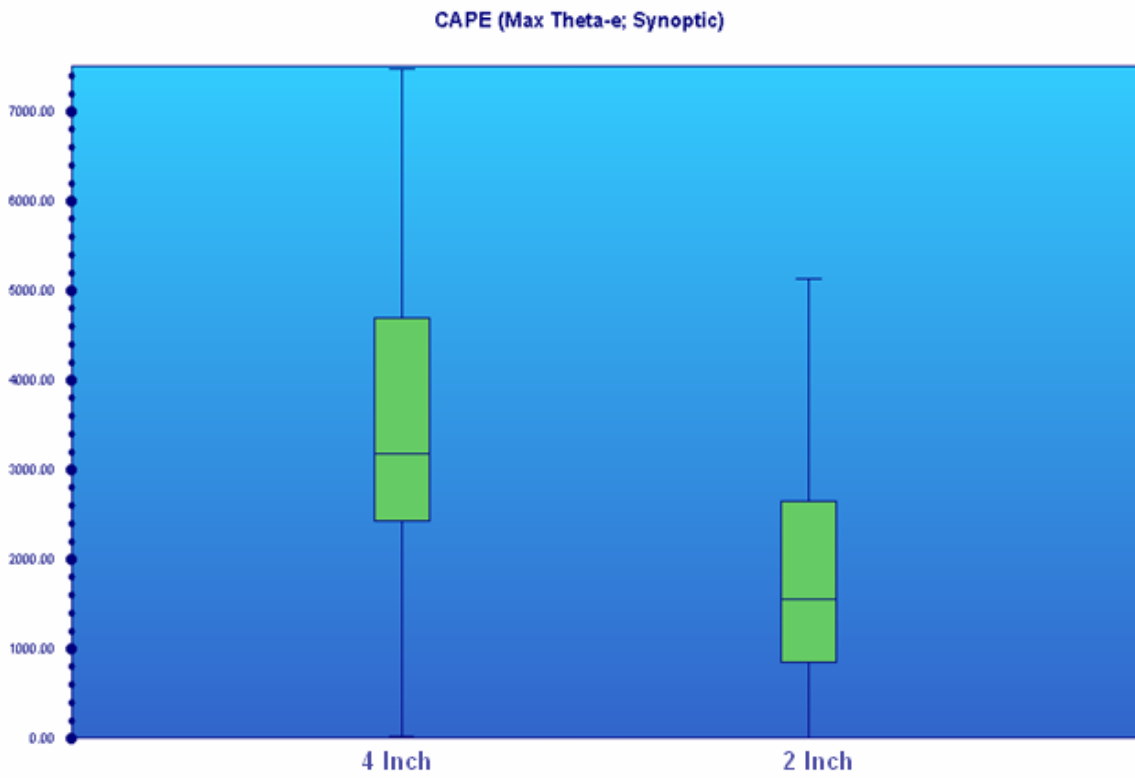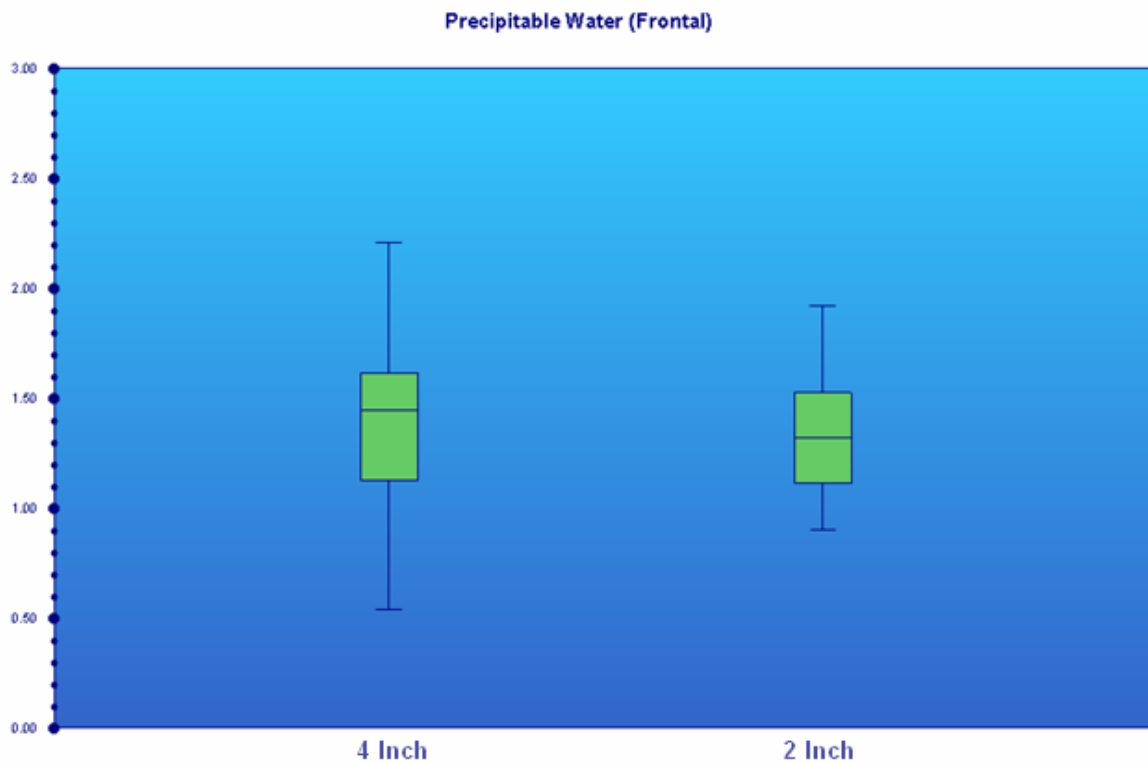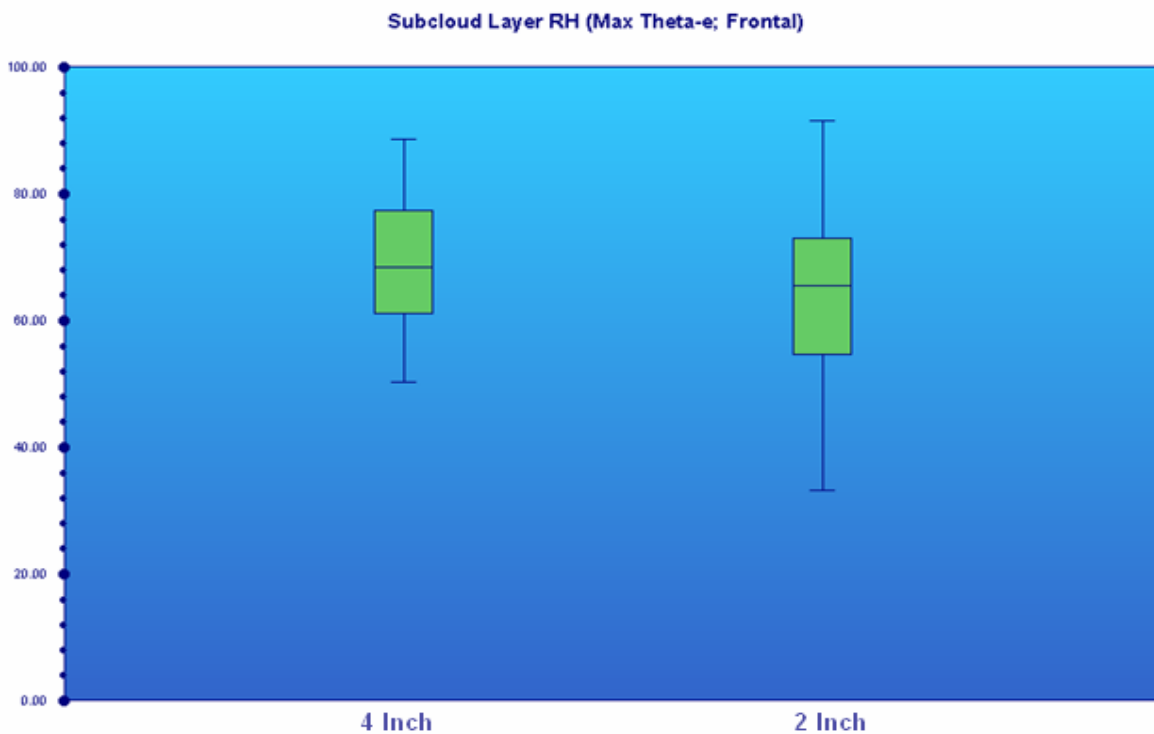**Figure 4.** Same as Figure 1, except for 850-500 hPa Convective Instability (values in Kelvin).

