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ESTIMATING THE STRENGTH OF THE CAPPING INVERSION AND THE PROBABILITY OF STRONG CONVECTION

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ABSTRACT

The strength of the capping inversion and the question "Will convection fire?" confronts the operational forecaster in the plains states numerous times each year. Two different techniques are introduced in this paper to aid the operational forecaster in determining the strength of the capping inversion and the possibility of strong convection. In both techniques, the forecaster must predict the maximum afternoon surface wet-bulb potential temperature and determine the strength of the forcing. Technique one requires use of the 12 hour NGM 850-700 mb thickness forecast, while the second technique requires use of the 12 hour 9000 foot temperature forecast from the FD wind product.

INTRODUCTION

As with many areas of operational meteorology, rules of thumb are used by forecasters to determine the strength of the lid. A lid is a warm dry airmass which is located above a moist and potentially unstable airmass. The intention of this paper is to provide the operational community with some new approaches to determining the strength of the lid and the likelihood of strong convection. These techniques, designed to be used mainly 4 to 8 hours in advance of late afternoon convection, should be used along with current techniques or rules of thumb. The first technique that will be discussed uses the 850-700 mb thickness to estimate the strength of the capping inversion, while the second technique uses the temperature at 9000 feet. Surface forcing, upper level forcing and the surface wet-bulb temperature are parameters that need to be determined in order to use either of these techniques.

The lid (capping inversion) plays a significant role in the severe thunderstorm environment in the Plains states during much of the spring and fall seasons. A lid that is very strong will typically suppress convection, while no lid or a very weak lid will allow widespread non-severe convection to develop. Sometimes, severe convection develops in a weakness in the lid or along the lid edge. In most instances, the lid and the associated high mid-tropospheric lapse rates need to be present to support severe convection.

The existence of a lid in the severe storm environment has been known for some time (Fawbush et al. 1951; Means 1952; Beebe and Bates, 1955). Typically, the high terrain of Mexico, Arizona, New Mexico and West Texas is extremely dry from late fall through late spring and nearly all of the energy received from the sun goes into sensible heating, producing a deep nearly dry adiabatic layer. (Carlson and Ludlam 1968 and Carlson, et al. 1980) If dry southwesterly winds prevail throughout this mixed layer, the hot dry air will be advected away from the source region and lose contact with the ground. When the hot dry air overruns a relatively cool and moist layer, it results in the formation of a lid. Besides the high terrain of the southwest, the high plains of Eastern Colorado, Eastern Wyoming, Western Kansas, and Western Nebraska are also a source region for lid formation, as was the case for the tornadic storms in Illinois and Indiana on August 28th 1990. Also, lid formation may result from subsidence associated with synoptic scale and mesoscale circulations. The elevated mixed layer and associated lid may be maintained or enhanced by short wave troughs (Doswell, et al. 1985).

Studies concerning the lid, conducted by the research community, have led to an overall better understanding of the lid and the severe storm environment. The ability of the elevated mixed layer to cap convection is dependent upon the temperature at lid level, the height of the lid above the ground, the vertical extent of the nose of the inversion, the the upper level forcing, the strength of the low level convergence and the wet bulb potential temperature of the air being lifted (usually near the surface).

Currently, forecast offices throughout the country receive temperature forecasts from the NGM (Nested Grid Model) in the form of temperature fields at 850 mb (approximately 5000 feet MSL) over all of North America and for specific sites at 6000 and 9000 feet MSL in the winds aloft forecasts. Unfortunately, the lid is usually located between 6000 and 9000 feet MSL. As a result, the NGM forecast temperatures do not provide the forecaster with enough information to resolve the strength of the capping inversion.

The geographical area considered in this study comprises that portion of the central United States enclosed within the dashed and solid lines depicted in Figure 1. A total of 74 cases from March, April, May and June 1990 were examined, subject to the following constraints:

1) The atmosphere had to be well mixed during the late afternoon and early evening hours.
2) A boundary to focus convection had to be present near the location of interest during the period of maximum heating.
3) The lid had to be located between 850 and 700 mb, as it was in all but a few instances during the period of this study.
4) There had to be some threat of severe thunderstorms in the area of interest.

Neither days during which the air in the elevated mixed layer was so warm that it was obvious that convection would not occur, nor days during which the cap was so weak that widespread convection was anticipated, were included in this study. Only days in which there was considerable uncertainty

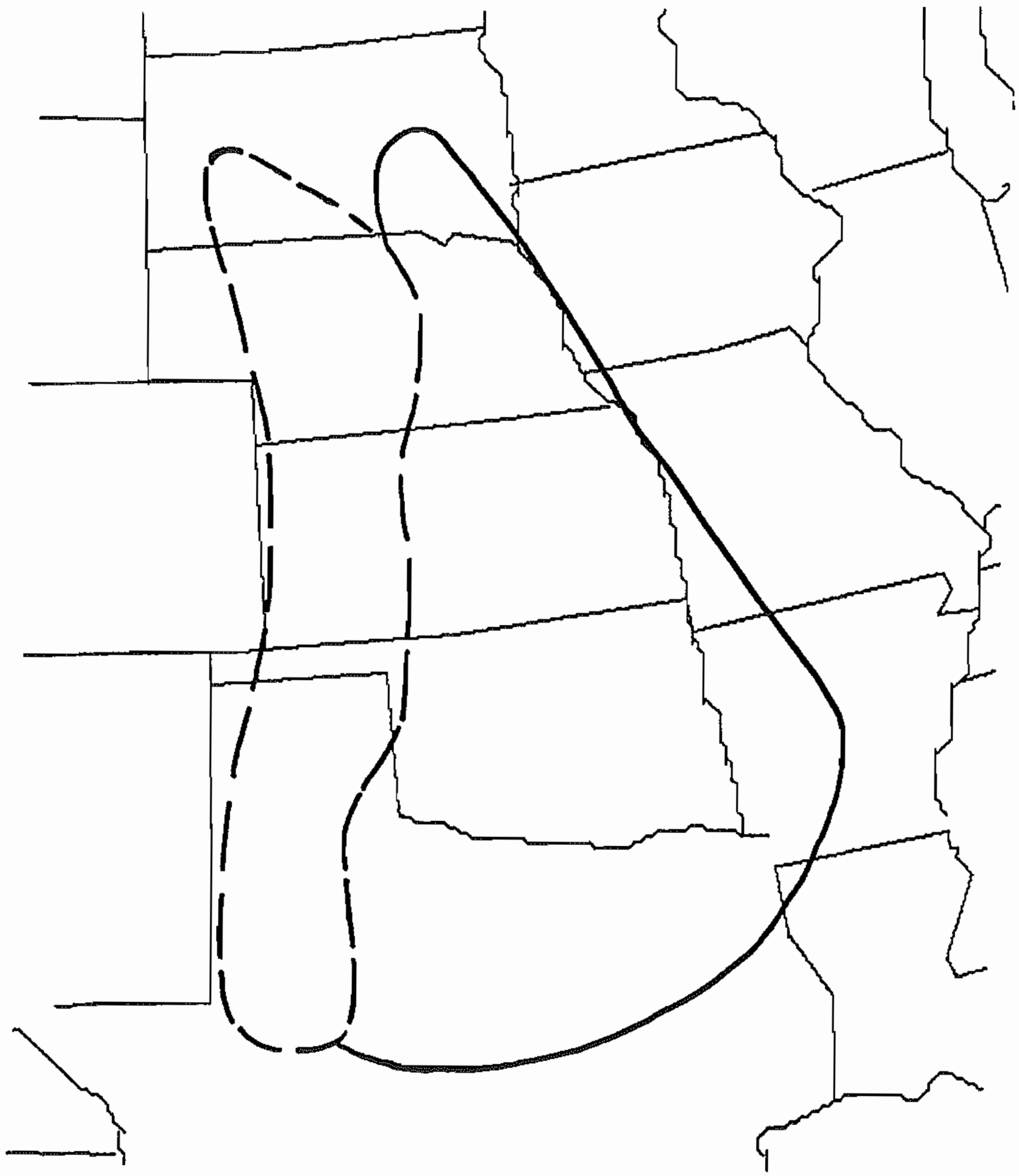

FIGURE 1. Data points used in this study. Solid line surrounds area for elevations below 2000 feet, while dashed line surrounds area for elevations above 2000 feet.

about overcoming the capping inversion were considered; the results are applicable only to evaluating the probability of convective development in the area of interest. The results are not relevant to cases in which convection develops upstream during the period of maximum heating and moves into the area of interest later in the evening.

Surface locations were divided into two groups for both techniques. The first group included all locations above 2000 feet MSL, while the second group included all locations below 2000 feet MSL. The decision to separate the two groups at 2000 feet was an arbitrary one and seemed to work quite well. The intention was to separate the locations that typically mix through the 700 mb level from those that do not.

Presented here are the results of the following two studies:
1) 850-700 mb thickness value versus the approximate late afternoon surface wet-bulb potential temperature.
2) 700 mb temperature versus the approximate late afternoon surface wet-bulb potential temperature.

850-700 MB THICKNESS VERSUS SURFACE WET-BULB POTENTIAL TEMPERATURE

In this section it was assumed that the 850-700 mb thickness, which is proportional to the mean temperature of the layer, is representative of the capping inversion. A total of 52 cases for locations with an elevation of less than 2000 feet MSL (located within the area outlined by the solid line in Figure 1) were examined, and the results are presented in Figure 2. A line of best fit was drawn separating the cases when strong convection occurred from those when weak or no convection occurred. In this paper, the term "strong convection" applies to intensities of at least VIP 5. Due to differences in upper level support, low level forcing and other synoptic and mesoscale features, six data points (12 percent) did not conform to this line of best fit. If strong overall forcing is present, then the line of best fit should be shifted slightly to the right. If weak overall forcing is present then the line of best fit should be shifted slightly to the left. Figure 3 shows the two adjusted lines of best fit along with the original line of best fit from Figure 2. It must be pointed out that these adjusted lines of best fit are purely arbitrary and no attempt was made to look at each individual case and apply an adjustment to it based on the strength of the overall forcing.

