3A.6 A CASE STUDY OF THREE SEVERE TORNADIC STORMS IN ALBERTA, CANADA

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1. INTRODUCTION

The Rocky Mountains are an impressive north-south mountain barrier extending 2400 km from Yukon to Texas. The impact on of the mountains is particularly evident in Alberta, whose boundaries extend from 49° to 60° N and 120° to 110° W, with the southwestern border following the Continental Divide (Fig.1). Central Alberta is highly susceptible to severe convection, having on average 52 days with hail fall each summer (Smith et al. 1998). Alberta thunderstorms that spawn tornadoes occur far less frequently (Newark 1984; Bullas and Wallace 1988). Hage (1994, 2003) compiled an extensive tornado climatology starting from 1879. He found that on average 10 tornadoes occur over Alberta each summer. A major mandate of a weather forecasting office (like the Meteorological Services of Canada) is to issue timely warnings of severe storms so that appropriate safety measures can be implemented. The forecasting of severe convective storms producing tornadoes will become increasingly important as the populated areas of Alberta continue to expand.

This study is focused on the evolution of three severe convective storms that spawned tornadoes in Alberta. We chose the three convective storm cases that had the most intense tornadoes recorded during 1983-2003. The cases were: The Edmonton storm of 31 July 1987 that resulted in 27 fatalities deaths and 250 million dollars of property damage (Bullas and Wallace 1988; Charlton et al.1998), the Holden storm of 29 July 1993 (Knott and Taylor 2000), and the Pine Lake storm of 14 July 2000 that resulted in 12 fatalities and 13 million dollars property damage (Joe and Dudley 2000; Erfani et al. 2002). The Edmonton tornado was classified as an F4 tornado on the Fujita F-scale (Fujita 1981). The detailed climatology of Alberta tornados compiled by Hage (1990, 2003) showed that the Edmonton tornado was the only case of an F4 tornado in Alberta during recorded history. The Holden and the Pine Lake tornados were both F3 cases. There were no other recorded F3 tornadoes in Alberta during the period 1983-2003.

We made a synoptic analysis of the three tornadic storms with an emphasis on the surface moisture and storm tracks. The development of these storms was compared to the conceptual model for severe convection suggested by Smith and Yau (1993a,b). They identified two stages leading to the formation of severe convective storms. Stage 1 is characterized by clear skies in subsiding air ahead of an approaching upper-level ridge. A strong inversion in the lower troposphere inhibits or “caps” any deep convection. Upper level warming produces a minimal amount of Convective Available Potential Energy (CAPE). There might be some shallow convection along the foothills as daytime heating removes the cap locally (Reuter and Nguyen 1993). Synoptic pressure gradients favor a light westerly flow which transports low-level moisture away from the foothills. Weak to moderate upper-level winds are associated with relatively weak wind shear. Convective activity is limited to cumulus clouds and isolated thunderstorms along the foothills.

Stage 2 of the conceptual model begins once the upper-level ridge moves eastward and an upper-level trough approaches. Convection again begins along the foothills during the day. However, strong cooling aloft and surface heating combine to form a large amount of CAPE. The synoptic pressure gradient over the plains now favors an easterly or southeasterly flow which advects moist air into the low-levels below the capping lid. There is a continued buildup of latent energy forming a “loaded gun” sounding. Localized convergence begins to break down the capping lid and vigorous convective storms form along the foothills. These cumulus towers move eastward with mid-tropospheric westerlies. The strong mid-level southwesterly flow ahead of the advancing trough combines with the intensifying low-level southeasterly flow causing strong vertical wind shear. A major consequence of the vertical shear is that the convection becomes organized into long-lasting multicell or supercell storms.

