Tornado Probabilities Derived from Rapid Update Cycle Forecast Soundings

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ABSTRACT

Tornado forecasting can be improved if forecasters incorporate data of the near-storm environment with radar data when considering tornado watches and warnings. To gain a better understanding of how tornado threat changes with changing environmental conditions, proximity soundings in the vicinity of supercells, derived from the Rapid Update Cycle model, were examined. These soundings were taken from the years 1999-2001 and 2003. A total of 644 supercell soundings were examined and split into three categories: nontornadic soundings (336), weakly tornadic soundings (217) and significantly tornadic soundings (91). Thermodynamic, moisture and wind shear parameters were compared against each other and contingency probability tables were produced for probabilities of any tornado and of a significant tornado.

The results of this investigation reinforce the findings of several previous proximity sounding studies. Notably, the parameter space of 0–1-km Bulk Shear versus MLLCL height was found very valuable in assessing the favorability of a supercell to produce a tornado. Also, in situations where values of MLLCL and 0–1-km Bulk Shear are favorable for tornado formation, large values of instability appear to increase the threat of significant tornado occurrence. As found in other studies, deep-layer shear does not appear to be a good indicator as to whether the environment is conducive to forming tornadic supercells.

1. Introduction

National Weather Service forecasters frequently issue tornado warnings for radar indicated supercell thunderstorms. Research by Burgess and Lemon (1990) suggests only about half of all supercells produce a tornado. This has resulted in the issuance of numerous tornado warnings by the National Weather Service that are not verified with tornado reports.

Incorporating environmental parameters can aid in severe thunderstorm forecasting (Rasmussen and Blanchard 1998). Brooks (1994) has said that a tornado warning strategy based on radar data alone is much less powerful than one combining radar data with information on a thunderstorm's environment. Brooks (1994) has also put forth the idea that a goal of severe weather researchers should be to see if environmental parameters can distinguish between environments conducive to tornadoes. The present study focuses on the probability a tornado will form given a supercell has developed. Tornado contingency probability plots were produced to examine severe weather parameters dealing with the thermodynamic, moisture, and wind profiles of the near-supercell environment. Proximity soundings derived from the Rapid Update Cycle (RUC) model will serve as the sources for environmental data. These tornado contingency probabilities may be used in local National Weather Service forecast offices to improve severe weather and tornado warnings. For instance, if a supercell forms and environmental factors suggest a high probability of tornado occurrence, forecasters will have higher confidence in issuing warnings. Conversely, if the severe weather parameters strongly suggest the environment is not favorable for tornadoes, forecasters will be more reluctant to issue tornado warnings for supercells with weak rotation. It is also possible that forecasters at the Storm Prediction Center utilize these plots as part of the watch and convective outlook decision making process (Brooks and Craven 2002). There are many benefits to reducing false alarms, including an increased trust in warnings by the public.

In this paper, the RUC model dataset, the calculation of tornado contingency probabilities, and the impacts of using tornado contingency probability plots in tornado forecasting will be discussed. Section 2 provides a general overview of past research done on proximity soundings applied to severe weather. Section 3 explains the data set used, as well as the methodology used to construct the tornado contingency probability plots. The plots are presented and their implications discussed in Section 4, and Section 5 presents limitations to the current study and suggestions for further research. Results are summarized in Section 6.

2. Background

For over sixty years, the environment near a severe thunderstorm has been thought to influence the occurrence of tornadoes, as the first paper on proximity sounding studies was published by Showalter and Fulks in 1943. A few decades later, Darkow (1968, 1969) looked into using proximity soundings to identify environments favorable to tornadoes. Brooks et al. (1994) has written a thorough review on the applications and limitations of tornado proximity soundings. Rasmussen and Blanchard (1998) looked at several severe weather parameters derived from soundings to formulate a baseline climatology of supercell and tornado parameters. These included measures of convective available potential energy (CAPE), shear, low-level moisture, and composite parameters.

Further studies by Thompson et al. (2003) investigated environmental parameters related to atmospheric thermodynamics, moisture, and wind shear and determined values for these parameters associated with the type of severe weather produced. In this study, soundings collected by Thompson et al. (2003) that represent the near-supercell environment were analyzed. The soundings were obtained from hourly analyses generated by the 40-km RUC analysis and forecast system. The data was collected between April 1999 and June 2001 for locations across the United States. The proximity soundings were categorized into three groups: those supercells that produced no tornado (hereafter "nontor"), those that produced F0 or F1 tornado damage (hereafter weak tornadoes or "weaktor"), and those that spawned F2 or greater tornadoes (hereafter significant tornadoes or "sigtor"). Several marginal and nonsupercell cases were also examined to serve as a basis for comparison. To be classified as a supercell required a rigorous inspection of the thunderstorm, as described by Thompson et al. (2003). These proximity criteria included radar signatures consistent with supercell thunderstorms, like characteristic reflectivity structures and cyclonic shear that persisted for at least 30 minutes. Most soundings in the data set were for a time within 30 minutes and a distance of within 40-km from a supercell (Thompson et al. 2003).

3. Data and Methodology

This study expands upon the work of Thompson et al. (2003). The focus is exclusively on hourly gridpoint soundings derived from the RUC model in the near supercell environment. The data set consists of the supercell soundings used by Thompson et al. (2003). Additional soundings generated by the RUC from 2003 have also been incorporated. The same supercell proximity criteria used in Thompson et al.

(2003) was applied to these and they are included with the set of soundings from 1999 to 2001. In total, 644 near-supercell soundings were analyzed. Of these soundings, 336 failed to produce a tornado, 217 were weaktor, and 91 were sigtor. With these numbers, we can compute a climatological frequency of tornadoes in the data set by dividing the total number of tornadoes by the total number of soundings. The climatological frequency of significant tornadoes in the data set can be found by dividing the total number of significant tornadoes by the total number of soundings. This yields a climatological frequency of tornadoes equal to .48 and the frequency of significant tornadoes equals .14.

RUC-2 soundings have been shown to represent the near-supercell environment reasonably well (Thompson et al. 2003). Other advantages of using RUC-2 proximity soundings include their much better spatial and temporal resolution compared to the sparse upper-air network in place across the United States, as they are produced on an hourly basis, whereas upper air soundings are usually taken only twice per day (Thompson et al. 2003).