Figure 5. Same as Figure 1, except for the most unstable parcel CAPE (values in Jkg^{-1}).
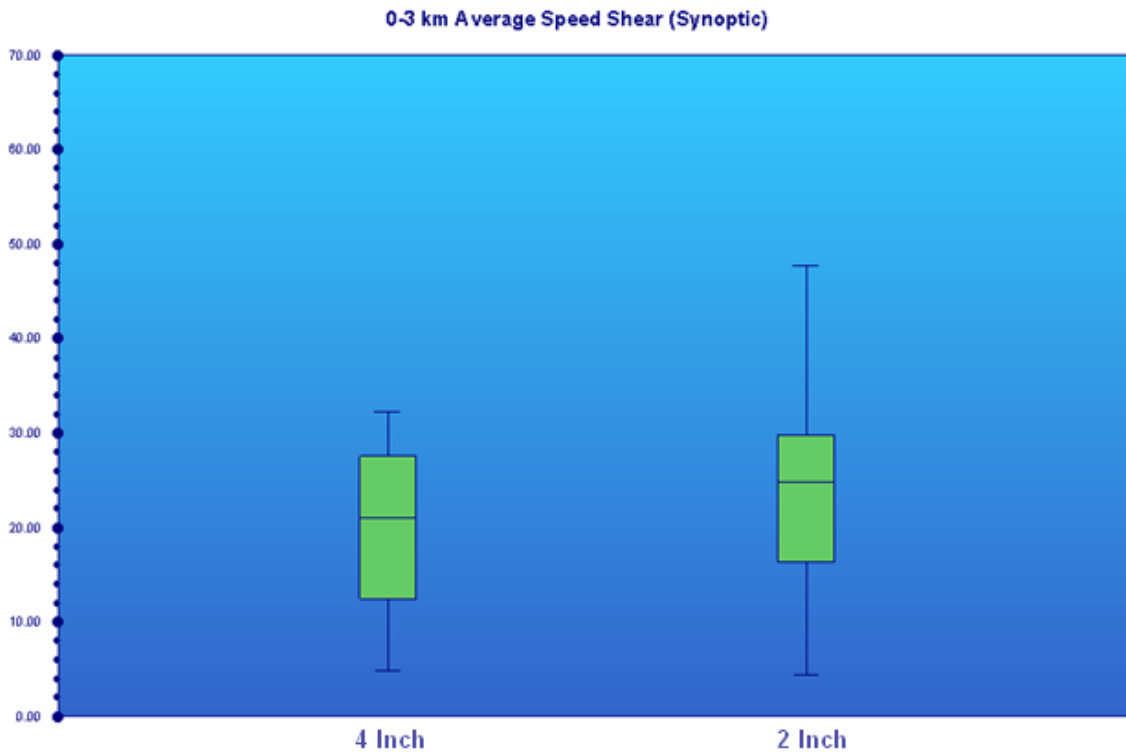
Figure 6. Same as Figure 1, except for 0-3 km Speed Shear (values in ms^{-1}).