The overall forcing discussed here was broken into two terms: 1) low level forcing along the boundary; and 2) upper level forcing over the boundary. The low level forcing was broken into three categories: weak, average and strong. The low level forcing was considered weak if the boundary of interest was barely discernible in the wind field (wind shift of at least 20 degrees across the boundary) and strong if the difference in wind direction across the boundary was at least 70 degrees

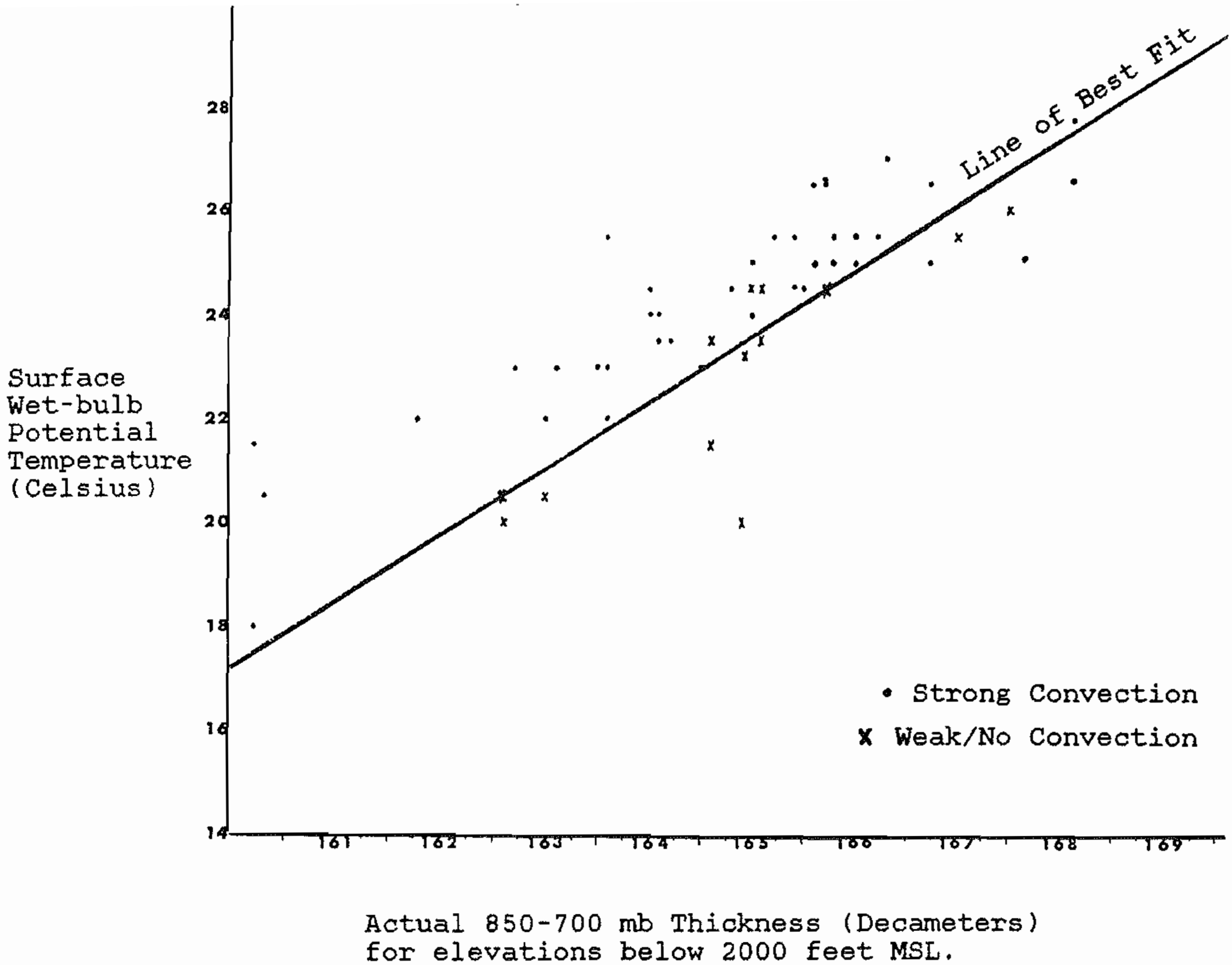

FIGURE 2. Surface wet-bulb potential temperature versus observed or interpolated 850-700 mb thickness for elevations below 2000 feet MSL. The wet-bulb potential temperature is in degrees Celsius and the 850-700 mb thickness is in decameters. A dot represents a location where strong convection occurred. An x represents a location where weak or no convection occurred. A line of best fit has been drawn to separate the strong convection cases from the weak or no convection cases.

and the wind speeds were at least 20 knots on the side where the wind flow was more perpendicular to the boundary. The low level forcing was considered average when the conditions defining strong and weak forcing were not applicable.

The upper level forcing was broken into 3 categories; negative, neutral or weak, and positive. The upper level forcing was considered negative when the vorticity value at 500 mb was forecast by the model to decrease by at least 6 radians/second during a 12 hour period. The upper level forcing was considered positive when the vorticity value at 500 mb was forecast by the model to increase by at least 6 radians/second during a 12 hour period. The forcing was considered neutral or weak when the conditions defining positive and the negative forcing were not applicable. Once the low level and upper level forcing had been determined, the overall forcing was determined from Table 1.

TABLE 1. DETERMINATION OF THE OVERALL FORCING

		LOW LEVEL FORCING		
		WEAK	AVERAGE	STRONG
UPPER LEVEL FORCING	NEGATIVE	WEAK	AVERAGE	AVERAGE
	NEUTRAL/WEAK	WEAK	AVERAGE	STRONG
	POSITIVE	AVERAGE	AVERAGE	STRONG

The lines of best fit from Figure 3 can be used by forecasters to narrow the uncertainty in determining the likelihood of strong convection. To use the results in Figure 3, the forecaster must predict the maximum afternoon surface wet-bulb potential temperature, determine the strength of the overall forcing and use the 850-700 mb thickness forecast from the NGM. The wet bulb potential temperature is determined by the following:

1) Draw a line upward along the dry adiabat which intersects the expected late afternoon temperature.
2) Draw a line upward along a saturation mixing ratio line from the expected late afternoon dew point.
3) Determine where the two lines intersect. From this point follow the moist adiabat down to 1000 mb. The wet-bulb potential temperature is the corresponding temperature in degrees Celsius.

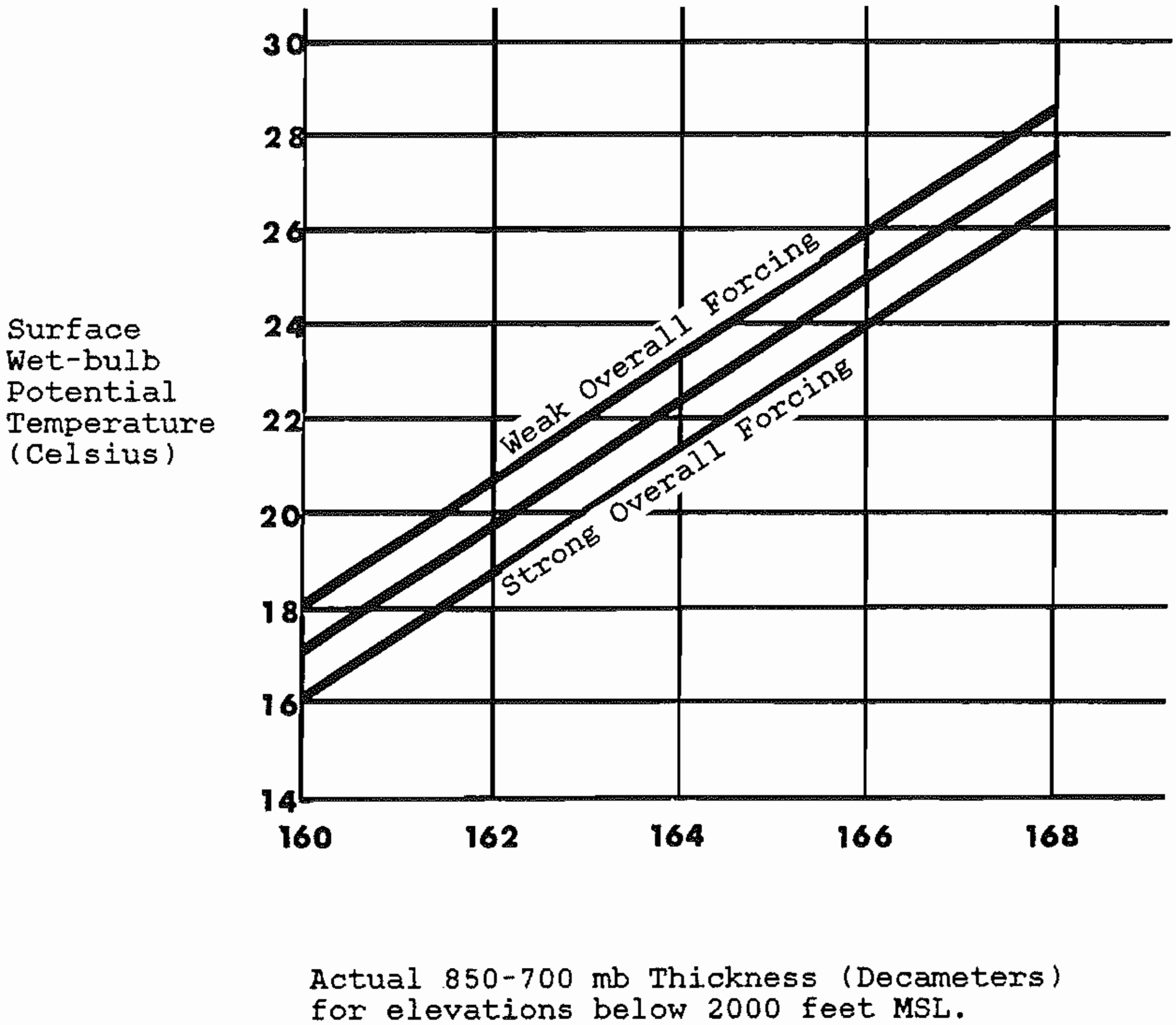

FIGURE 3. Surface wet-bulb potential temperature versus observed or interpolated 850-700 mb thickness for elevations below 2000 feet MSL. The wet-bulb potential temperature is in degrees Celsius and the 850-700 mb thickness is in decameters. The center solid line is the line of best fit from Figure 2. The top solid line is the adjusted line of best fit for cases with weak overall forcing. The lower solid line is the adjusted line of best fit for cases with strong overall forcing.