Several things should be noted concerning the data collected for this study. First, soundings have not been collected for every supercell that occurred in the United States over the four-year period of interest (Thompson et al. 2003). On days when supercell outbreaks occurred, usually only about two soundings were collected. In some cases, no soundings were collected on a given day. Also, the operational version of the RUC has changed during data collection (Thompson et al. 2003). Soundings from 1999-2001 were produced on the RUC-2 model, a version with 40-km resolution. The 2003 soundings came from the RUC-20, a newer version of the Rapid Update Cycle with better resolution

(20-km). Thompson et al. (2003) have found that Storm Prediction Center forecasters have not seen any undesirable changes in the model since the implementation of the RUC-20. Therefore, we will treat forecasts from both versions of the RUC as being equally valid and draw no further distinction between the two. Hereafter, they will simply be referred to as RUC model soundings with no regard to differences in resolution.

In order to calculate tornado contingency probabilities, first, two parameters were paired against each other in the x-y plane and a grid was created on the plane. As an example, consider 0–1-km Bulk Shear (kts) and Mixed Layer Lifting Condensation Level (MLLCL, in meters above ground level (AGL)). Based on the bounds of the dataset, MLLCL ranged from 0-3500 m AGL and 0–1-km Bulk Shear ranged from 0-50 kts. To create the grid, MLLCL values were divided by 50 (Brooks and Craven 2002), making a grid of values that ranged from 0-70 in the MLLCL-direction and 0-50 in the 0–1-km Bulk Shear direction. This division was done to normalize the data to a scale which allowed later calculations to be simplified.

To compute probabilities at a given grid point, the number of nontor, weaktor, and sigtor soundings located near each grid point was determined. For each of the 644 soundings in the data set, the distance from each point on the grid was found using the formula

$$((x - MLLCL/50)^2 + (y - shear)^2)^{1/2}$$

(Brooks and Craven 2002) where x represents a value of MLLCL on the grid, y a value of shear on the grid, and MLLCL and shear are sounding-derived data points.

In the case of 0–1-km Bulk Shear versus MLLCL, when the distance computed from the formula above was less than 12 length units, a sounding was counted as being near enough to the data point (i.e. Brooks and Craven 2002). The value chosen of 12 in this case is somewhat arbitrary and its main function is to serve as a smoother for the results. Since the data set used in this study is relatively small, the distance was chosen to be large enough so the results obtained are meaningful. A radius of nearness equal to 12 makes an axis in the shear-direction of 12 kts and in the MLLCL-direction of 600 m AGL. These are similar to axes used by Brooks and Craven (2002) of 15 kts in the shear-direction and 375 m AGL in the MLLCL-direction. Radii of nearness greater than 12 and less than 12 were tested in the probability calculations and yielded similar probabilities. Therefore, the radius used to define nearness to gridpoints in the final calculations was the one which gave the probability plots the desired smoothness.

Figure 1a shows a tornado probability plot for 0–1-km Bulk Shear and MLLCL. The probabilities were found at each grid point by dividing the total number of tornadic soundings by the total number of soundings. A similar plot was made for the probability of a significant tornado and the calculations done in an analogous way. In Figure 1a, note there are several areas with probabilities that appear discontinuous compared to surrounding probabilities. This results from a lack of data points at these locations. Where there is little data, there is also little confidence in the ability to make conclusions about the calculated probabilities. As a result, probabilities were not contoured at grid points associated with less than 10 soundings. A revised probability plot that does not show conclusions for points with insufficient data is shown in Figure 1b. Take note that just because a given location does not have a contoured tornado probability, the combination of shear and MLLCL do not necessarily give a zero percent chance a supercell will become tornadic. Instead, uncontoured areas should be seen as locations in the parameter space with either less than a 10 percent chance a supercell will produce a tornado or where there is insufficient data to generate conclusions.

Besides the pairing of parameters discussed above, 0–1-km Bulk Shear versus mixed layer convective available potential energy (MLCAPE), Surface (Sfc) –6-km Bulk Shear versus MLCAPE, Sfc–6-km Bulk Shear versus MLLCL, and MLLCL versus MLCAPE were examined. Tornado contingency probabilities and plots were produced analogously to the example above. The dimensions of the grid spacing used and the threshold of nearness to a grid point varied slightly for each pair of parameters; however, small variations in these quantities have little effect on the results.

4. Results

a. 0–1-km Bulk Shear versus MLLCL

As in previous proximity sounding studies, MLLCL and 0–1-km Bulk Shear continue to show a strong signal as to whether a supercell will become tornadic (Thompson et al. 2003). In Figure 1b, lower MLLCL heights combined with higher low-level shear corresponds to higher probabilities of a supercell producing a tornado. This concurs with work done by Brooks and Craven (2002). Examining the contingency probabilities for occurrence of significant tornadoes (Figure 2a), we notice the same trend. Of special interest, however, concerns the distribution of the probability contours. In low shear environments, sigtor probabilities depend on both MLLCL and shear. However, once 0–1-km Bulk Shear climbs above 30 kts and as long as MLLCL height is sufficiently low (less than 1500 m AGL), probabilities depend almost exclusively upon shear, increasing with increasing values of shear. These results have also been seen recently by other researchers (Brooks, personal correspondence).

To investigate this result further, a plot of weaktor contingency probabilities was produced (Figure 2b). While it too shows that probabilities increase as MLLCL height decreases, the highest probabilities of a weak tornado occur in a low MLLCL - weak low-level shear environment (shear less than 30 kts). These results suggest MLLCL height is a very strong distinguisher for determining if a supercell will or will not become tornadic, consistent with findings of Rasmussen and Blanchard (1998). However, the strong dependence significant tornado occurrence has on low-level shear suggests the amount of low-level shear present may be important in assessing the potential for a supercell to produce a significant tornado (Craven et al. 2002).

b. 0–1-km Bulk Shear versus MLCAPE

Previous studies have suggested (Rasmussen and Blanchard 1998) that higher values of 0–1-km Shear and CAPE increase the threat of tornado occurrence. This is also seen in Figure 3a. Figure 3b shows sigtor contingency probabilities for this set of parameters. Notice how sigtor probabilities depend strongly on both MLCAPE and 0–1-km Bulk Shear, most probable in environments with both high values of shear and MLCAPE. This is in contrast to the threat of any tornado, it being more dependent on the value of 0–1-km Bulk Shear. This suggests that, while tornadoes can form with any value of MLCAPE, the likelihood of a tornado being significant increases with higher values of MLCAPE in proximity to a supercell.