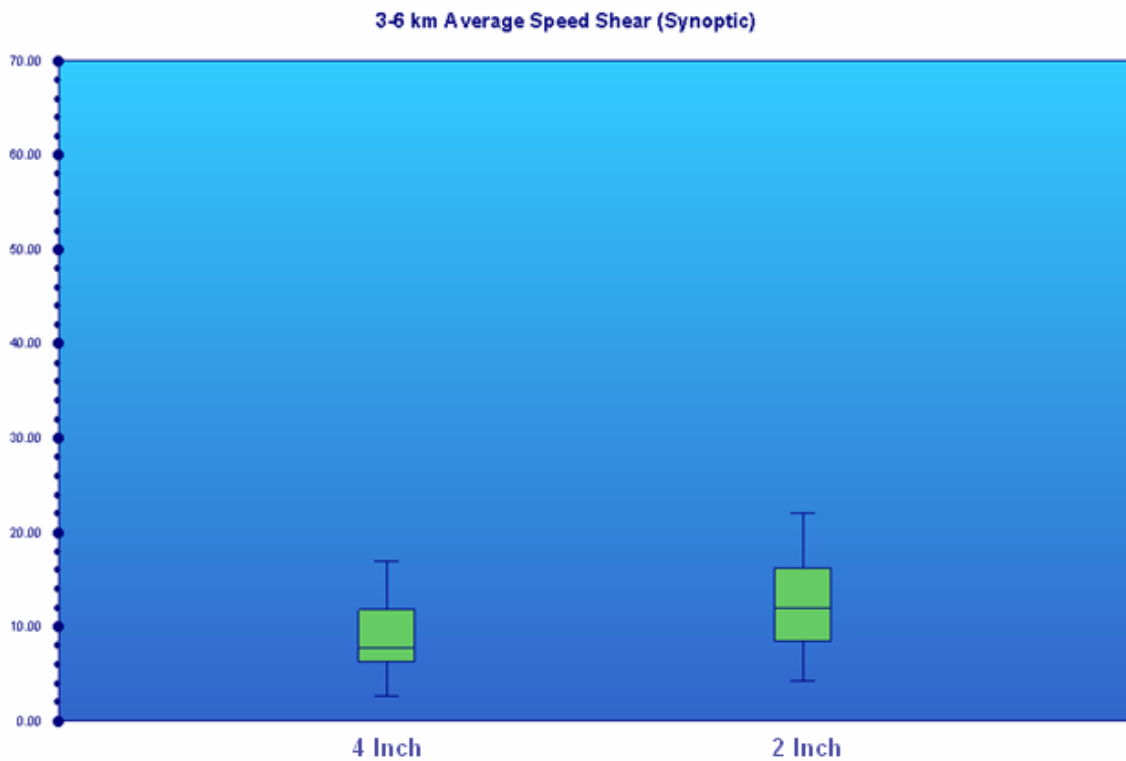
Figure 7. Same as Figure 1, except for 3-6 km Speed Shear (values in ms^{-1}).
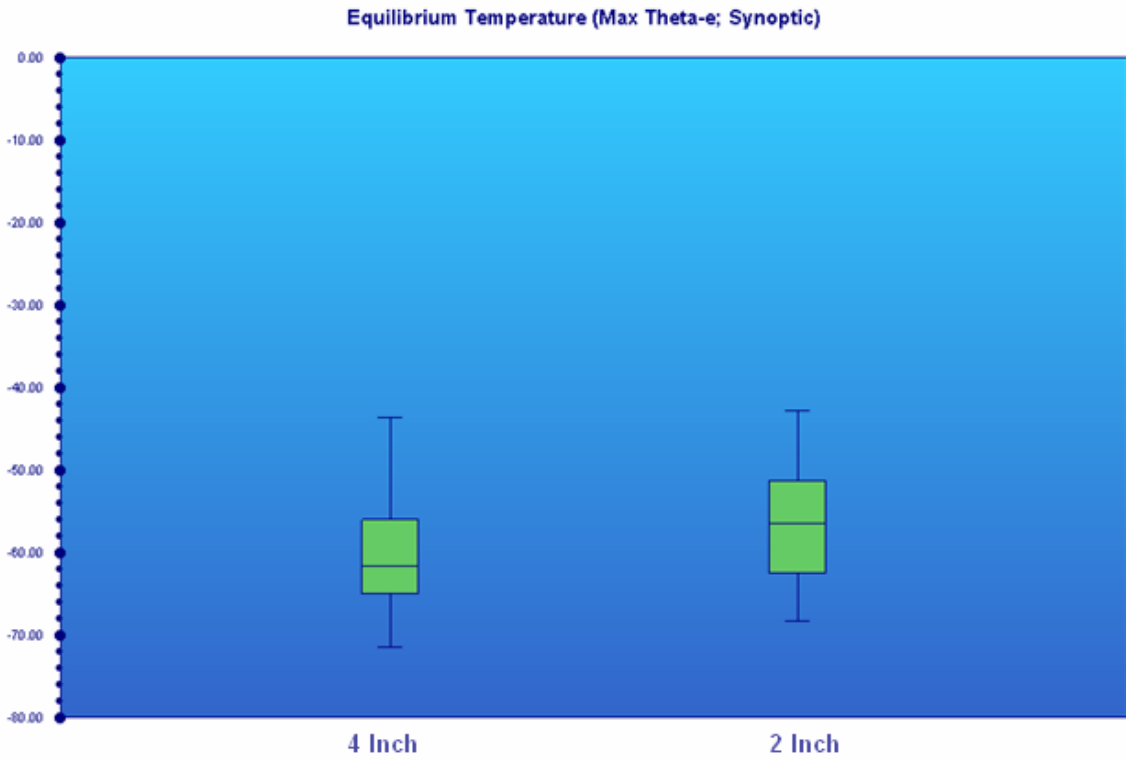
Figure 8. Same as Figure 1, except for Equilibrium Temperature using the most unstable parcel (values in °C).