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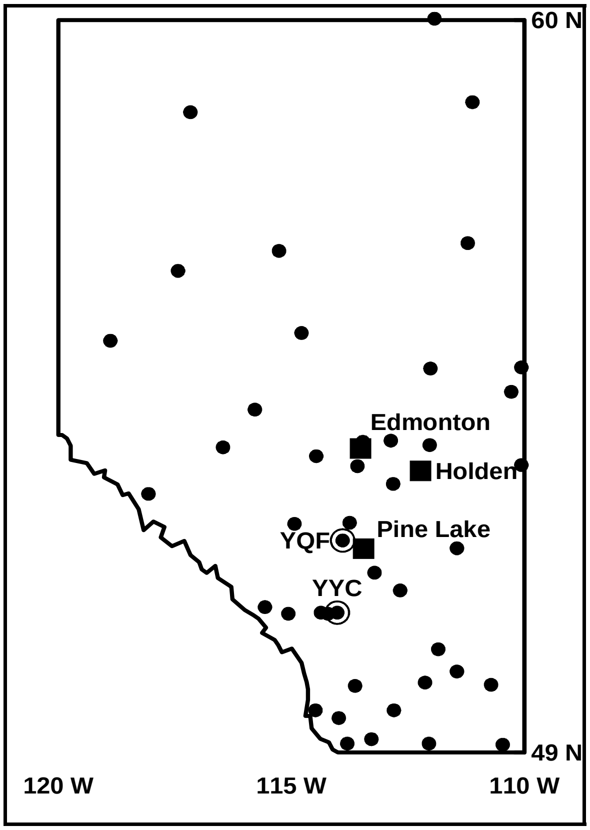

Fig. 1. Location of surface weather observing stations (dots) within the province of Alberta. The squares show the sites of the Edmonton, Holden, and Pine Lake storms, and the circles show the cities of Red Deer (YQF) and Calgary (YYC).

Supercells tend to form in huge CAPE conditions and strong veering occurs below cloud base level (Chisholm and Renick 1972). The focus of our research is on stage two of development which results in severe thunderstorm outbreaks. Smith and Yau (1993a,b) outline four conditions which are associated with the occurrence of severe storms: a large amount of CAPE, a capping inversion allowing the build up latent energy, large wind shear, and a trigger to break the cap to release the latent energy. These ingredients are similar to those identified by other researchers (e.g. Fawbush et al 1951; Miller 1972). Synoptic features for the three thunderstorm events will be compared to determine the validity of Smith and Yau's conceptual model.

A focus of our storm analysis is the evolution of the surface moisture field. Schaefer (1986) suggested that a moisture front triggers thunderstorm development. A moisture front, referred to as a dryline (Fujita 1958), is a synoptic-scale feature that initiates and organizes summertime convection (e.g. Rhea 1966; Ziegler 1993). The typical criterion for a dryline is a dewpoint gradient of 10 °C/100 km or more (Schaefer 1974). In addition, the strong dewpoint gradient must last for at least 6 h. The 12 °C isodrosotherm (corresponding to vapor mixing ratio of 9 g kg^{-1}) was found useful to locate the dryline position (Schaefer 1973). In the dry air, temperature soundings typically display dry adiabatic lapse rates through the lower troposphere (Schaefer, 1986), whereas the moist air tends to show a low-level capping inversion. Above the capping lid the air can be well-mixed. The capping lid allows for the buildup of a large CAPE. Thunderstorms that break through the cap can result in supercells. Although the moisture gradient across the dryline is large, the virtual potential temperature contrast is generally small (Ziegler, 1993). A diurnal variation of the moisture gradient often exists (Rhea, 1966) with the afternoon gradient stronger than the early morning gradient.

Continuing increases in computing power have allowed for a steady improvement of the resolution of numerical weather prediction, physical parameterization and initialization. Even so, numerical prediction models cannot resolve the atmosphere to the small spatial scales of individual thunderstorms. Numerical prediction of individual thunderstorms and tornadoes will remain problematic (e.g. Brooks et al. 1992). Thus identifying the key mesoscale and synoptic-scale features in the thermodynamic and wind fields that control the outbreak of severe convection can be useful for forecasting severe thunderstorms.

2. SYNOPTIC STORM ENVIRONMENT

Table 1 lists the beginning and end times of the three thunderstorms which spawned each of the tornadoes. The times for touching the ground were: 2100-2200 UTC for the Edmonton Tornado, 0345–0405 UTC for the Holden Tornado, and 0045-0115 UTC for the Pine Lake Tornado. The 0000 UTC synoptic charts were chosen for the diagnostic analyses of the three storms. The Pine Lake thunderstorm was well developed at 0000 UTC. The Edmonton thunderstorm was still active at 0000 UTC with the tornado dissipating. The Holden thunderstorm was developing at 0000 UTC (Knott and Taylor 2000) with the tornado occurring later.