Similar plots were also generated with surface-based CAPE (SBCAPE) replacing MLCAPE. No significant changes in probabilities were noted.

c. Surface–6-km Bulk Shear versus MLCAPE

As when comparing low-level shear to MLCAPE in regards to the probability of a supercell producing a tornado, higher values of deep-layer shear and MLCAPE yield higher tornado probabilities (Figure 4a). However, the pair of Sfc–6-km Bulk Shear and MLCAPE does not distinguish between tornado probabilities quite as well as does the pair of 0–1-km Bulk Shear and MLCAPE. This is manifested in a larger portion of the MLCAPE - Sfc–6-km parameter space falling nearer to the climatological probability of a tornado in the data set of .48. Also, the gradient of probabilities is stronger in the plot of 0–1-km Bulk Shear versus MLCAPE than in Sfc–6-km Bulk Shear versus MLCAPE.

Figure 4b displays sigtor probabilities for this parameter space. Higher values of deep-layer shear and MLCAPE correspond to higher probabilities of significant tornado formation. One feature of interest on this plot is the bullseye of high probabilities around 4500 J/kg CAPE and 80 kts shear. This is likely an erroneously high probability resulting from a small data set and very few soundings falling near that part of the parameter space. Indeed, many grid points in that region have barely above the required 10 data points for contouring. Also, when substituting SBCAPE for MLCAPE, such a bullseye no longer appears.

d. Surface–6-km Bulk Shear versus MLLCL

When comparing the tornado contingency probabilities for the Sfc–6-km Bulk Shear versus MLLCL parameter space (Figure 5a), the probabilities depend more on MLLCL height than deep-layer shear, evidenced by the nearly vertical nature of the probability contours. This agrees with Brooks and Craven's (2002) finding that deep-layer shear provides a poor discriminator between tornadic and non-tornadic thunderstorms. It is also consistent with Rasmussen and Blanchard's (1998) suggestion that the LCL height may be used to distinguish tornadic from non-tornadic supercells. However, when generating plots for sigtor (Figure 5b), the probabilities are somewhat more dependent on shear, as probabilities increase with lower values of MLLCL and higher values of Sfc–6-km Bulk Shear when MLLCL height is lower than 1500 m AGL. These results imply that, while deep-layer shear is not a good discriminator when it comes to the formation of any tornado, environments with stronger deep-layer shear may favor tornado formation more than environments with weaker deep-layer shear. Even so, the MLLCL - Sfc–6-km Bulk Shear parameter space does not give nearly as strong a positive signal to the potential of significant tornado formation as do any of the other parameter spaces tested. This further casts doubt on the ability of deep-layer shear to distinguish an environment favorable to tornadic supercell formation.

e. MLLCL versus MLCAPE

Figure 6a depicts the probability of a supercell producing any tornado for values of MLLCL versus MLCAPE. As would be expected, higher values of MLCAPE and lower values of MLLCL increase the probability of a tornado. Since the probability contours only slope gently upwards to the right, the probability of any tornado is likely more dependent on MLLCL height than MLCAPE. This agrees with Rasmussen and Blanchard's (1998) assertion that the parameter with the most utility for distinguishing supercells from tornadic supercells is LCL height.

A sigtor plot of MLLCL and MLCAPE also shows the highest probabilities fall where MLCAPE is high and MLLCL is low (Figure 6b). An interesting result is that when MLLCL height is less than 1000 m AGL, the probability of a significant tornado has a strong dependence on the value of MLCAPE, with higher values of MLCAPE yielding higher probabilities of significant tornado formation. When MLLCL is above 1000 m AGL, the probability is more dependent on MLLCL than MLCAPE. What is significant from this chart is that large instability (i.e. MLCAPE) when MLLCL heights are low seems to be important when assessing the risk for a supercell producing a significant tornado. This result is also apparent in a weaktor probability chart. Notice how lower values of MLCAPE are associated with weak tornadoes given a low MLLCL (Figure 7).

Once again, the results put forth above for the MLLCL-MLCAPE parameter space are essentially unchanged if SBCAPE is replaced by MLCAPE.

5. Discussion

There are some areas in the parameter spaces examined above where probabilities are contoured, yet experienced forecasters would not expect tornado-producing supercells. Some of these can be attributed to the smoothing mechanism used in the probability calculations. However, much of this can be avoided when considering the climatology of the data set. When interpreting the tornado probability plots presented above, locations in the parameter spaces with a heightened risk of supercells becoming tornadic or significantly tornadic are those with probabilities greater than what climatology suggests. Therefore, regions with an enhanced threat for a supercell producing a tornado are those with probabilities greater than .48 and regions with probabilities greater than .14 have an enhanced threat for significantly tornadic supercells. Areas with probabilities lower than these have less of a chance to bear tornadic supercells than climatology would suggest.

While the data set of RUC soundings used in this study is adequate to make conclusions, it does have several limitations. First, it would be nice to have a larger data set taken from more than just four years. If more soundings were available, less smoothing of the data would be needed to obtain useful results, as a very large number of data points lends itself to natural smoothing. It is also likely that more data points would increase gradients and enhance regions of maximum and minimum probabilities, even if less of a smoothing mechanism is incorporated into the methodology.

A more significant problem than relatively small sample size could result from failing to obtain RUC proximity sounding data from every supercell that formed within the domain of the RUC model. The only way to compute a true tornado probability for supercells is to sample each supercell that formed during the period of study. In this way, it would be assured that there is no bias in selecting the cases to be studied, as they all would be studied. In this project, the soundings were chosen by humans. Hence, it is possible that the relative frequency of tornadoes and significant tornadoes in this study is different than what is actually observed in the atmosphere.

To combat these shortcomings, future studies utilizing proximity sounding data to create tornado contingency probabilities should try to include one sounding associated with each supercell thunderstorm that forms over the time period of interest. This requirement, while stringent, will not only lead us closer to calculating a true tornado probability, but will help to ensure the formation of a large data set over a relatively short time period. Use of a large dataset is also desirable, as it will allow for conclusions to be made over a larger parameter space than in this study.