The 850-700 mb thickness can be determined by graphically subtracting the 850 mb forecast height from the 700 mb forecast height. Of course, the use of Figure 3 is dependent on the accuracy of the height forecast by the NGM. The next section will look into the accuracy of these forecasts.

A total of 22 data points (located inside the dashed line in Figure 1) were included for elevations above 2000 feet (Figure 4). Unlike the data points for elevations below 2000 feet, a straight "line of best fit" could not be applied to these points. In this case, a curve of best fit was used. It is apparent from looking at Figure 4, that with a surface wet-bulb potential temperature of 23.5 degrees Celsius or greater, strong convection would likely occur. In the high terrain, the temperature and moisture fields needed to produce a surface wet-bulb potential temperature of 23.5 degrees or greater could only be achieved if the capping inversion was located close to the ground. Strong heating of this shallow moist layer was sufficient to break the capping inversion in these instances. When the lid was initially located well above the surface, afternoon heating resulted in a deep and relatively dry mixed layer with a wet-bulb potential temperature well below 23.5 degrees. This is a common phenomenon west of the dryline during the spring. The curve of best fit was shifted towards the lower right for strong forcing and towards the upper left for weak forcing (Figure 5). It appears that the strength of the forcing is not as important in the higher elevations due to the relative closeness of the lid to the ground. Thus, the amount of shift due to forcing for elevations above 2000 feet is not as large as that for elevations below 2000 feet. Figure 5, in the same manner as Figure 3, is used to determine the likelihood of strong convection above 2000 feet. Once again, the adjusted lines of fit are quite subjective.

In order for the results of this study to be used effectively as a forecast tool, it is imperative that good 850-700 mb thickness be available from the NGM. Forecast and observed thickness values were examined for each case used in this study, and the results are presented in Figure 6. The solid line represents an 850-700 mb thickness identical to the observed thickness, while the dashed lines represent errors of one decameter above or below the observed thickness values. In 71 percent of the cases examined, the forecast and the observed thickness values differed by no more than a decameter. The NGM forecast values were more than a decameter high in 12 percent of the cases and more than a decameter low in 17 percent of the cases. In 56 percent of the cases examined, the NGM forecast verified too low, perhaps suggesting a tendency for the model to underforecast 850-700 mb thickness values. Nevertheless, the NGM forecast values appear to be sufficiently accurate that they can be used successfully with forecast surface wet-bulb temperatures to evaluate the probability of strong convection.

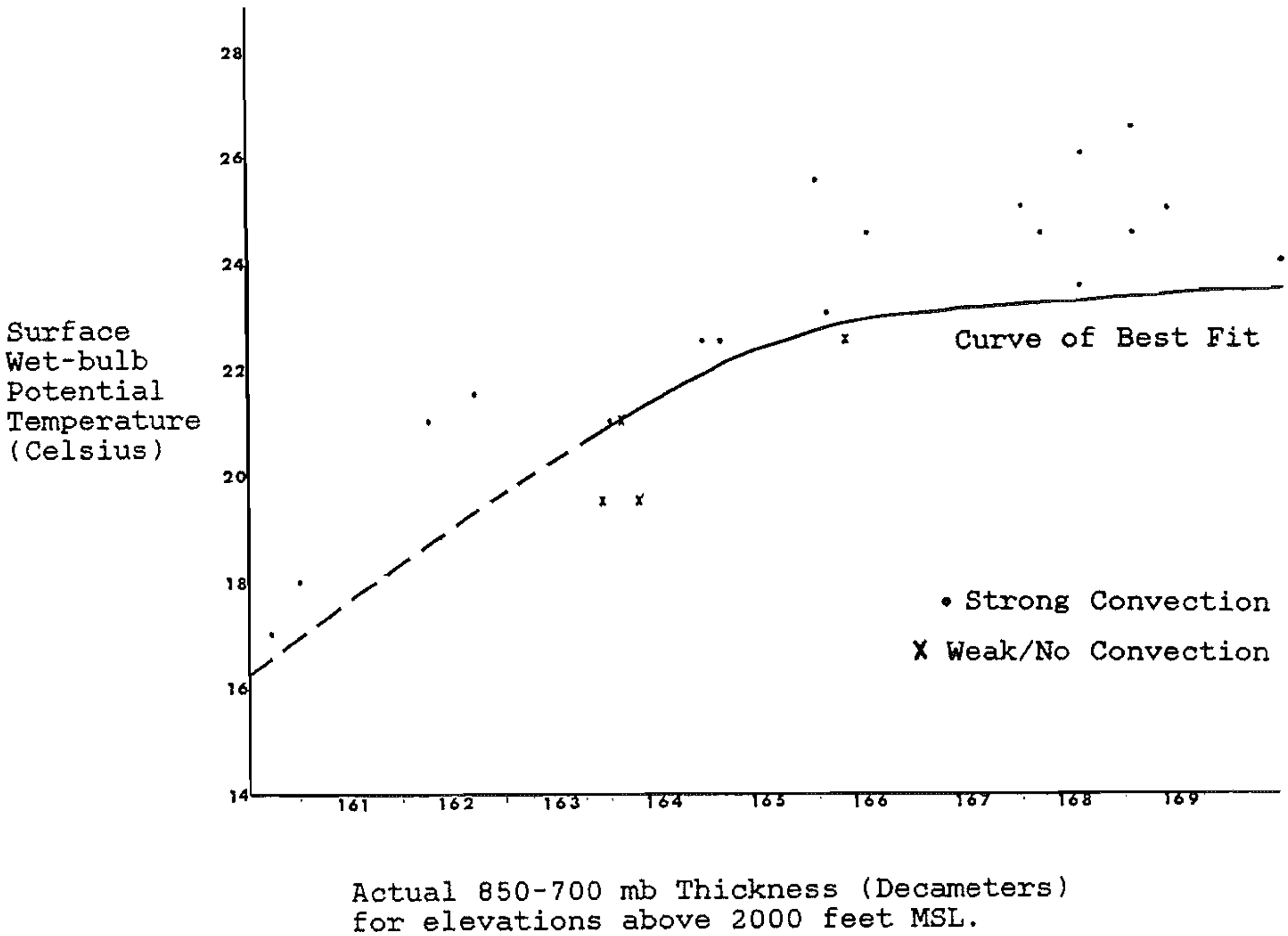

FIGURE 4. Surface wet-bulb potential temperature versus observed or interpolated 850-700 mb thickness for elevations above 2000 feet MSL. The wet-bulb potential temperature is in degrees Celsius and the 850-700 mb thickness is in decameters. A dot represents a location where strong convection occurred. An x represents a location where weak or no convection occurred. A curve of best fit has been drawn to separate the strong convection cases from the weak or no convection cases.