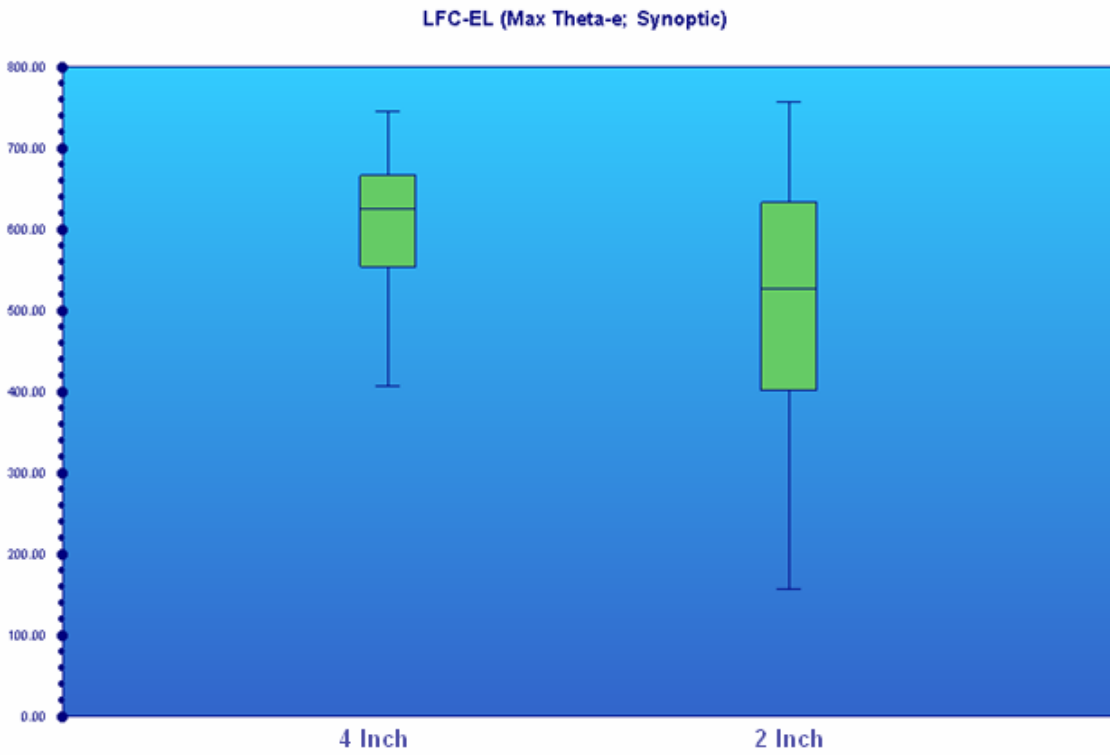
Figure 9. Same as Figure 1, except for the distance between the LFC to the EL using the most unstable parcel (values in hPa).
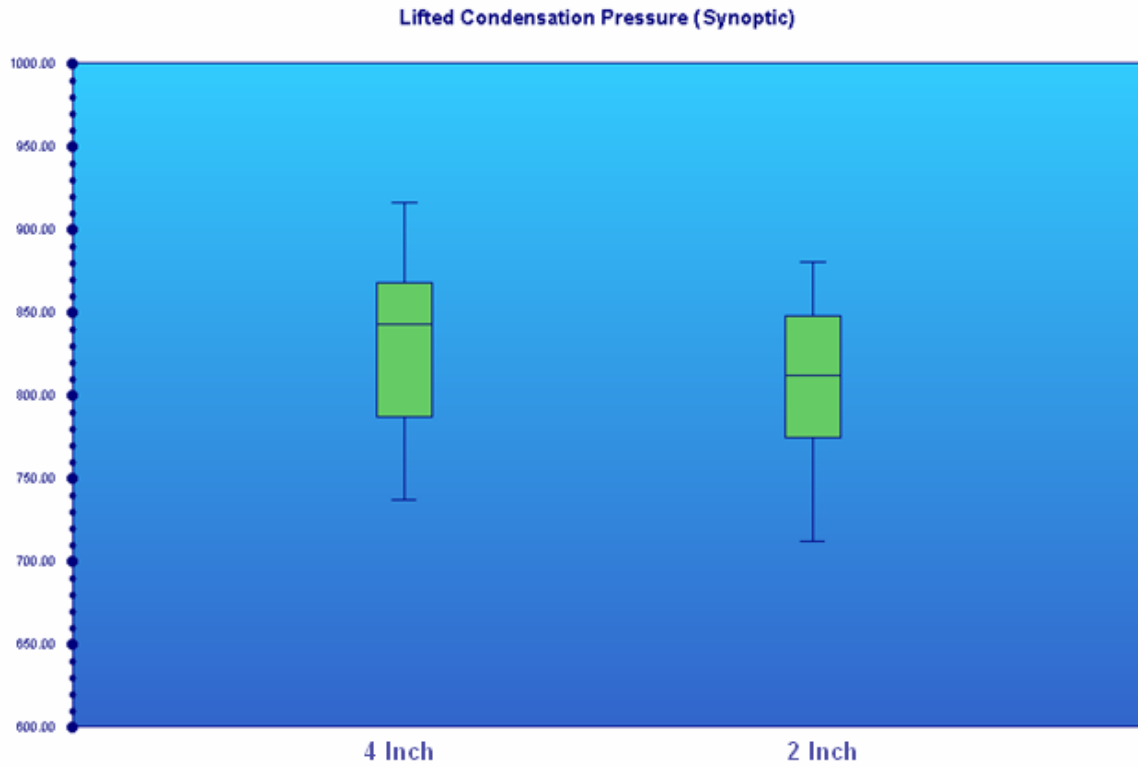
Figure 10. Same as Figure 1, except for LCP (values in hPa).