Of the tornado, weaktor, and sigtor plots produced, current forecasting goals dictate the tornado contingency probability plot is the most useful of the three to operational weather forecasting. When the National Weather Service issues tornado warnings, they are forecasting an imminent tornado threat. If there are indications that a tornado will form, regardless of its strength, a tornado warning should be issued. However, in situations where environmental conditions suggest an increased threat for significant tornadoes, the wording in the text of a warning could then be enhanced to communicate the urgency of the situation. Since warnings are issued for any strength tornado, the chart with probabilities for any tornado is most important.

The next step is to create tornado contingency probability tables pitting three variables against each other instead of two. Future research should aim for this goal, as it would take into account more factors that influence a supercell's potential to produce tornadoes.

6. Conclusions

In this study, Rapid Update Cycle-produced soundings in close proximity to supercell thunderstorms were examined. Charts were created indicating the probability a supercell will produce a tornado or a significant tornado given two severe weather parameters. These charts lead to the following conclusions:

1) The plot of 0–1-km Bulk Shear versus MLLCL discriminates very well as to the probability a supercell will produce a tornado. When examining the sigtor plot from this parameter space, when MLLCL height is low and 0–1-km Bulk Shear exceeds 30 kts, the probabilities depend highly on shear.
2) When comparing 0–1-km Bulk Shear and MLCAPE, sigtor probabilities are more dependent on the value of MLCAPE than is the probability of any tornado. These probabilities increase with increasing values of MLCAPE.
3) The parameter space of Sfc–6-km Bulk Shear and MLCAPE does not distinguish as well as the parameter space of 0–1-km Bulk Shear and MLCAPE when it comes to supercells producing tornadoes and significant tornadoes.
4) When graphing Sfc–6-km Bulk Shear versus MLLCL height, the likelihood of a supercell producing a tornado is dependent mainly on the value of MLLCL. Environments with strong deep-layer shear may be slightly more favorable to a supercell producing a significant tornado than environments with weak deep-layer shear.
5) When MLLCL height is less than 1000 m AGL, the probability of a significant tornado in the MLLCL-MLCAPE parameter space depends heavily on the value of MLCAPE, increasing with increasing instability.

7. Acknowledgments

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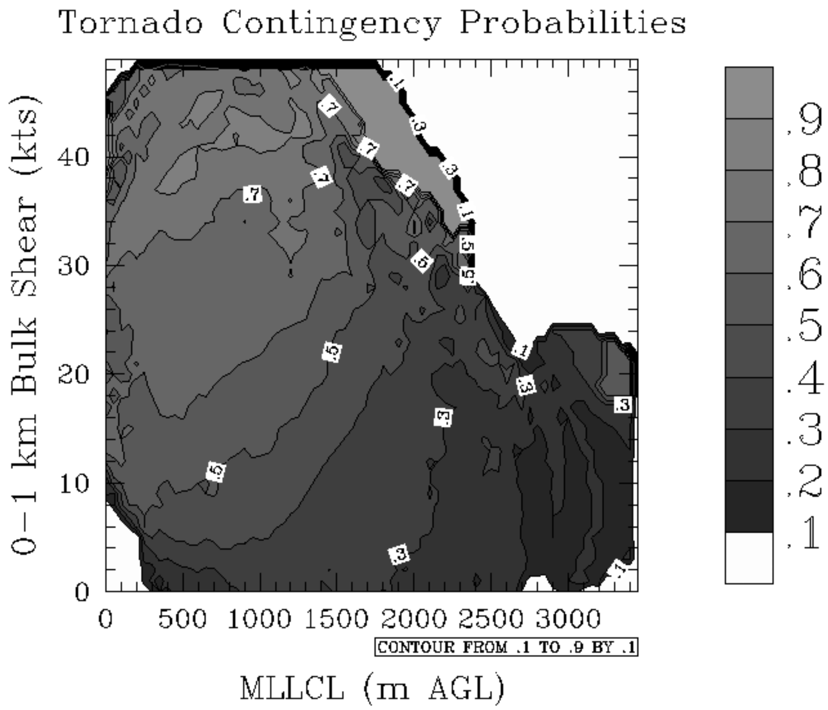

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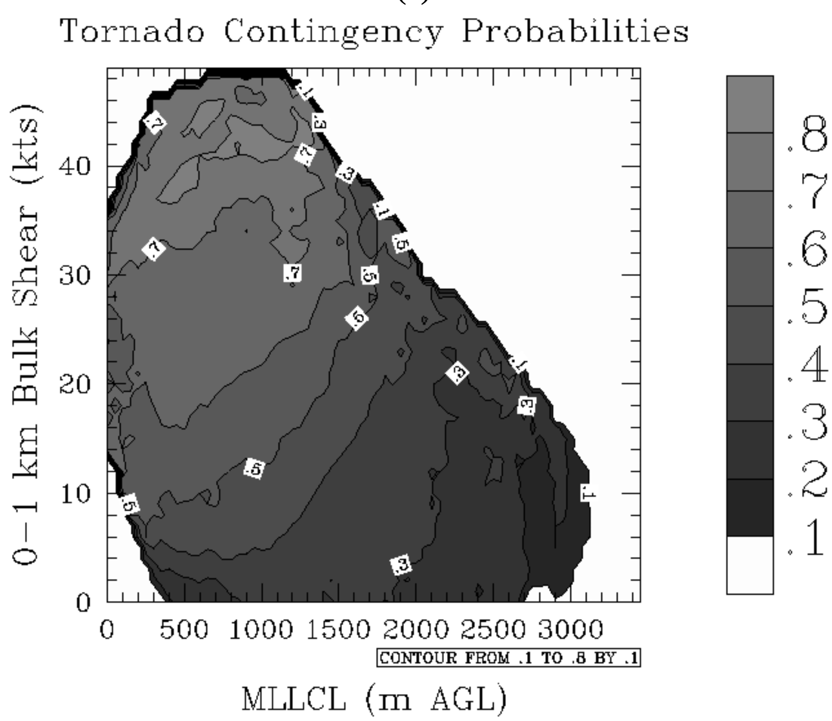
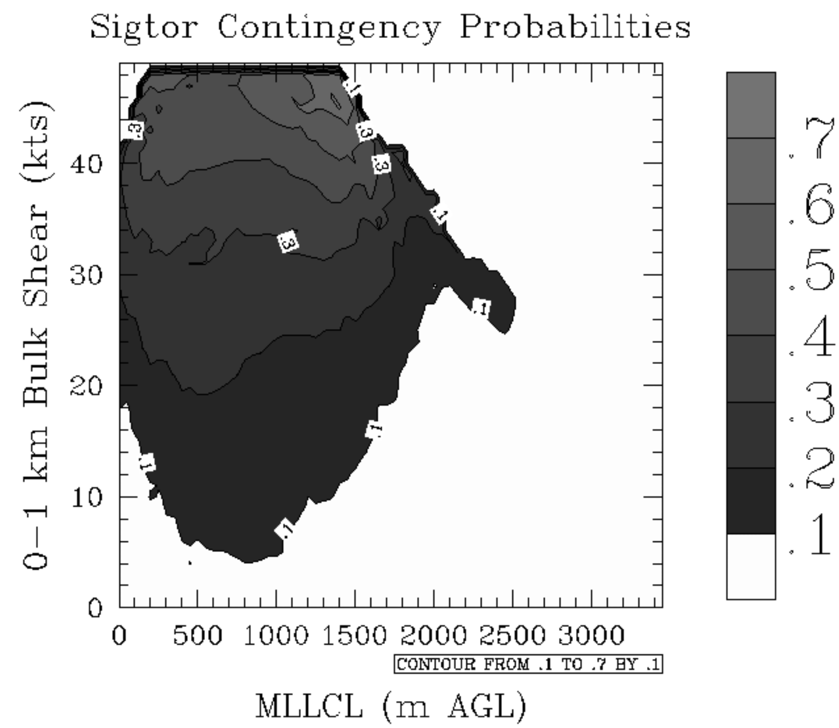