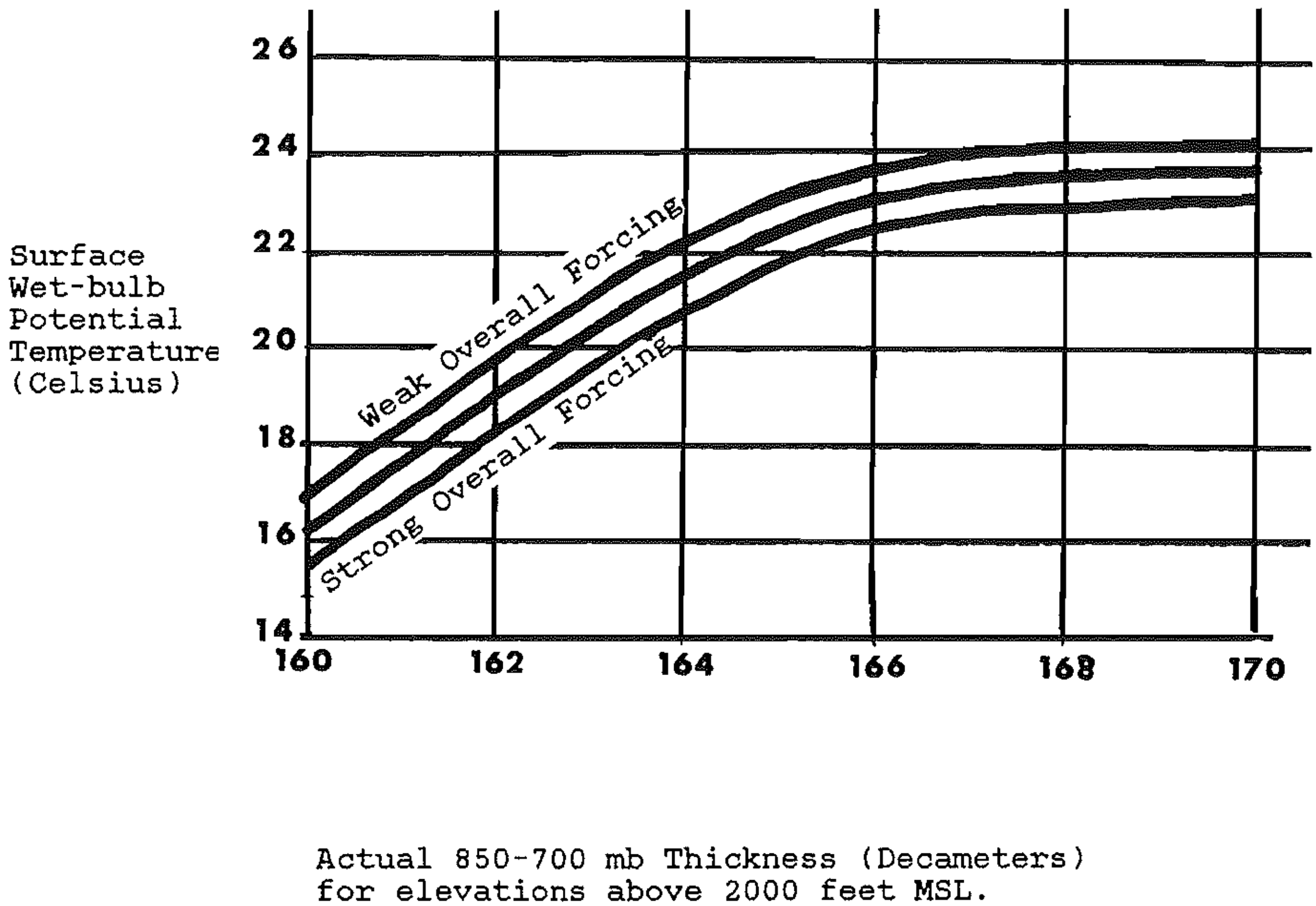

FIGURE 5. Surface wet-bulb potential temperature versus observed or interpolated 850-700 mb thickness for elevations above 2000 feet MSL. The wet-bulb potential temperature is in degrees Celsius and the 850-700 mb thickness is in decameters. The center curved line is the same as that in Figure 4. The top solid curve is the adjusted curve of best fit for cases with weak overall forcing. The lower solid curve is the adjusted curve of best fit for cases with strong overall forcing.

700 MB TEMPERATURE VERSUS SURFACE WET-BULB POTENTIAL TEMPERATURE

Many forecasters use the 700 mb temperature as a means of determining the strength of the lid. This approach works well when the lid is close to 700 mb or when the temperature at the 700 mb level fortunately represents the lid layer. In order to check the validity of using 700 mb temperature as a forecast tool, each case used in the previous section was reexamined using 700 mb temperature instead of 850-700 mb thickness as a measure of cap strength. The results of this study for elevations below 2000 feet MSL are presented in Figure 7, and the results for elevations above 2000 feet MSL are presented in Figure 8. A line of best fit was drawn for elevations below 2000 feet (Figure 7). This line separates the cases when strong convection occurred from those when weak or no convection occurred. Due to differences in upper level forcing, low level forcing and other synoptic and mesoscale features, three data points (6 percent) do not conform to this line of best fit. Similar to Figure 4, a straight "line of best fit" could not be applied to the data points in Figure 8 and a curve of best fit was used. Due to reasons discussed earlier, a few of the data points did not conform to the curve of best fit. However, data point A (North Platte, Nebraska from 0000 GMT on May 14 1990) was significantly in error. The sounding from that evening is shown in Figure 9. Shortly after this sounding was taken, a very strong short wave moved into the area and the lifting associated with it removed the lid, allowing strong convection to develop. It must be pointed out that in rapidly developing situations both methods of estimating the strength of the lid might fail. It is apparent from Figure 8 that with a surface wet-bulb potential temperature of 23.5 degrees Celsius or greater strong convection will likely occur.

The lid is very rarely located at 700 mb, but it does appear that the 700 mb temperature provides an accurate representation of the capping inversion for all elevations. At this time, 700 mb model forecast temperatures are not available to meteorologists at forecast offices; the nearest forecast level routinely available is at 9000 feet in the FD wind product. Assuming the atmosphere is nearly dry adiabatic between 9000 feet and 700 mb (this is typically the case above a lid in an elevated mixed layer), the temperature at 9000 feet will be about 3 degrees Celsius warmer than the temperature at 700 mb. Figures 10 and 11 were derived from Figures 7 and 8 by applying this three degree adjustment to the x-coordinate of each graph. The line of best fit and the curve of best fit were shifted toward the lower right for strong overall forcing and toward the upper left for weak overall forcing. Figures 10 and 11 may be used as predictive tools in the same manner as Figures 3 and 5 discussed previously. The forecaster must predict the maximum afternoon surface wet-bulb potential temperature, determine the strength of the forcing and use the 12 hour forecast temperature at

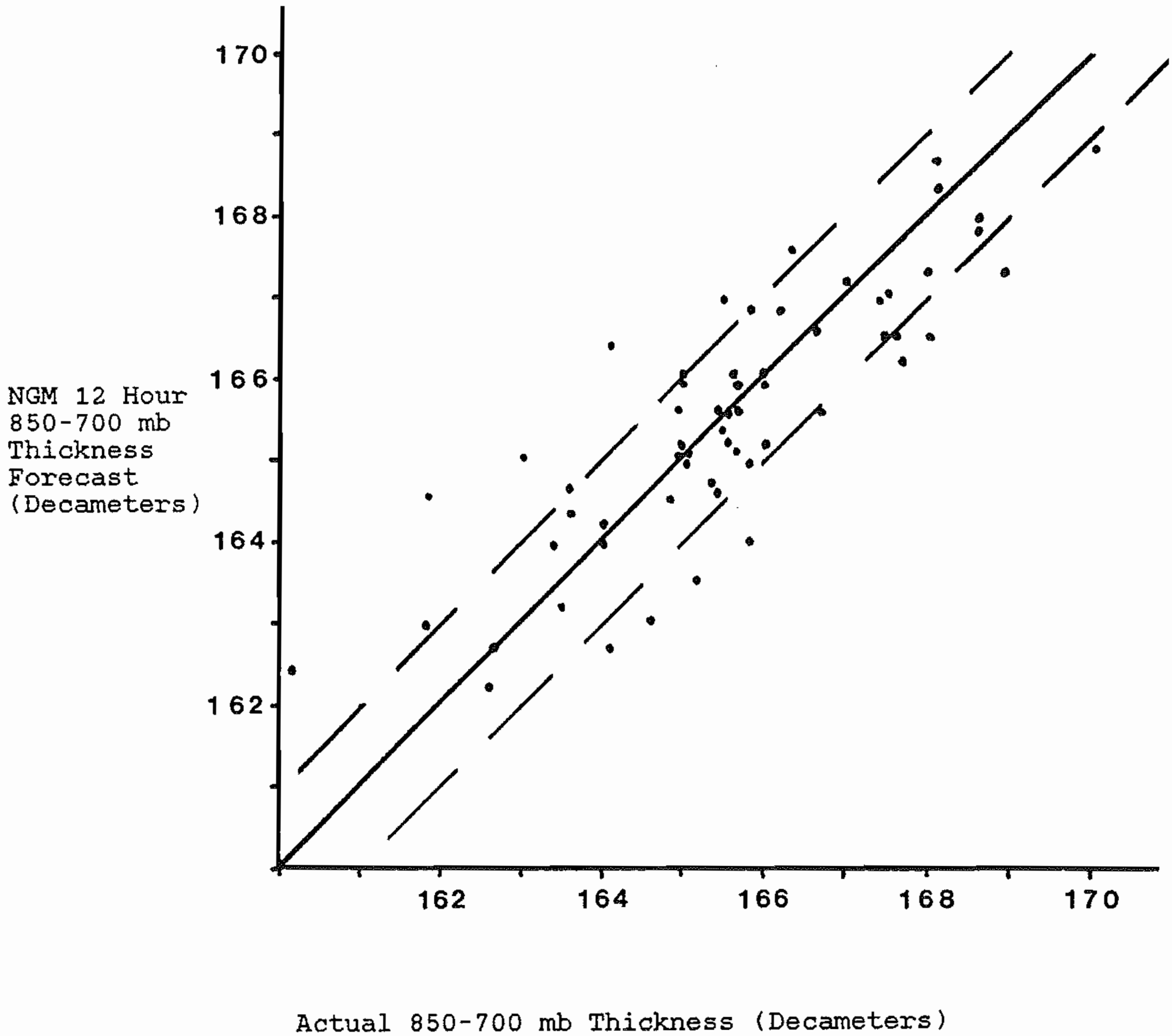

FIGURE 6. NGM 12 hour 850-700 mb thickness forecast versus actual 850-700 mb thickness. The forecast and the actual thickness are in decameters. The solid line represents values where the forecast thickness and the actual thickness are the same. The dashed lines represent an error of +/- 1 decameter in the model forecast.