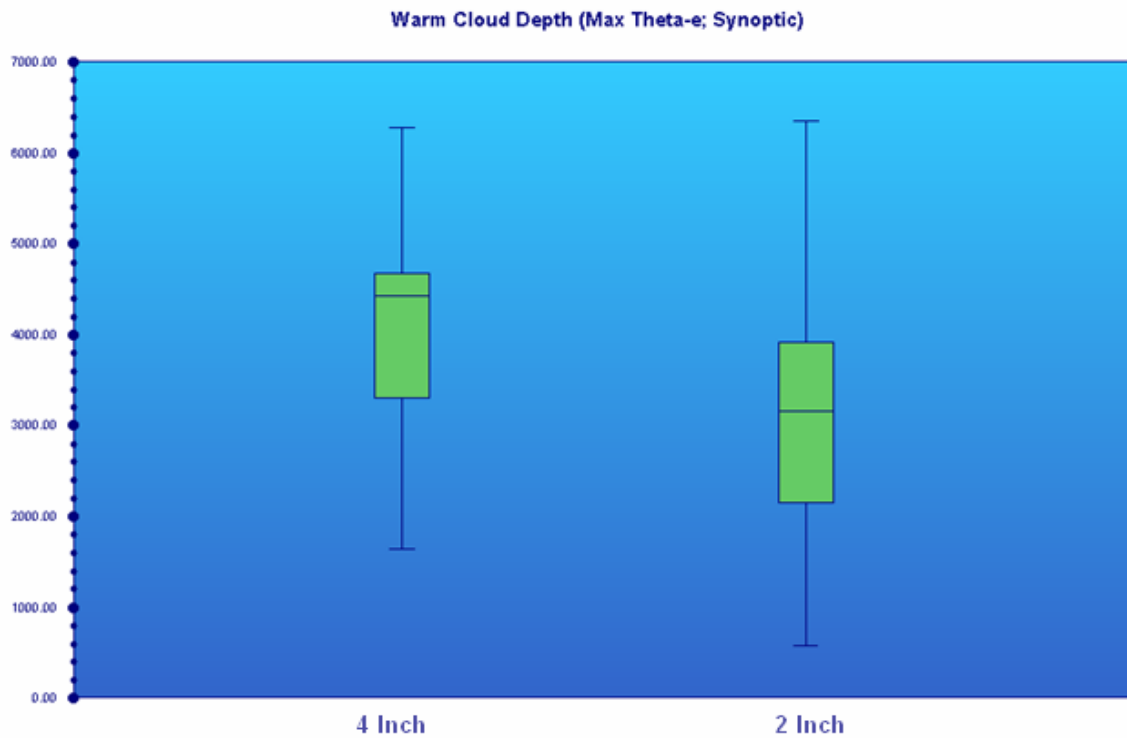
Figure 11. Same as Figure 1, except for Warm Cloud Depth using the most unstable parcel (values in meters).

Figure 12. Boxplots of PW for 4-inch (left) and 2-inch (right) rainfall days associated with a frontal-type heavy rainfall setting (values in inches).

Figure 13. Same as Figure 12, except for Subcloud Layer Relative Humidity using the most unstable parcel (values in %).