The 500 mb charts valid for 0000 UTC for the Edmonton, Pine Lake and Holden cases are depicted in Fig. 2. All three cases show a trough located over central British Columbia and a leading ridge extending over Saskatchewan. The synoptic pattern was consistent with the Smith and Yau model, which describes an approaching upper level trough and a ridge moving east of Alberta. The wind speeds at this level over central Alberta were similar in all three cases, ranging from 23 to 29 m s^{-1}. The wind direction during the Edmonton and Holden storm was southerly while the Pine Lake storm had a southwest direction.

At 850 mb a trough, or low pressure area, was over central Alberta for both the Edmonton (Fig. 2b) and Holden storms (Fig. 2d). This feature would maintain an easterly flow into the storm areas throughout the events. Meanwhile the Pine Lake case showed a trough over extreme eastern Alberta, well to the east of the storm location (Fig. 2f). The location of this trough resulted in a north flow across central Alberta. All three cases showed a baroclinic zone over central Alberta. The 850 mb temperature gradient over the baroclinic zone was about 3-4 °C /100 km.

TABLE 1. A comparison between the Edmonton, Holden, and Pine Lake Tornadoes. The parameters are described in the text.

	Edmonton	Holden	Pine Lake
Tornado intensity (Fujita scale)	F4	F3	F3
Maximum hail size (cm)	10	8	4
Number of fatalities	27	0	12
Insured property damage ($ million)	250	3	13
Start time of tornadic storm	1900 UTC 31 July 1987	0100 UTC 29 July 1993	2000 UTC 14 July 2000
End time of tornadic storm	0000 UTC 01 August 1987	0400 UTC 30 July 1993	0200 UTC 15 July 2000
Start time of tornado track	2100 UTC 31 July 1987	0345 UTC 29 July 1993	0045 UTC 15 July 2000
End time of tornado track	2200 UTC 31 July 1987	0405 UTC 29 July 1993	0115 UTC 15 July 2000
500 mb wind speed (m s^{-1})	29	24	23
500 mb wind direction	170º	180º	220º
850 mb wind speed (m s^{-1})	9	1	7
850 mb wind direction	100º	150º	350º
12 h ΔT (°C) at 500 mb	+0.4	+0.6	-2.8
12 h ΔT (°C) at 850 mb	+4.0	+3.0	-4.4
Surface temperature (°C)	25	26	23
Surface dewpoint (°C)	19	17	14
Cloud base MSL (km)	2.0	2.0	1.8
Cloud base temp (°C)	15	14	13
Precipitable Water (mm)	34	30	23
$\Delta T / \Delta x$ (°C/100 km) at 850 mb	3.3	4.3	2.7
CAPE (J kg^{-1})	2690	3290	2250
Lifted Stability Index	-8,6	-8.8	-8.2
Wind shear 0-6 km (m s^{-1} km^{-1})	5.1	5.2	4.0
Bulk Richardson Number	13	42	18