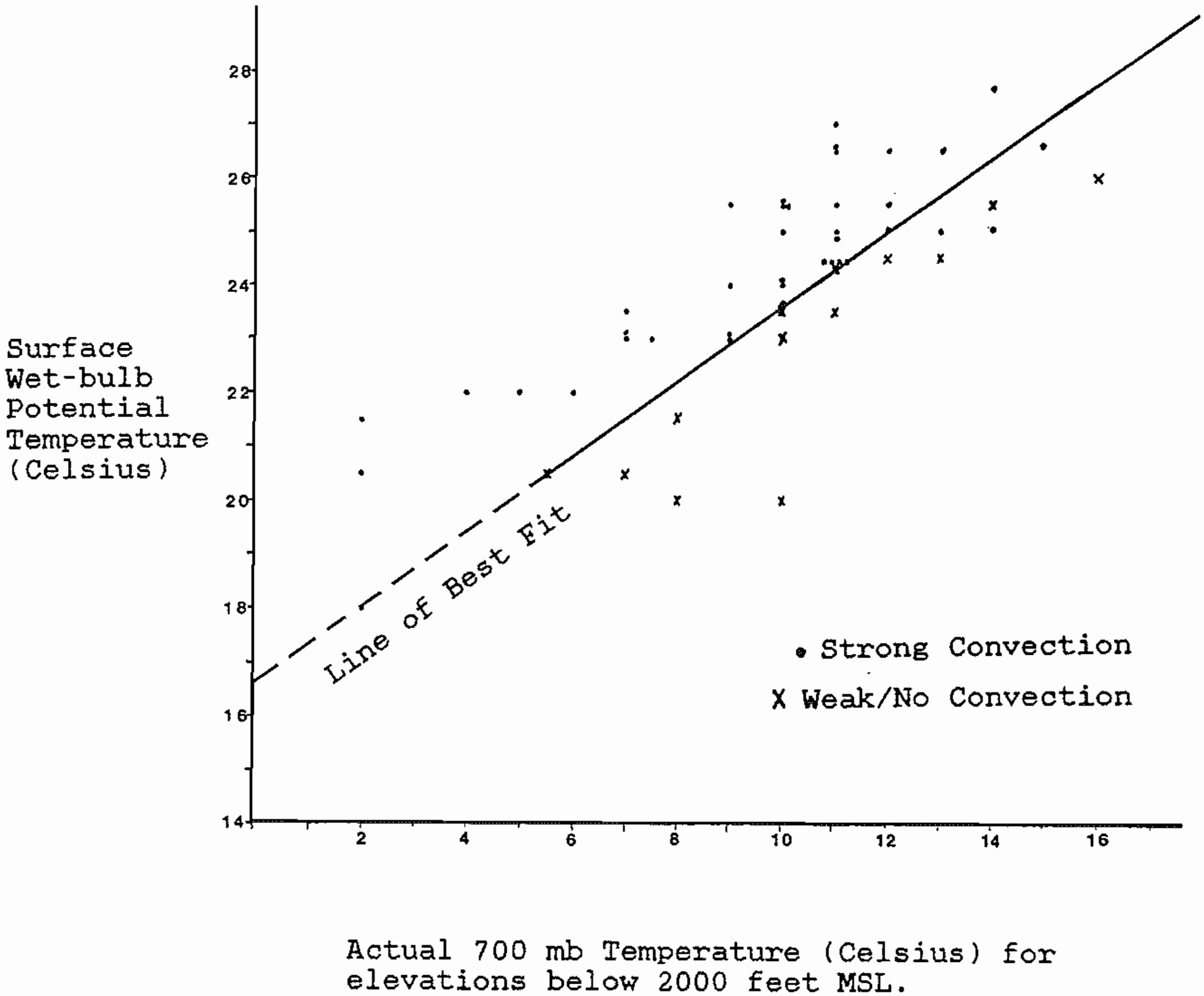

FIGURE 7. Surface wet-bulb potential temperature versus observed or interpolated 700 mb temperature for elevations below 2000 feet MSL. The wet-bulb potential temperature and the 700 mb temperature are in degrees Celsius. A dot represents a location where strong convection occurred. An x represents a location where weak or no convection occurred. A line of best fit has been drawn to separate the strong convection cases from the weak or no convection cases.

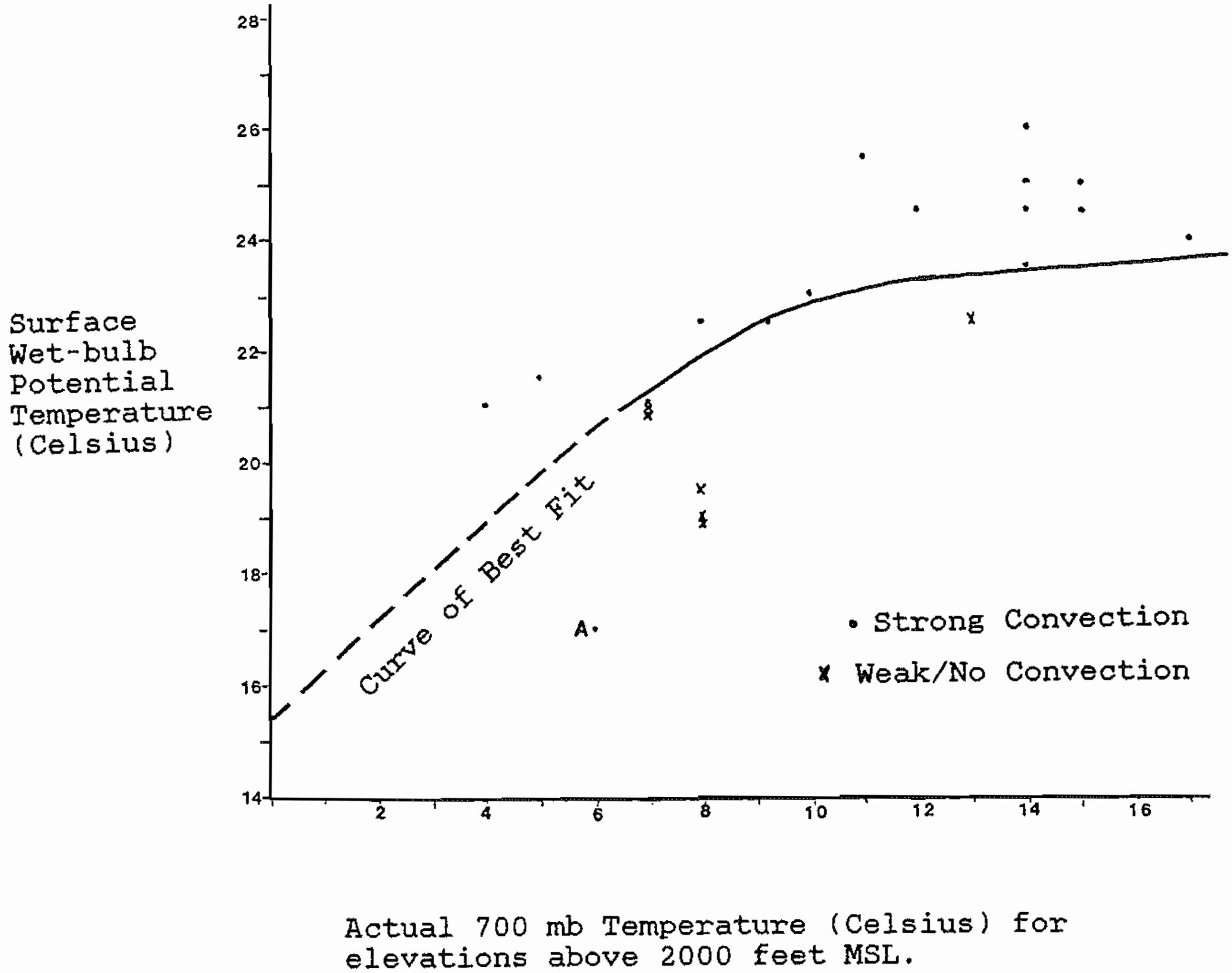

FIGURE 8. Surface wet-bulb potential temperature versus observed or interpolated 700 mb temperature for elevations above 2000 feet MSL. The wet-bulb potential temperature and the 700 mb temperature are in degrees Celsius. A dot represents a location where strong convection occurred. An x represents a location where weak or no convection occurred. A line of best fit has been drawn to separate the strong convection cases from the weak or no convection cases.

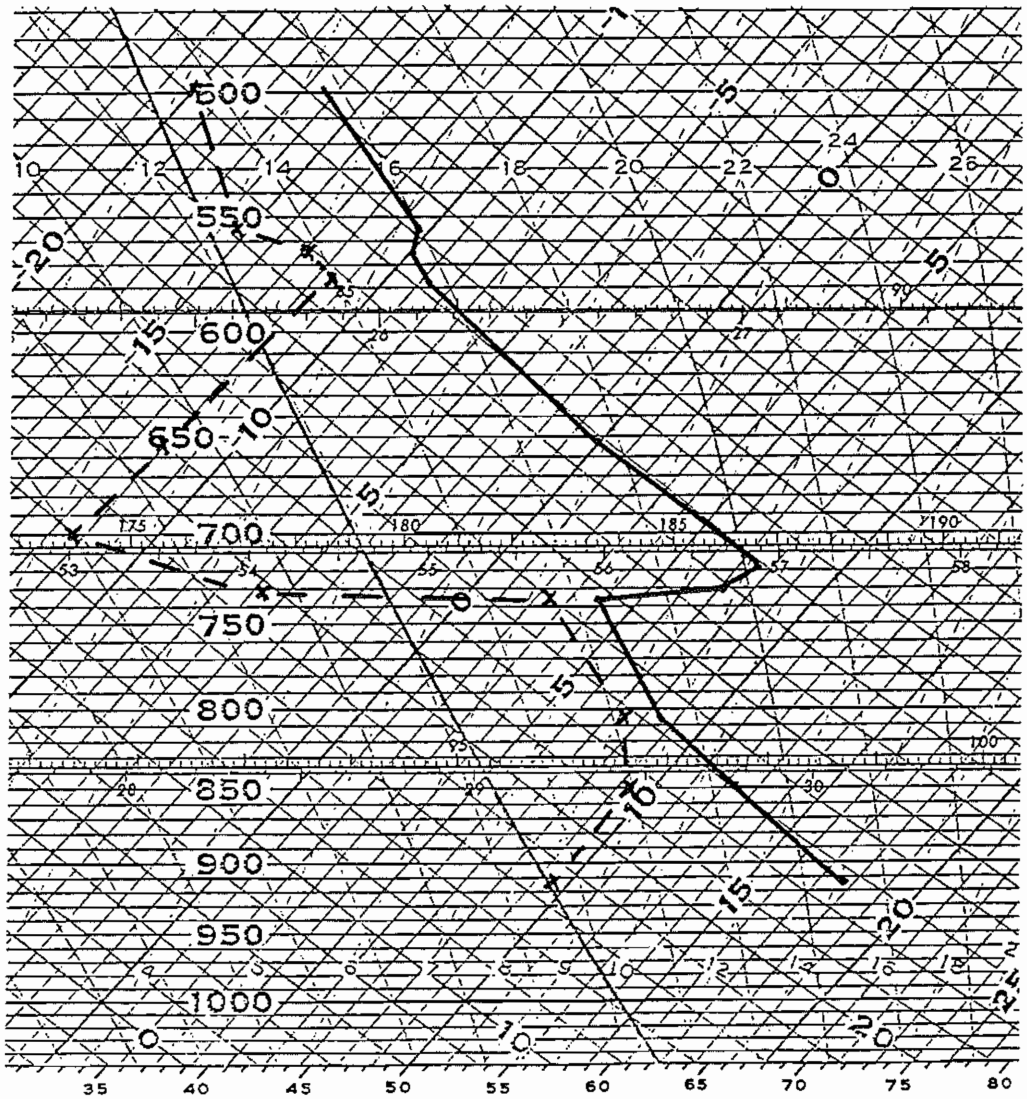

FIGURE 9. Sounding from North Platte, Nebraska at 0000 GMT on May 14, 1990. Solid line represents temperature profile and dashed line represents moisture profile.