(b)

Figure 1. Given a supercell has formed, these plots give the probability a tornado will form. In (a), each region of the plot with at least one data point is shaded, while in (b) only those regions with at least 10 data points are shaded. MLLCL (m AGL) is plotted on the x-axis and 0–1-km Bulk Shear, in kts, is plotted on the y-axis. The radius used to define nearness is 12.



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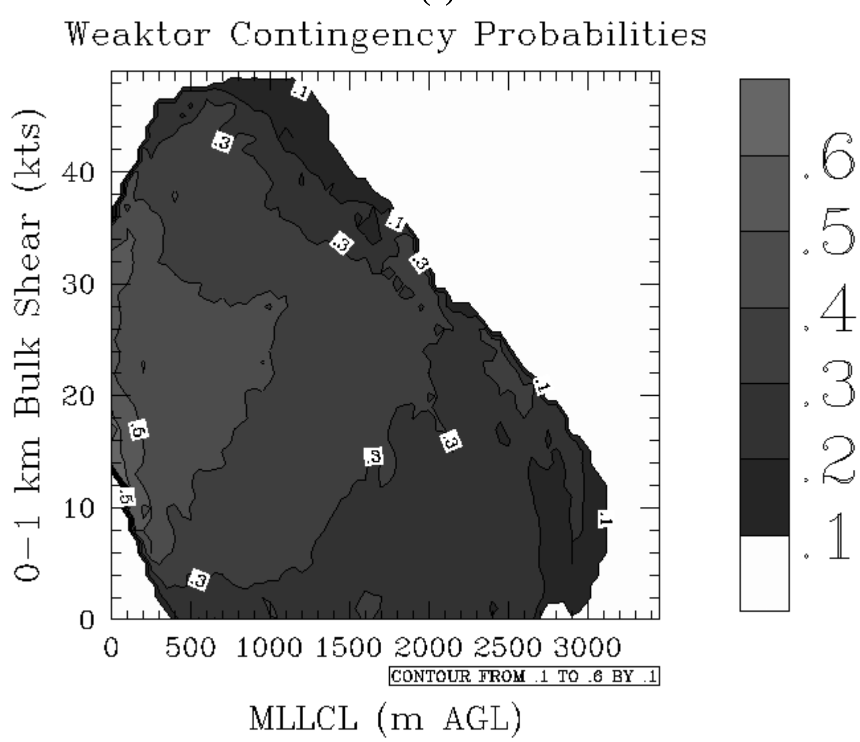
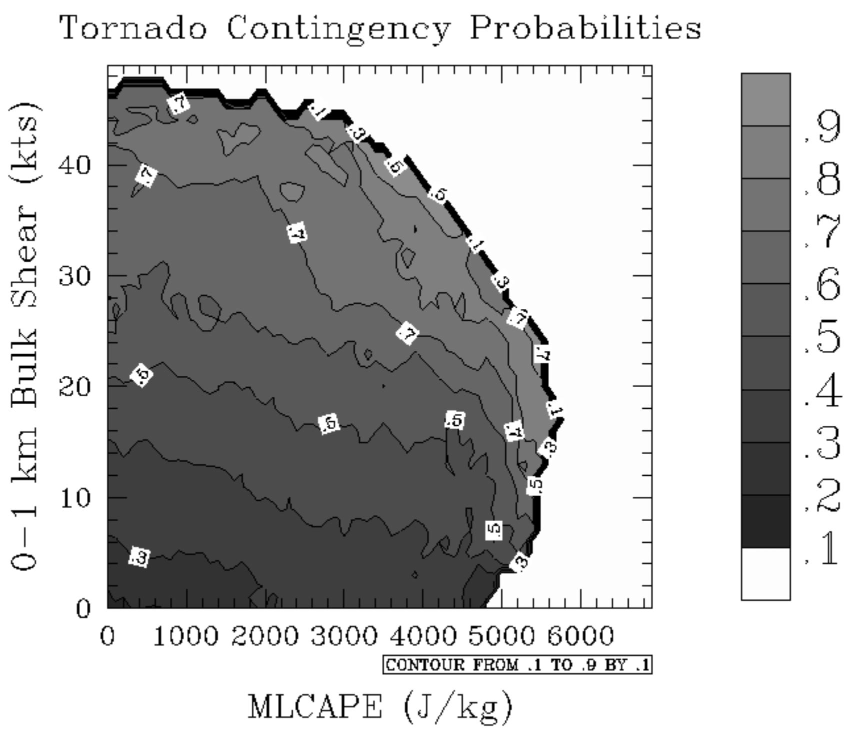


(b)

Figure 2. The (a) probability a significant tornado (F2 damage or greater) and (b) the probability a weak tornado (F0 or F1 damage) will form if a supercell forms. MLLCL (in m AGL) is plotted on the x-axis and 0–1-km Bulk Shear, in kts, is plotted on the y-axis.