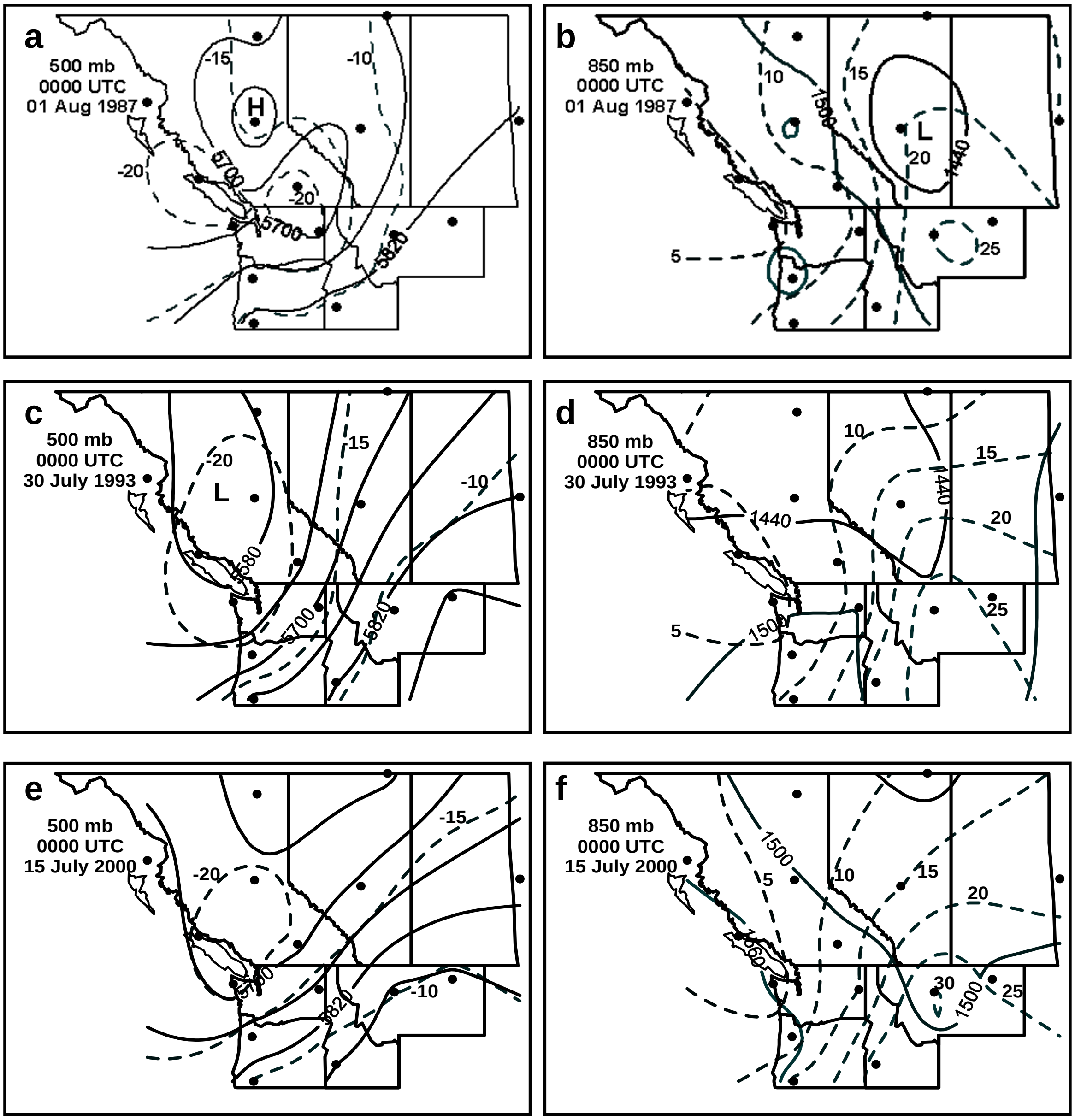

Fig. 2. 500 mb and 850 mb height contour maps at 00 UTC for the Edmonton tornado (top panel), Holden tornado (middle panel) and Pine Lake tornado (bottom). Geo-potential heights (solid) are contoured every 60 m, isotherms (dashed) are contoured every 5°C.

At the surface the Edmonton storm had a similar pattern to the Holden storm (Knott and Taylor 2000) with both showing a low pressure center just west of Edmonton. Meanwhile, the Pine Lake storm had a low pressure center well into Saskatchewan indicating the more rapid eastward progression of the synoptic pattern than the other two events.

The 12-h temperature change (ΔT) profile is shown in Fig. 3. The ΔT is the change from the 1200 UTC (morning) sounding to the 0000 UTC (evening) sounding on the day of each tornado event. Fig. 3 indicates that the Edmonton storm profile showed warming ($\Delta T > 0$) throughout most of the column. Only a narrow region from about 700 to 750 mb showed some cooling. This suggested that the airmass destabilized due to differential advection. The Smith and Yau conceptual model suggests that mid-upper level cooling is likely, implying that the Edmonton storm differs somewhat from the model. The Holden storm showed significant warming below about 800 mb (the surface warmed by about 11 °C) coupled with cooling of the mid and upper levels from about 800 to 550 mb. This pattern is consistent with the conceptual model of Smith and Yau which has mid-upper level cooling initiated by an advancing trough while the low levels are warmed through daytime heating. Meanwhile the Pine Lake case showed warming in the boundary layer (from the surface to about 900 mb) and cooling at all levels above. The cooling in the mid-upper levels was greater than in the lowest level which served to destabilize the airmass.