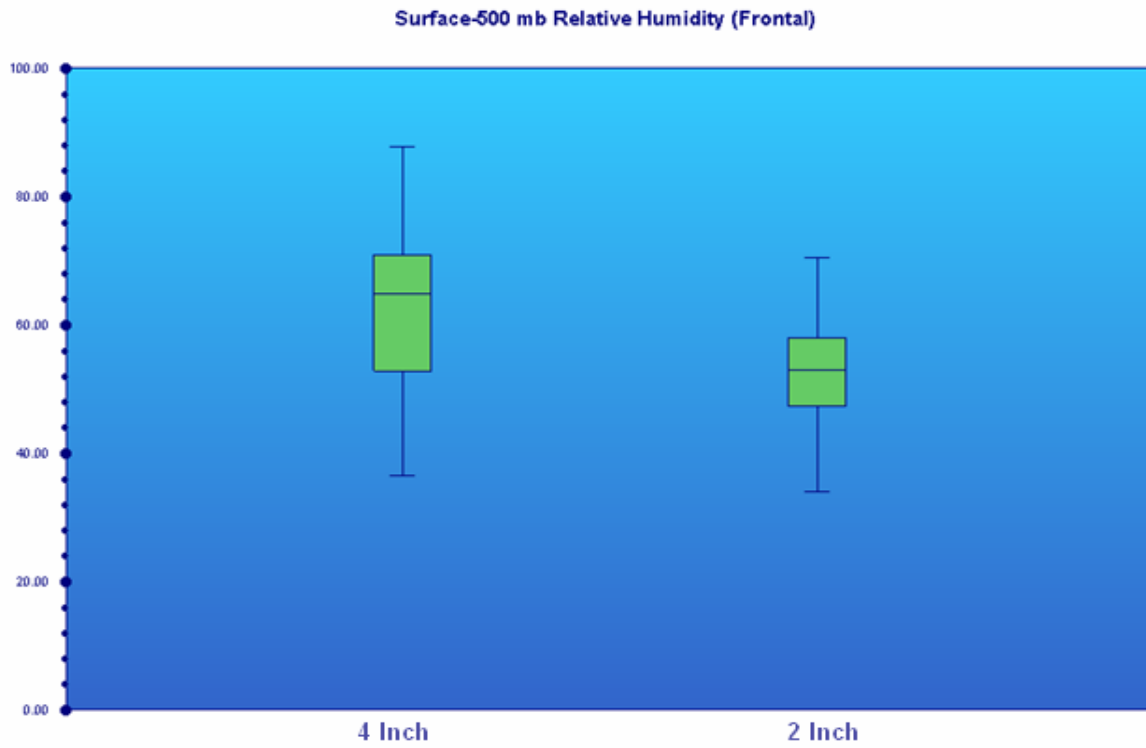
Figure 14. Same as Figure 12, except for Surface to 500 hPa Relative Humidity (values in %).
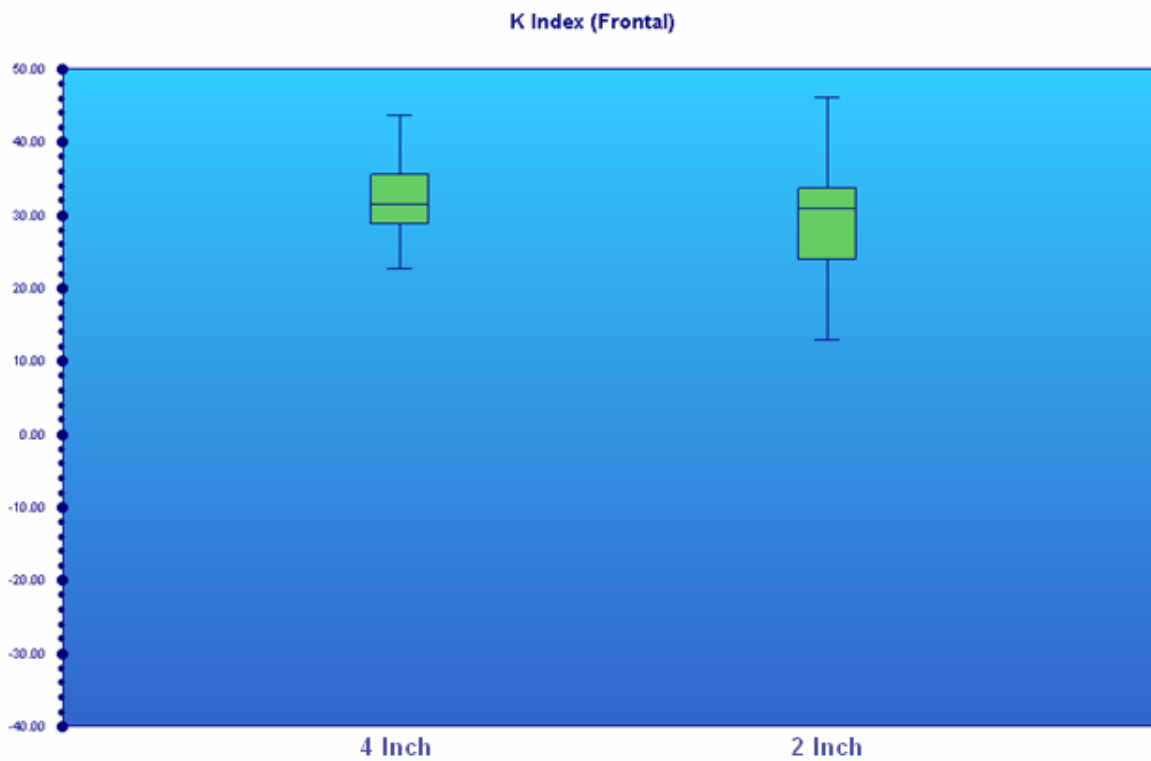
Figure 15. Same as Figure 12, except for K Index.