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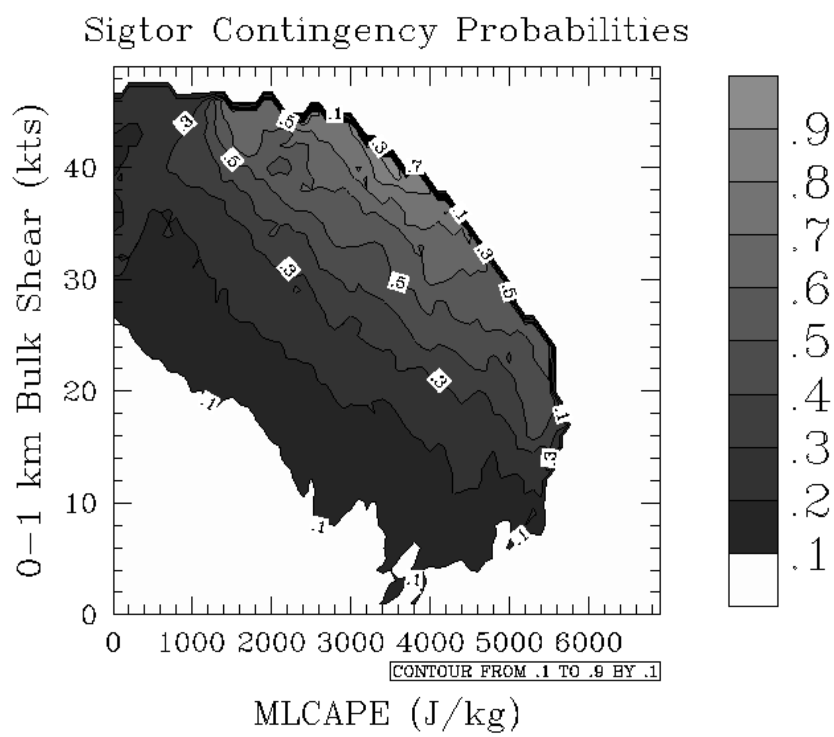
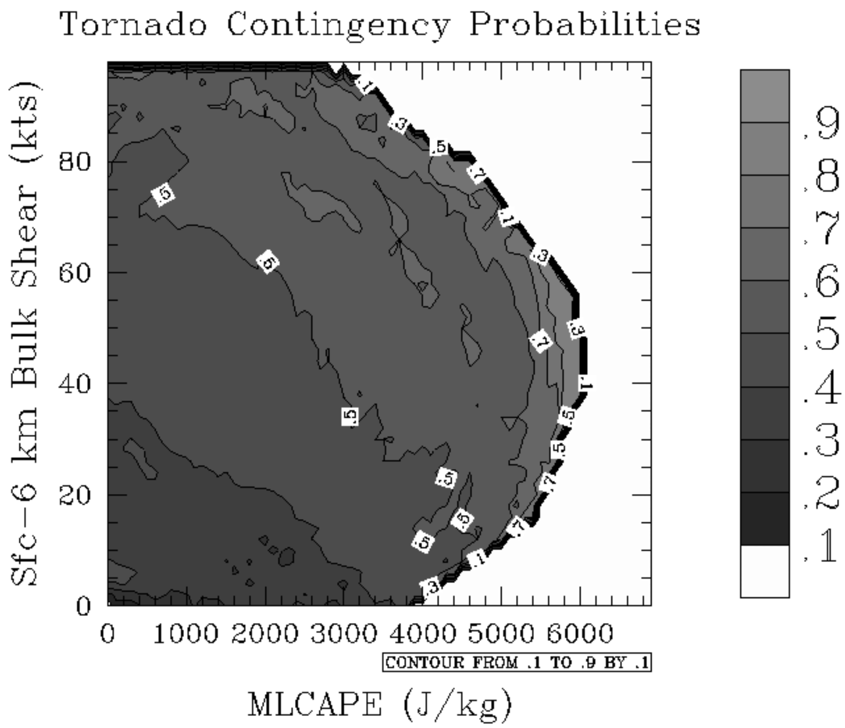


(b)

Figure 3. Given a supercell has formed, these plots show (a) the probability a tornado will form and (b) the probability a significant tornado will form. MLCAPE (Joules / Kilogram) is plotted on the x-axis and 0–1-km Bulk Shear, in kts, is plotted on the y-axis.