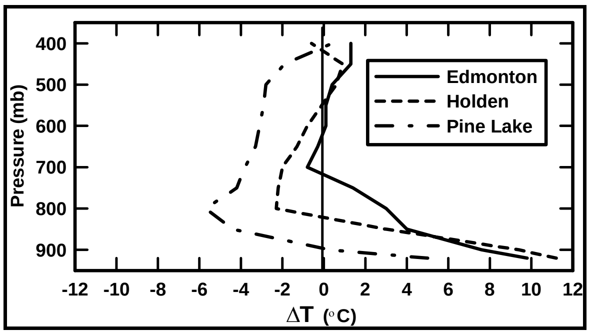

Fig. 3. Vertical profile of the 12-h temperature change (ΔT) from 12 UTC to 00 UTC for the three tornado cases.

3. SOUNDING ANALYSIS

When examining the convective stability properties of the storm environment it is crucial to use a proximity sounding that indeed contains the thermodynamic profiles of the airmass that feeds the convection. Since the convective environment is not uniform in space and time, it is important to select a sounding representative for the storm environment (Brooks 1994). Monteverdi (2002) suggests to use the observed sounding that is nearest in space and time, or alternatively to interpolate the upper-air data to the time and space of the event. Both approaches estimate the mesoscale thunderstorm environment from synoptic-scale observations.

We have adopted the following approach to synthesize proximity soundings for the three tornadic storm cases. We made low-level adjustments to the temperature and dewpoint observations sampled by a balloon sounding released from Stony Plain (WSE), located about 40 km west of Edmonton (Fig. 1). The local surface temperatures and dewpoints for each storm were obtained by extrapolating from the nearest neighbouring weather reporting sites. The temperature profile was then adjusted below 850 mb to ensure that the ambient temperature was adiabatic. The dewpoint values for heights above the surface were not modified for the Edmonton and Holden storms. For the Pine Lake event, however, the 900 mb dewpoint profile was smoothed to eliminate a large decrease in value between the surface and 850 mb.

The 1200 UTC sounding from WSE for the Edmonton tornado (Fig. 4a) represented conditions prior to thunderstorm development. Very moist conditions prevailed from the surface to about 770 mb. Capping lids were evident at 850 mb and 730 mb. The lower capping lid was consistent with the conceptual model of a pre-thunderstorm environment, however, the second cap could even add even more to the buildup of CAPE. Over-coming both caps by surface heating alone would require the surface temperature to reach 30 °C. Above the two capping lids there is a significantly drier layer. The wind data sampled by the b alloon sounding were not recorded at 1200 UTC.

The 1200 UTC sounding for the Holden storm is shown in Fig. 4c. In this case there is only one capping lid located at about 800 mb. This single cap is more typical of the conceptual model. Overcoming this cap by surface hearting alone would require a temperature of about 30 °C, similar to the Edmonton case. The Holden storm environment was drier compared to the Edmonton tornado storm case. For the Holden case, the air was close to saturation only the near surface. The observed wind profile showed weak flow below the cap with veering indicative for low-level warm air advection. The flow became stronger aloft blowing from the southwest at mid-levels. The hodograph was consistent with the conceptual thunderstorm model of Smith and Yau.

The 1200 UTC sounding for the Pine Lake storm environment is depicted in Fig. 4e. A capping lid was evident at about 850 mb but the inversion was weaker compared to the Holden case. The surface temperature would have to reach 27 °C to break the capping lid by surface heating alone. The Pine Lake sounding was the driest of the three cases, showing no layers with saturated air. The Pine Lake wind profile was similar to that of the Holden case. Below the capping lid the wind was weak. Above the cap the flow became strong blowing from the southwest in the upper levels. The soundings for all three cases showed a low- level capping lid allowing for the