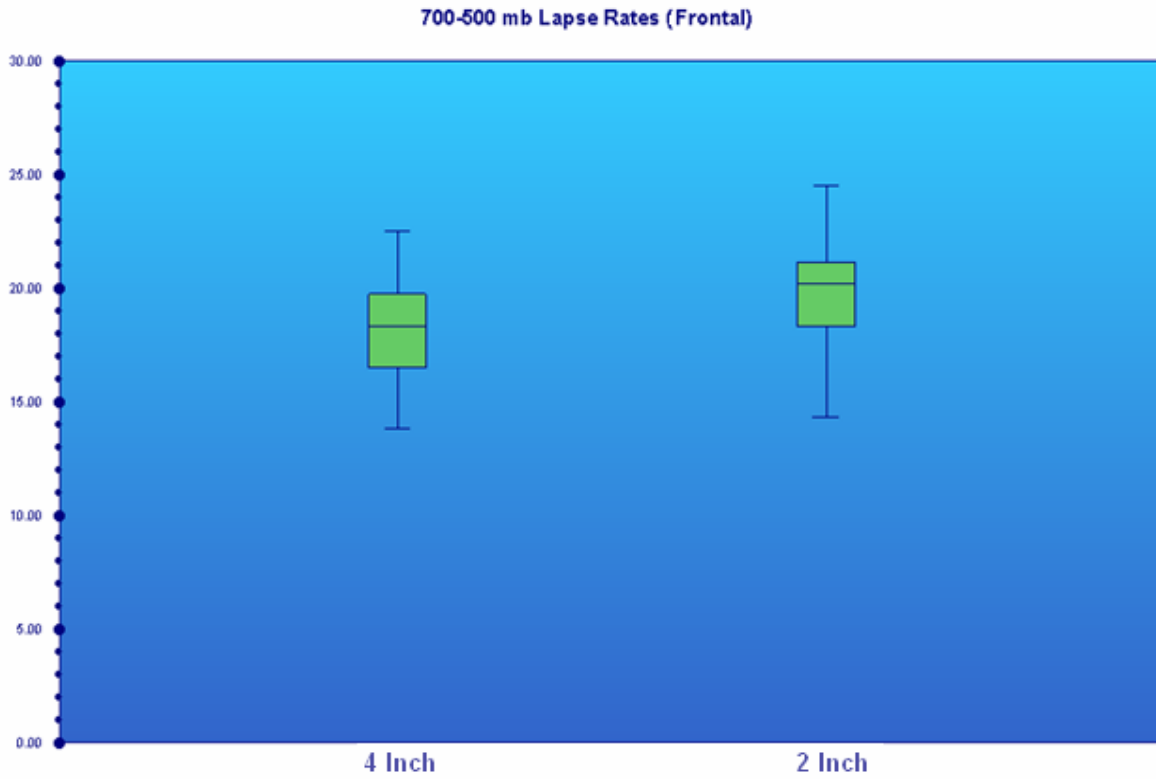
Figure 16. Same as Figure 12, except for 700 to 500 hPa Lapse Rates (vales in °C).

Figure 17. Same as Figure 12, except for 850 to 500 hPa Convective Instability (values in Kelvin).
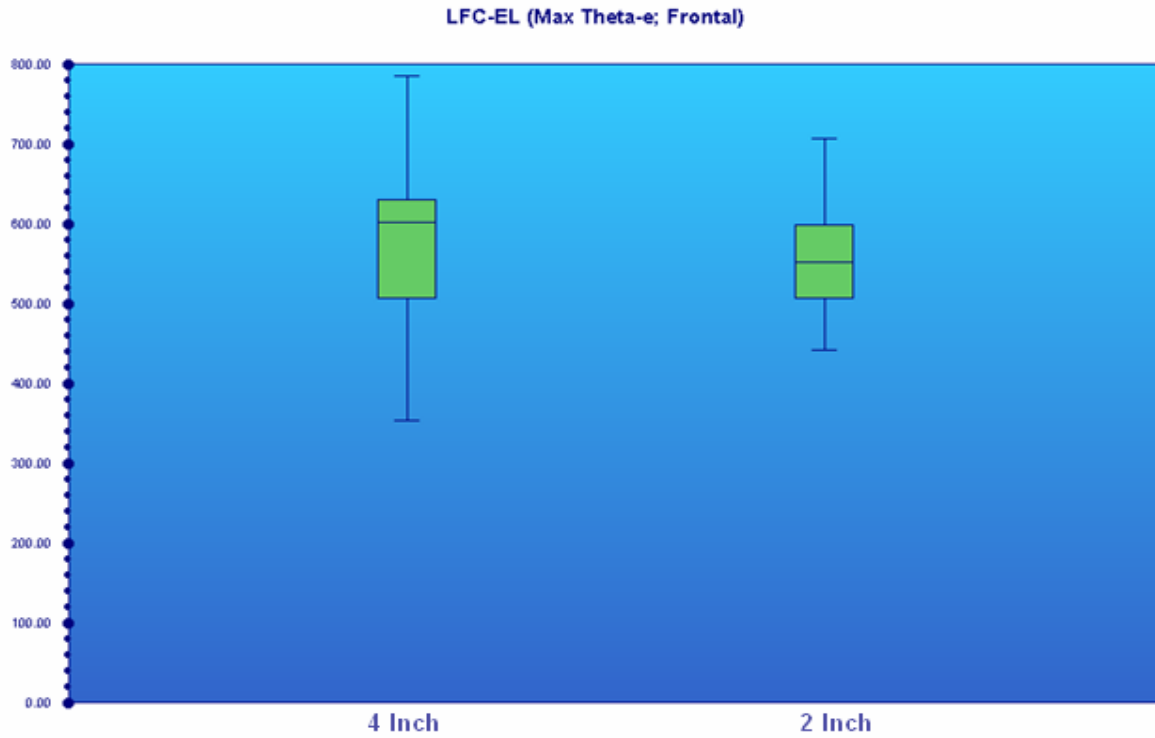
Figure 18.   Same as Figure 12, except for the distance between the LFC to the EL using the most unstable parcel (values in hPa).