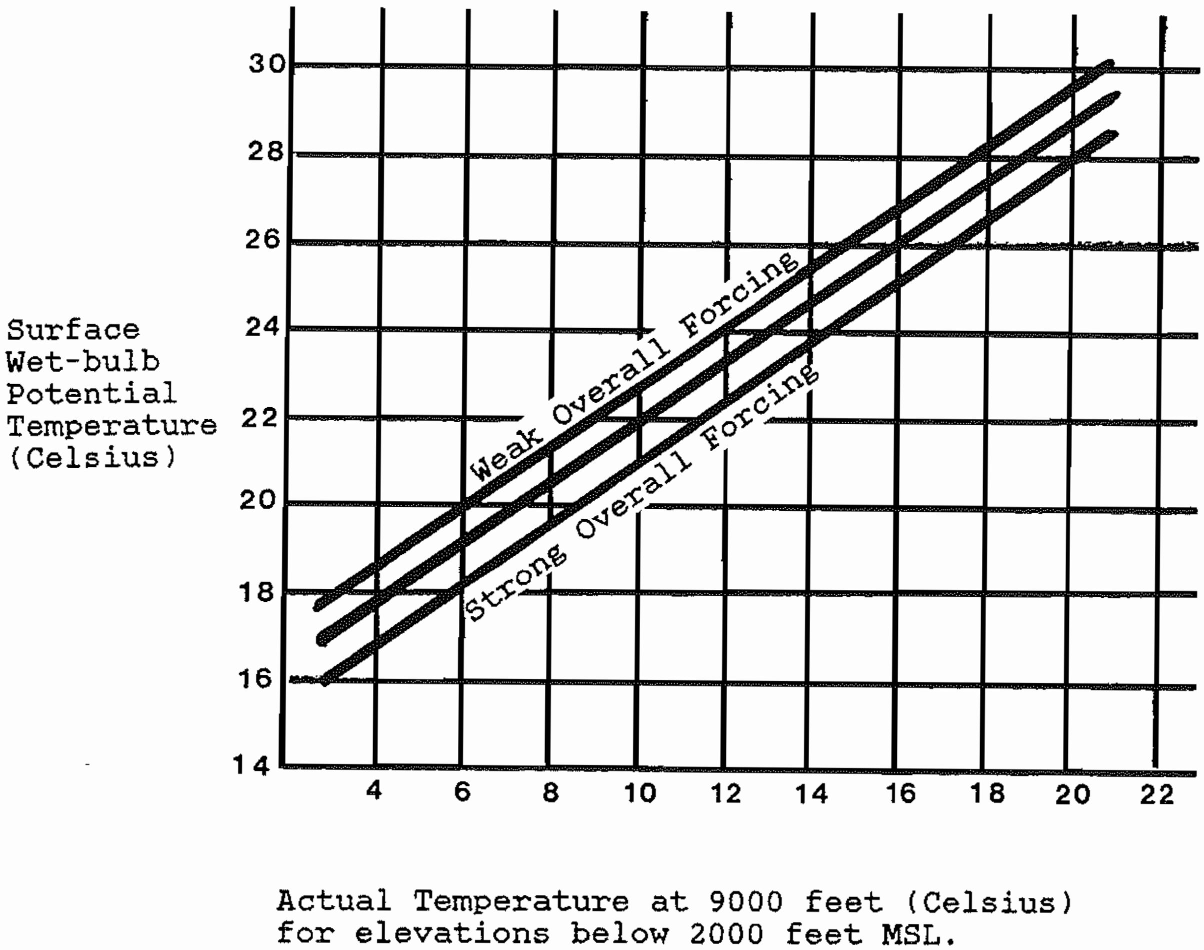

FIGURE 10. Surface wet-bulb potential temperature versus temperature at 9000 feet for elevations below 2000 feet MSL. The wet-bulb potential temperature and the temperature at 9000 feet are in degrees Celsius. The center solid line is the line of best fit from Figure 7 (3 degrees warmer). The top solid line is the adjusted line of best fit for cases with weak overall forcing. The lower solid line is the adjusted line of best fit for cases with strong overall forcing.

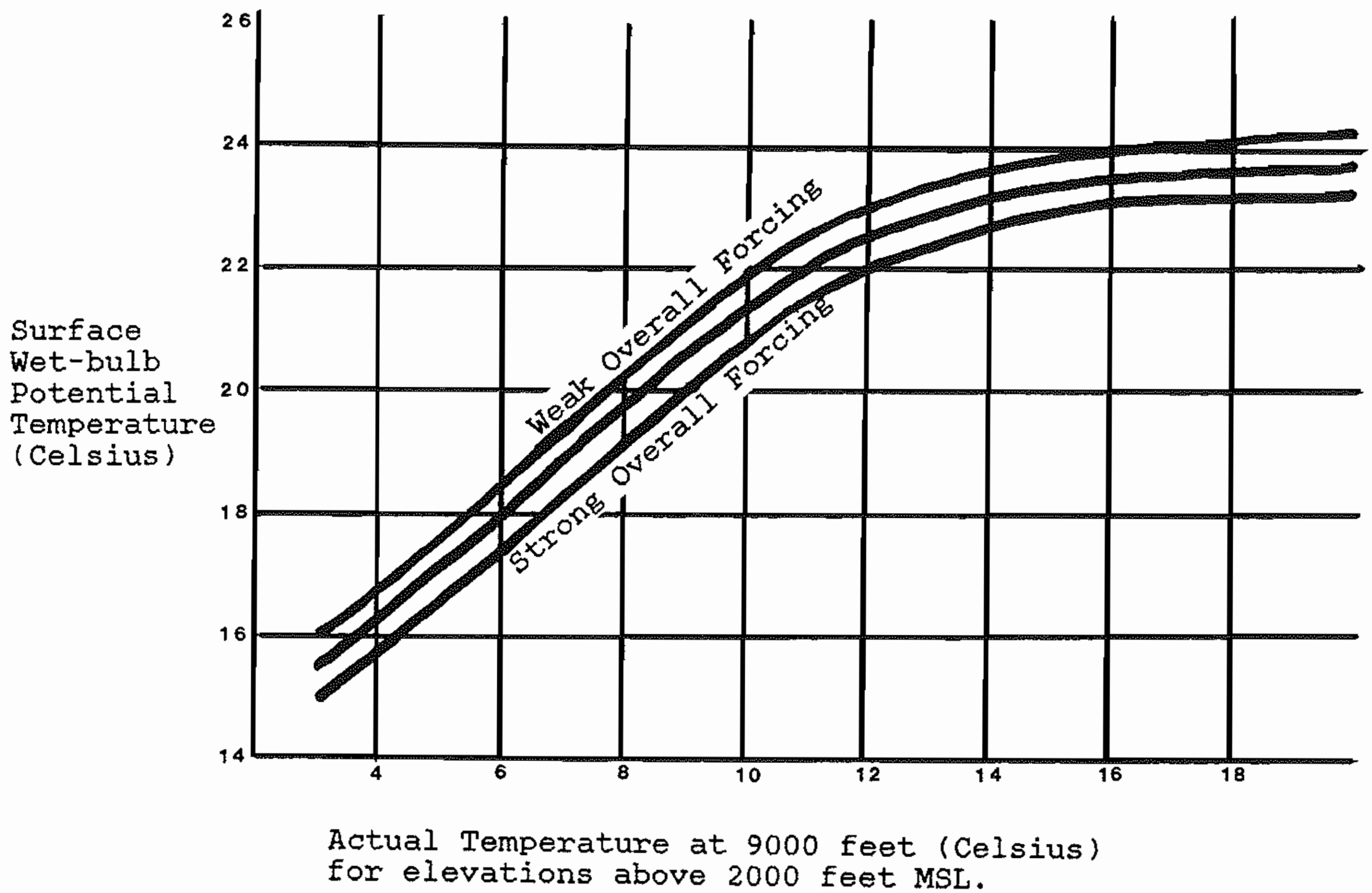

FIGURE 11. Surface wet-bulb potential temperature versus temperature at 9000 feet for elevations above 2000 feet MSL. The wet-bulb potential temperature and the temperature at 9000 feet are in degrees Celsius. The center solid curve is the curve of best fit from Figure 8 (3 degrees warmer). The top solid curve is the adjusted curve of best fit for cases with weak overall forcing. The lower solid curve is the adjusted curve of best fit for cases with strong overall forcing.

9000 feet. Once again, the adjusted lines of best fit for Figures 7, 8, 10 and 11 are subjective.