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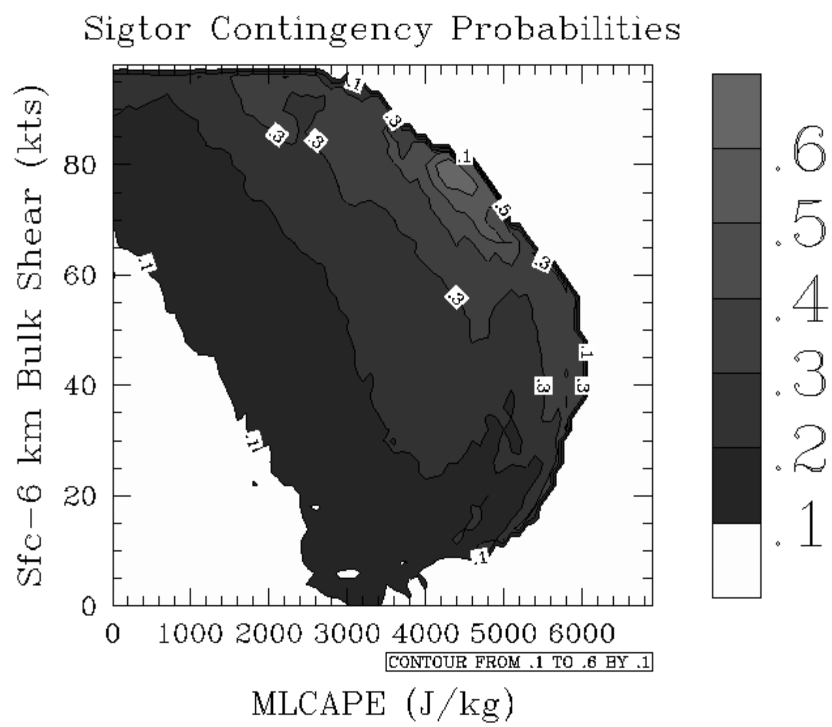
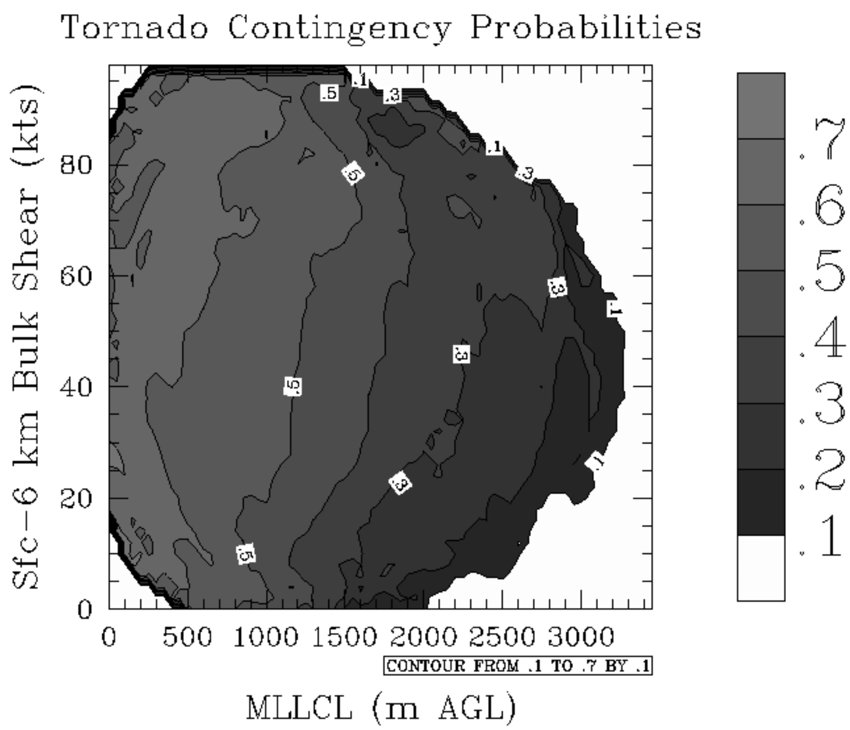


(b)

Figure 4. Same as Figure 3, except MLCAPE (J/kg) is plotted on the x-axis and Sfc–6-km Bulk Shear, in kts, is plotted on the y-axis.



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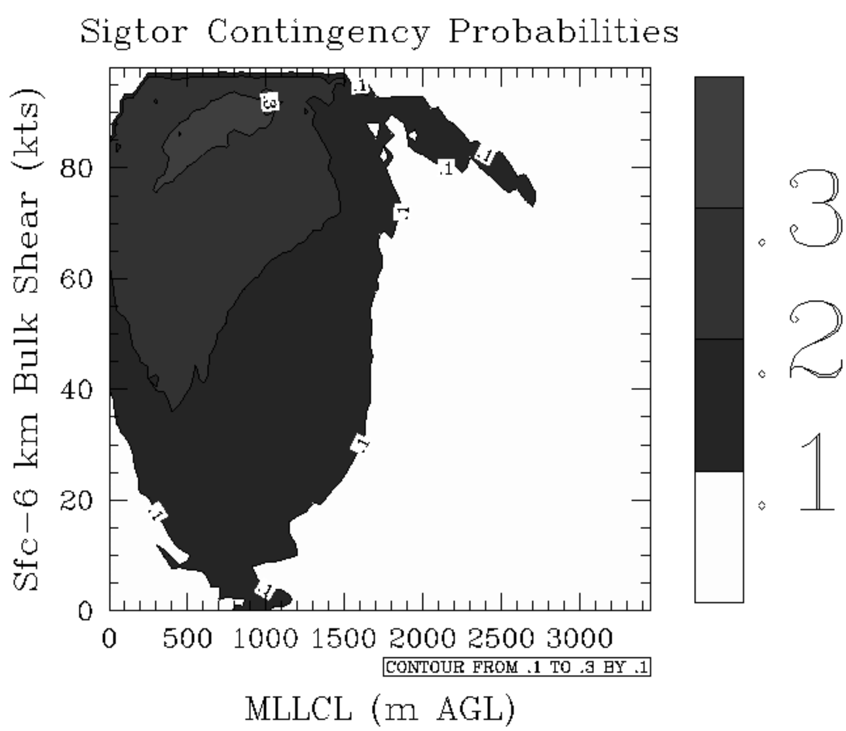
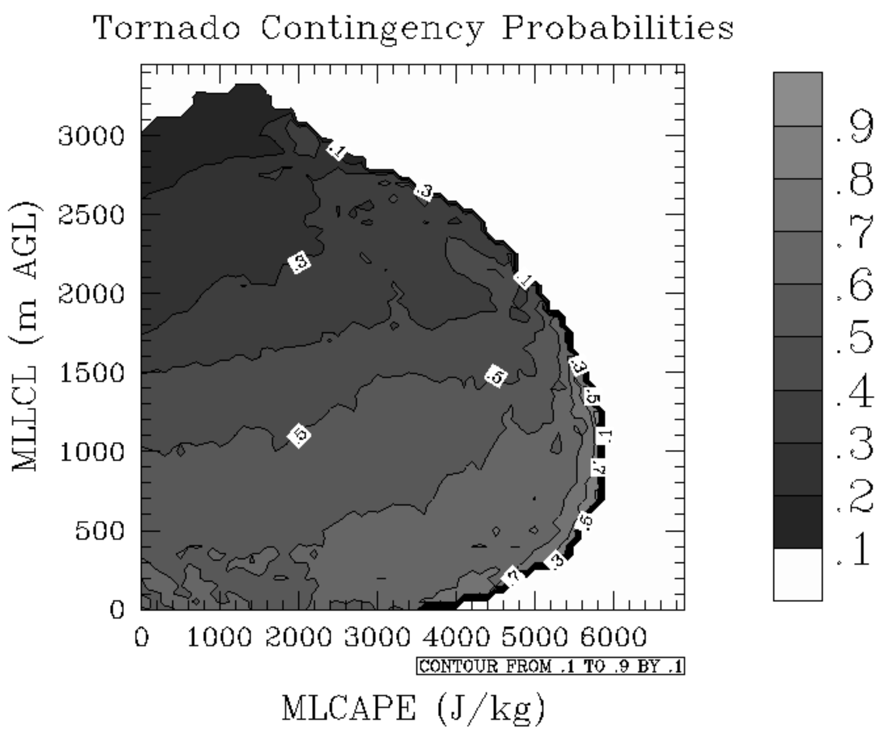


(b)

Figure 5. Same as Figure 3, except MLLCL (m AGL) is plotted on the x-axis and Surface–6-km Bulk Shear, in kts, is plotted on the y-axis.