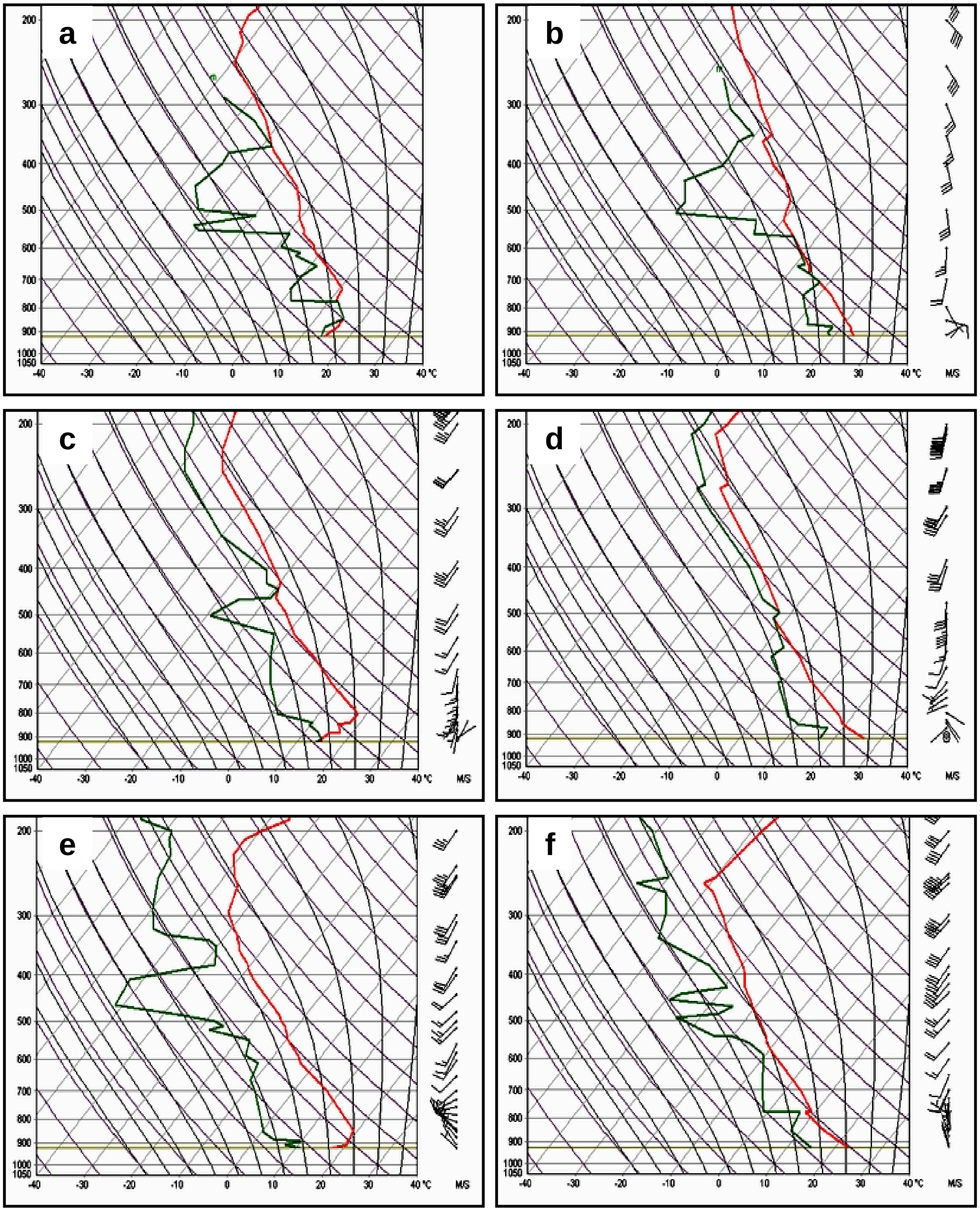

Fig. 4. Skew T-log *p* diagrams for the Edmonton tornado (top panel), the Holden tornado (middle panel), and the Pine Lake tornado (bottom panel) for a) 00 UTC, b) 12 UTC, c) 00 UTC, d) 12 UTC, e) 00 UTC, and f) 12 UTC. Wind vectors (in m s^{-1}) are shown at selected pressure levels at the right of each sounding.

buildup of CAPE, consistent with the Smith and Yau's conceptual storm model.