To determine the accuracy of the 12 hour 9000 foot temperature forecast verifying at 0000 GMT, a two week study using six stations within the solid and dashed lines in Figure 1 was undertaken. Out of the 82 forecast temperatures, 89 percent (73) were within 2 degrees Celsius of the observed temperature. In general, the 9000 foot temperatures were forecast to be 0.2 degrees higher than the observed.

CASE STUDY 1-May 19th 1990

The morning sounding taken in Norman, Oklahoma on May 19th is shown in Figure 12. At this time, very moist air was located in the lowest 5000 feet of the atmosphere over central Oklahoma and much of the surrounding area. The 850-700 mb thickness (164.1 decameters) was fairly representative of the capping inversion. The lid at 1200 GMT was located at 810 mb. A nearly dry-adiabatic layer was located between 700 and 560 mb and the change in temperature between 700 and 500 mb was about 20.5 degrees Celsius. Unfortunately, the NGM was not available the morning of the 19th; therefore, a 24 hour NGM forecast for the 850-700 mb thickness was used instead of the 12 hour forecast. The 24 hour thickness forecast for Oklahoma City was 164.3 decameters. For comparison purposes only, the 12 hour LFM 850-700 mb thickness forecast for Oklahoma City was 164.4 decameters. The forecast high temperature for Oklahoma City that day was 85 degrees (from the early morning package). A weak cold front was expected to move slowly southward through the northwestern half of Oklahoma during the day. It appeared that surface dewpoints in advance of this front would remain in the upper 60s throughout the day. As a result, a surface wet-bulb potential temperature of 23.5 degrees Celsius was expected during the late afternoon. The low level forcing was expected to be average (from Figure 14) and the upper level forcing was forecast to be neutral/weak (vorticity increased by 3 radians/second in 12 hours). Thus, when considering both the low level and the upper level (Table 1), the overall forcing was expected to be average. Using the forecast surface wet-bulb potential temperature of 23.5 degrees, the forecast 850-700 mb thickness of 164.3 decameters and the middle line from Figure 5, it appeared that convection would fire in or near the Oklahoma City area. The lid was weaker in northeastern Oklahoma than in southwestern Oklahoma and the surface wet-bulb potential temperatures were expected to be higher in central and northeastern Oklahoma than in the southwest. Therefore, if convection developed, it would likely start along the boundary in northeast Oklahoma and build southwestward towards Oklahoma City.

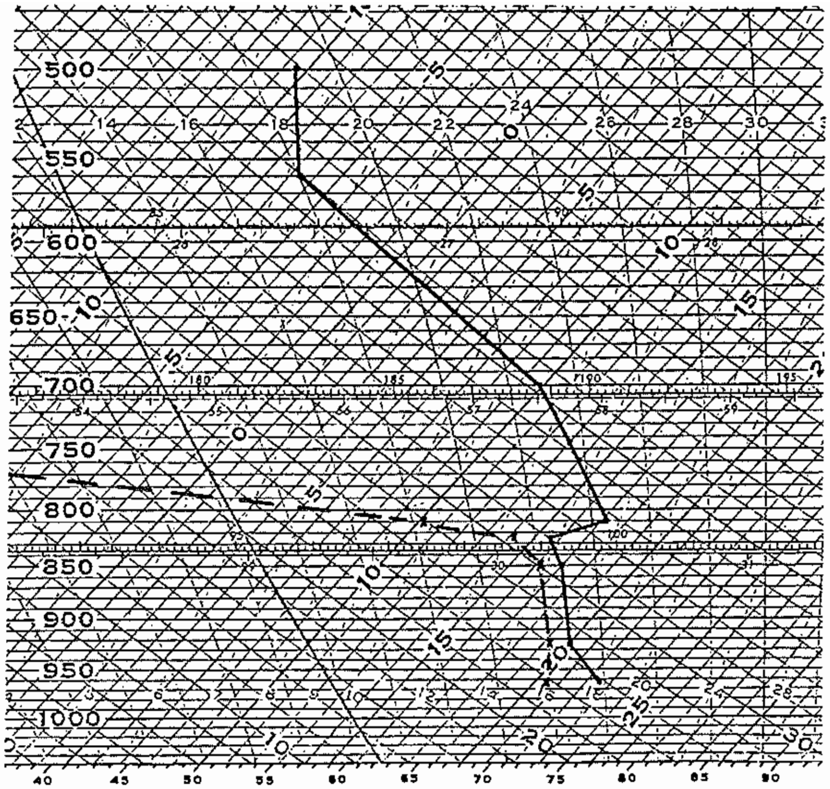

FIGURE 12. Sounding from Norman, Oklahoma at 1200 GMT on May 19, 1990. Solid line represents temperature profile and dashed line represents moisture profile.

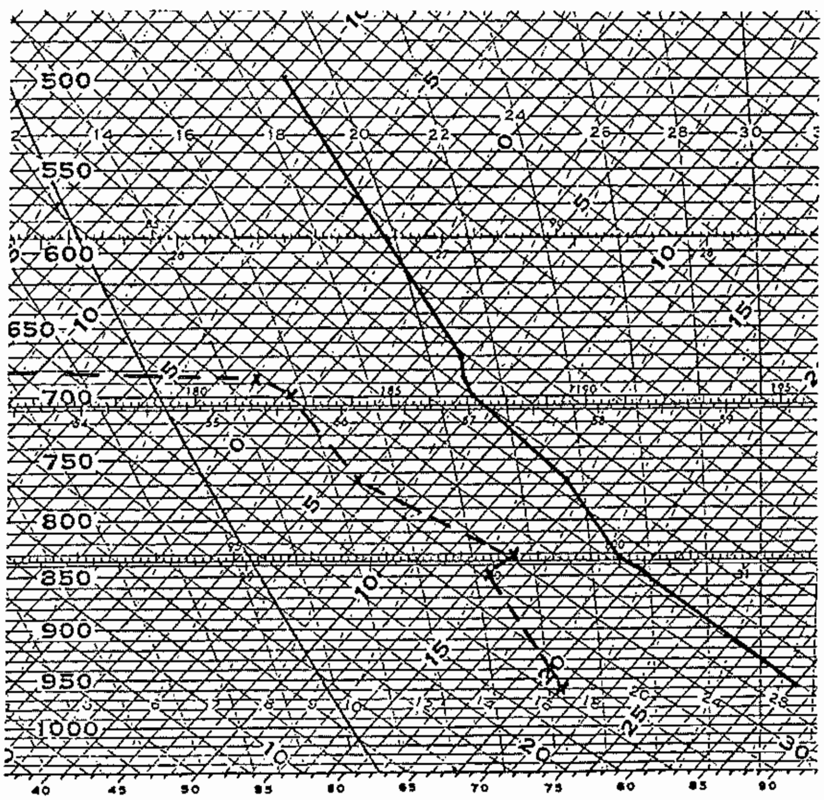

FIGURE 13. Sounding from Norman, Oklahoma at 0000 GMT on May 20 1990. Solid line represents temperature profile and dashed line represents moisture profile.

The high temperature in Oklahoma City on May 19th was actually 90 degrees with surface dewpoints late in the day in the upper 60s. The resulting surface wet-bulb potential was just above 23.5 degrees Celsius. The sounding from Norman, Oklahoma at 0000 GMT on the 20th (Figure 13) showed only a hint of the elevated mixed layer from the morning. The actual 850-700 mb thickness was 164.2 decameters. Late in the day, the surface front extended from northeast to southwest across the state and by 0000 GMT the front was located just north of Oklahoma City (Figure 14).

Convection developed along the cold front near Tulsa, Oklahoma during the early afternoon hours and developed slowly southwestward into the Oklahoma City metropolitan area by late in the day. Numerous reports of large hail were received from just west of Oklahoma City to near Tulsa. A location in Northwest Oklahoma City received hail larger than 3/4 inch 5 different times during the evening and nightime hours. The largest hail that fell at this location was greater than 3 inches in diameter.

On this particular day the NGM 850-700 mb thickness forecast was nearly flawless and the charts developed in this study worked quite well. Note, in southwestern Oklahoma the 850-700 mb thickness forecast was 164.3 decameters and the late afternoon surface wet-bulb potential temperature was 21.5 degrees Celsius. Applying these numbers to Figure 3, it appeared that convection was unlikely in southwest Oklahoma. The farthest westward extent of the convection is shown in Figure 15.

CASE STUDY 2-June 1st 1990

In this case the area of interest was near Huron, South Dakota. The surface weather map on the morning of June 1st 1990 showed a cold front moving through the high plains of the western Dakotas. Surface dewpoints were near 60 during the morning hours in advance of the front across most of the northern and central Plains. The cold front was expected to approach Huron, South Dakota during the late afternoon or early evening hours. Afternoon temperatures were expected to be in the upper 70s with dewpoint temperatures in the low to mid 60s. The NGM 12 hour 850-700 mb thickness forecast for this area was 165.0 decameters and the maximum surface wet-bulb potential temperature was expected to be around 22.0 degrees Celsius. The low level forcing was expected to be average, while the upper level forcing was forecast to be neutral/weak (vorticity increasing by 3 radians/second in 12 hours). Thus, when considering both the low level and the upper level forcing (Table 1), the overall forcing was expected to be average. Using the forecast surface wet-bulb potential temperature of 22.0 degrees, the forecast 850-700 mb thickness of 165.0 decameters and the middle line from Figure 3, convection was not expected to develop along the cold front near Huron, South Dakota.