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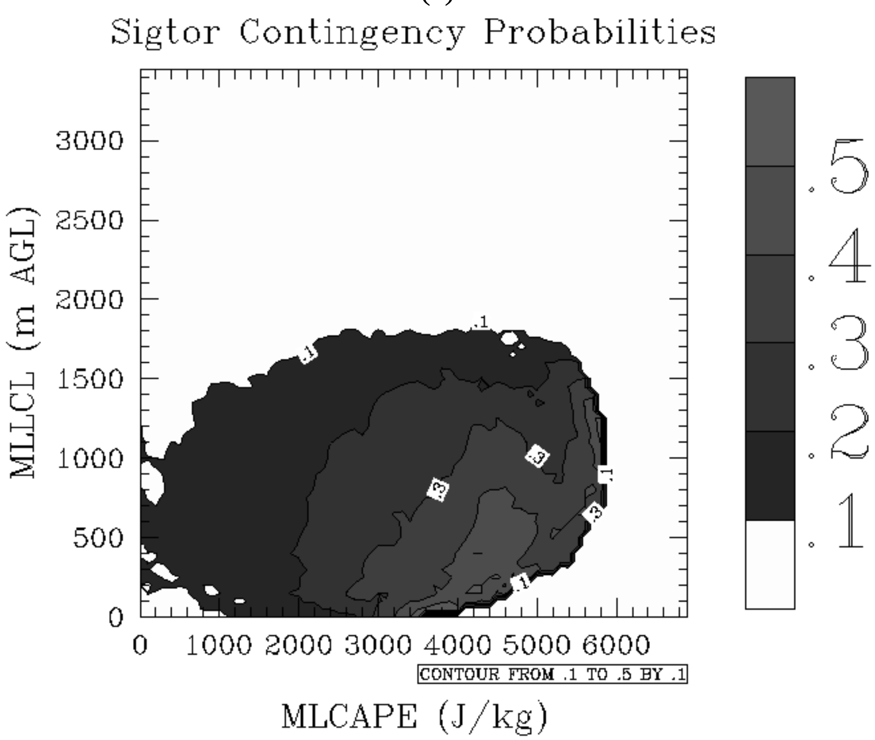

(b)

Figure 6. Same as in Figure 3, except MLCAPE (J/kg) is plotted on the x-axis and MLLCL (m AGL) is plotted on the y-axis.

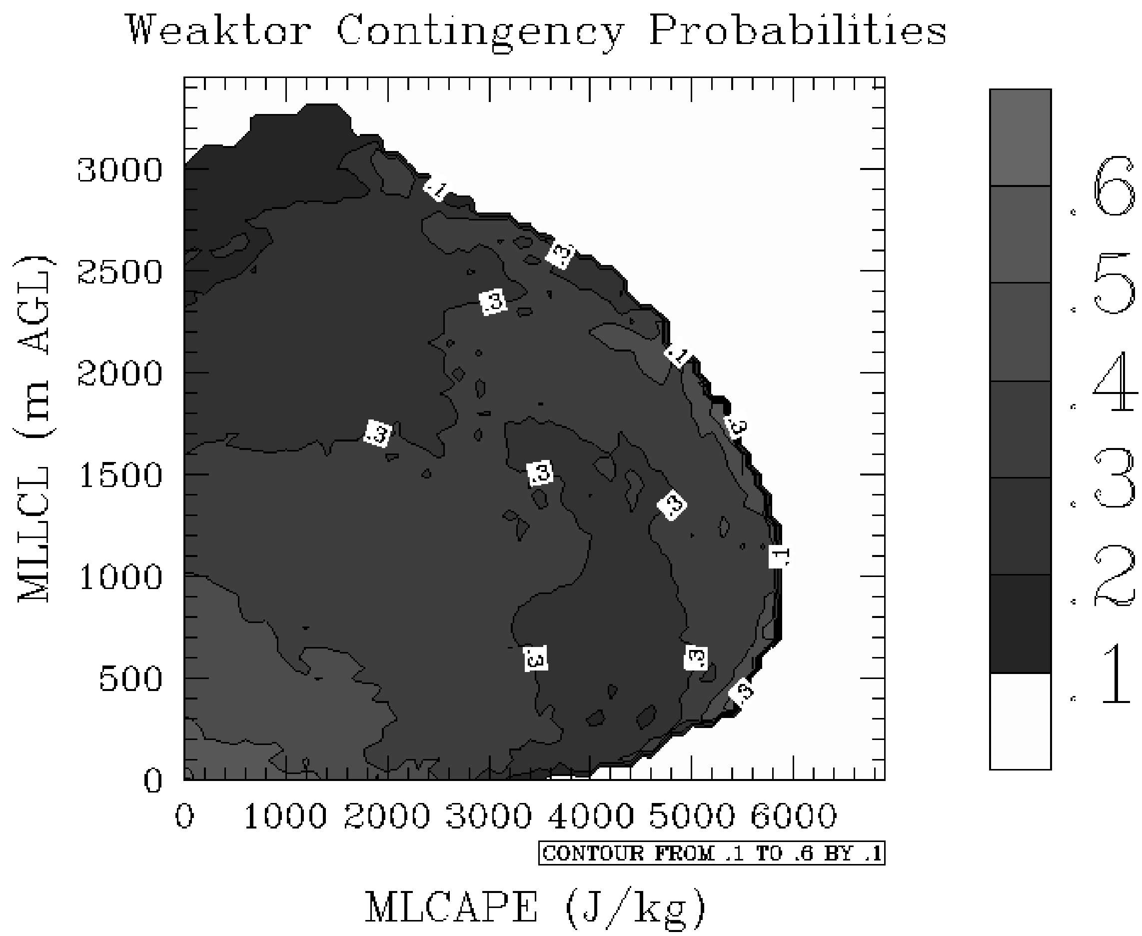

Figure 7. Plot showing the probability a weak tornado will form given a supercell has formed. MLCAPE (J/kg) is plotted on the x-axis and MLLCL (m AGL) is plotted on the y-axis.