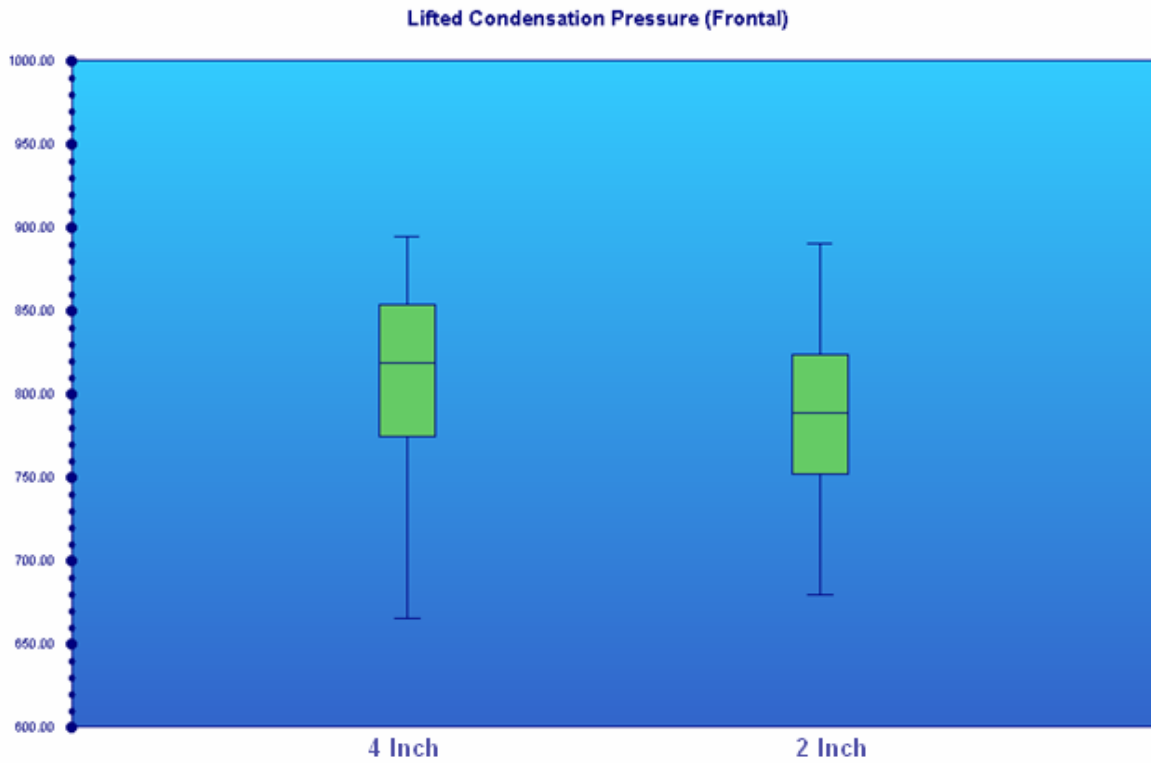

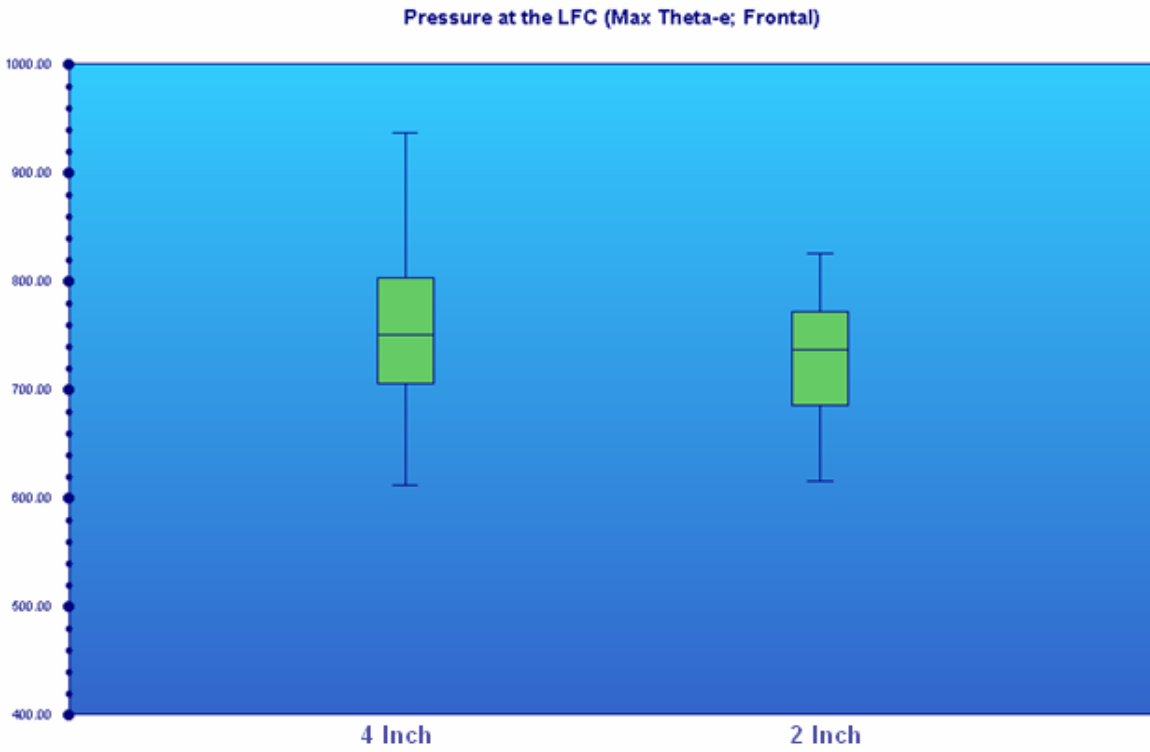**Figure 19.**   Same as Figure 12, except for the LCP (values in hPa).

Figure 20. Same as Figure 12, except for the pressure at the LFC using the most unstable parcel (values in hPa).