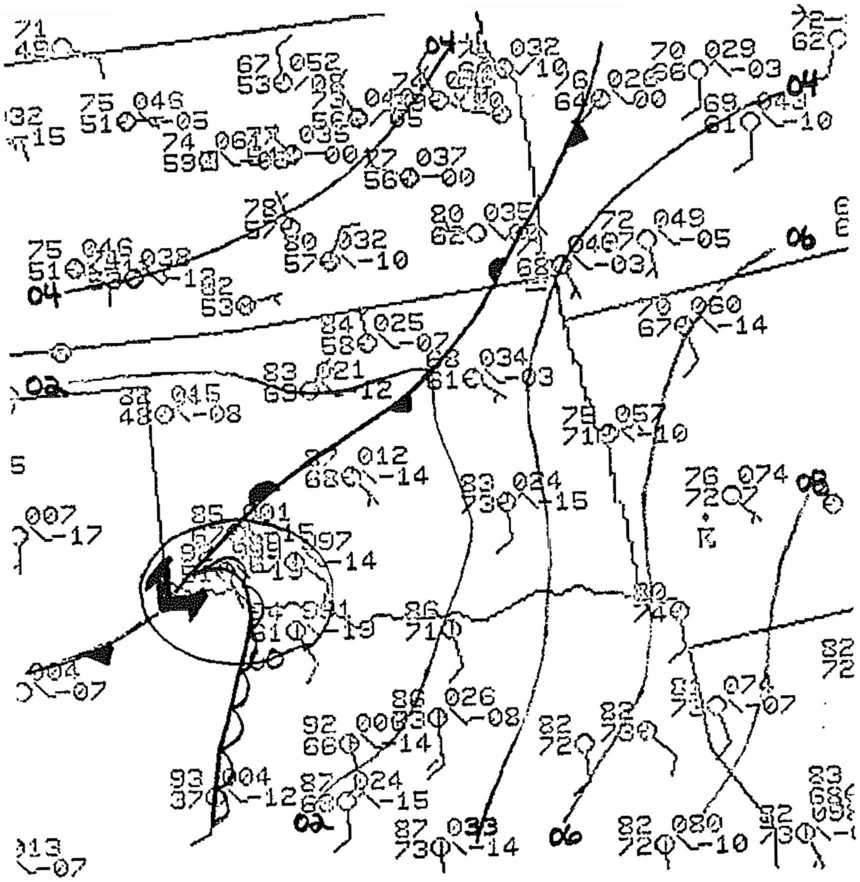

FIGURE 14. Surface Map at 0000 GMT May 20, 1990.

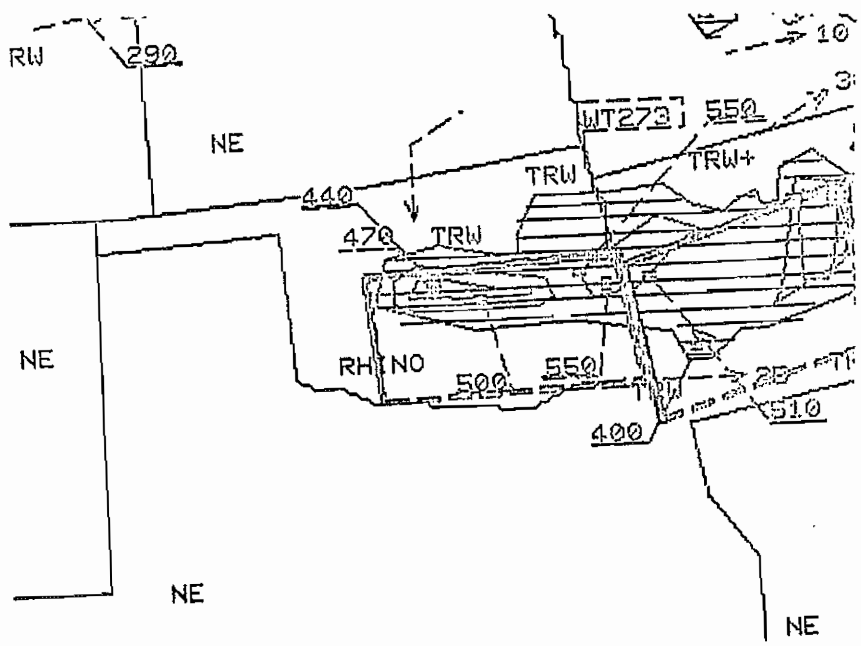

FIGURE 15. Radar Composite Chart at 0335 GMT May 20, 1990.

At 0000 GMT on the 2nd the temperature in Huron was 77 degrees with a dewpoint temperature of 66 (not shown). The cold front was located about 40 miles west of Huron at 0000 GMT. Strong convection associated with the cold front moved into the Huron area shortly after 0000 GMT.

This forecasting scheme did not work in this case due to a large error in the forecast 850-700 mb thickness field. The actual 850-700 mb thickness was 163.0 decameters, while the forecast thickness was 165.0 decameters. Note, if the NGM had forecast the correct 850-700 mb thickness, strong convection would have been expected (Figure 2). The 0000 GMT sounding from Huron, South Dakota (Figure 16) shows only a small capping inversion located above 700 mb.

CONCLUSION

The results of these two forecasting techniques should aid the operational forecaster in determining the probability of strong convection in a capped environment. These results are directly dependent upon the accuracy of the forecast maximum afternoon surface wet-bulb potential temperature. The techniques presented here are also significantly influenced by the accuracy of the NGM forecast. In general, the NGM provided an accurate forecast of the 850-700 mb height fields (technique 1) and temperature fields at 9000 feet (technique 2). For both of these techniques, the operational forecaster predicts the afternoon maximum surface wet-bulb potential temperature along and just ahead of the surface boundary and the strength of the low level and upper level forcing. The low level forcing and the maximum surface wet-bulb potential can change rapidly, especially if an intense upper level short wave is approaching. As a result, even with a accurate forecast of the 850-700 mb heights and the temperature at 9000 feet, this scheme may fail in a rapidly changing situation.

These techniques, to be used with other forecasting tools and rules of thumb, are primarily designed to be used during the morning update for the afternoon. However, these results could be used beyond that to gain some insight into a developing situation. More than likely, the forecast accuracy of the NGM decreases as the forecast time increases. When looking beyond a 12 hour forecast, the trend of the model forecast may be more important than the actual forecast.

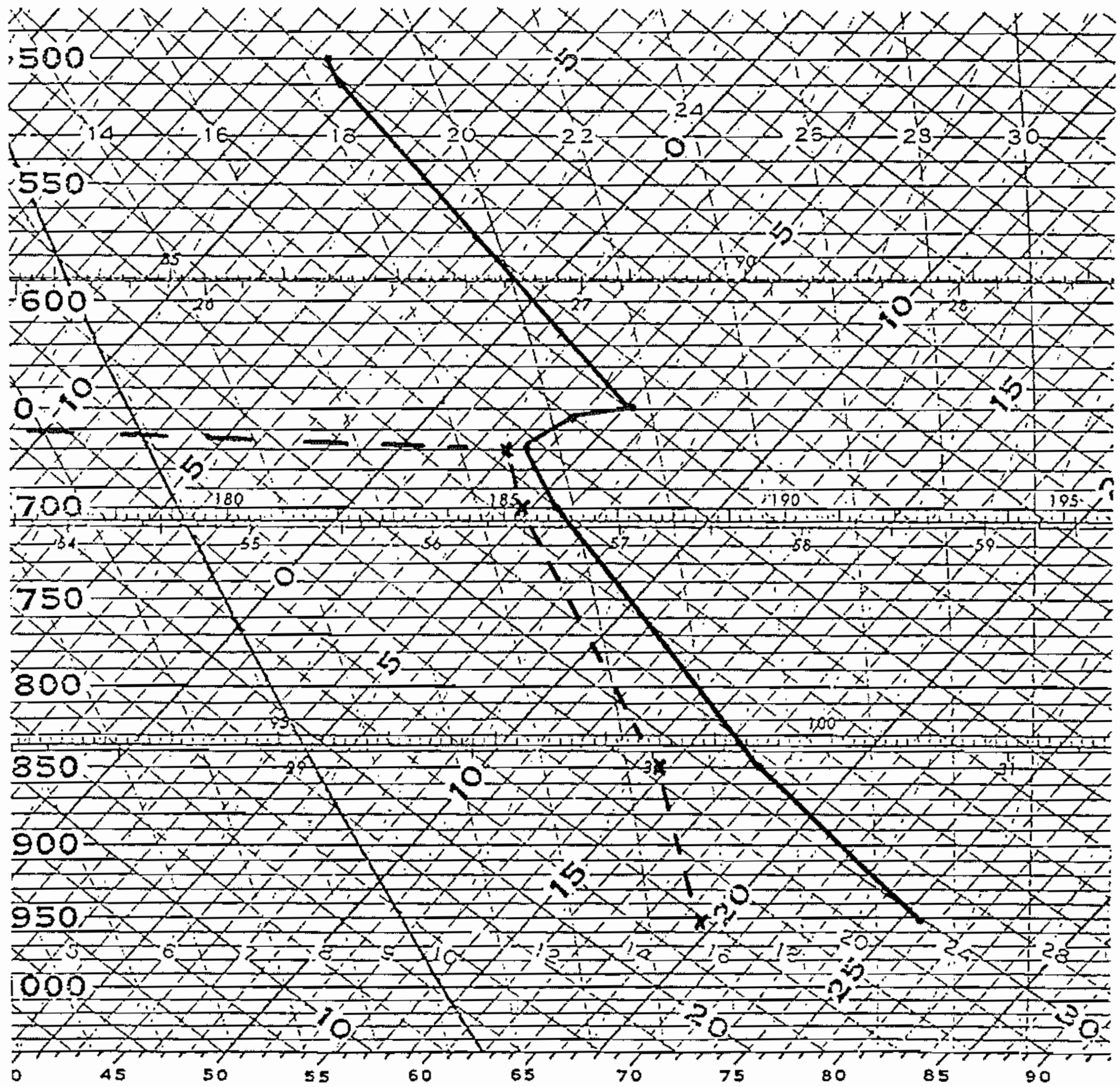

FIGURE 16. Sounding from Huron, South Dakota at 0000 GMT on June 2, 1990. Solid line represents temperature profile and dashed line represents moisture profile.

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