The 0000 UTC sounding for the Edmonton tornado (Fig. 4b) depicts environmental conditions about 2 hours after the tornado had dissipated, but with the thunderstorm still active. The low-level temperatures and dewpoints were adjusted towards the observed values of surface temperature (25°C) and dewpoint (19 °C). There was several degrees of warming from the surface to about 730 mb which was evident from the 850 mb synoptic pattern (Fig. 2b) This low level warming has eliminated the caps. There is also drying from 850 to about 790 mb. There was very little temperature change above 700 mb. The winds in the low levels remained light easterly which continued to advect moist air. Above this the winds veered to southerly which increased the moisture in the mid levels causing a near saturated layer from 700 mb to about 550 mb. This is slightly different than the conceptual model which would suggest a drier southwest flow in the mid-levels as the upper trough approaches. The 0000 UTC sounding for the Holden storm (Fig. 4d.) shows that the boundary layer remained moist with drier air above. Also similar to the Edmonton storm, a south flow in the mid levels has resulted in a nearly saturated layer from 600 to 500 mb. The 0000 UTC sounding for the Pine Lake storm (Fig. 4f) follows the conceptual model more closely than the previous two cases. Significant cooling occurred from just above the surface to about 400 mb, consistent with the approaching upper trough. The 12-h surface temperature change was only a few degrees indicating that low level heating alone was not the main factor in breaking the cap. A drier southwest flow in the mid-upper levels did not allow for saturation of the airmass at those levels, unlike the Edmonton and Holden cases.

Fig. 5a compares the wet-bulb potential temperature (θ_w) profiles for the three cases. All three storms indicated the presence of convective instability below 850 mb (as indicated by a decrease in θ_w with increasing height). The Edmonton and Holden storms had roughly similar θ_w profiles below 850 mb while the Pine Lake case had smaller θ_w values. While the Holden and Pine Lake storms remained unstable above 800 mb, the Edmonton case showed a neutral and a stable layer between 800 and 700 mb. The Edmonton storm was much warmer in the mid-levels than the other two, with the Pine Lake case being consistently coolest. The mixing ratio (q_w) profiles (Fig. 5b) show the Edmonton storm consistently having the greatest moisture from the surface to 600 mb. Overall, the Edmonton storm was the warmest and contained the highest moisture of the three cases.

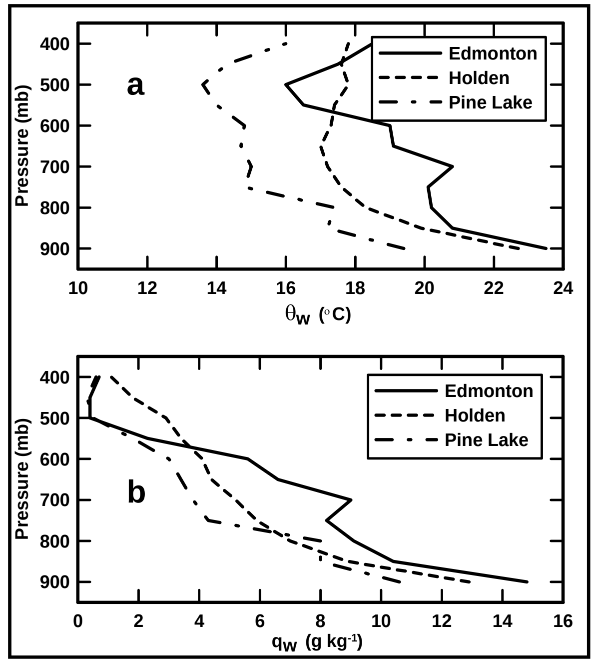

Fig. 5. Vertical soundings of a) wet-bulb potential temperature (θ_w in °C), b) vapor mixing ratio (q_w in g kg^{-1}) for the Edmonton, Holden, and Pine Lake storms.

Table 1 compares the three events. The Edmonton Tornado was the moist intense (F4) on the Fujita damage scale. The 500 mb 12-h temperature changes showed a slight warming in the Edmonton and Holden storms, while the Pine Lake storm cooled by about 3 °C. At 850 mb the 12-h temperature showed warming of 3-4 °C during the Edmonton and Holden storms, unlike the Pine Lake event which cooled by about 4 °C. The difference of temperature advection at 850 mb also shows up in the 850 mb wind direction. The 850 mb wind blew from the southeast for the Edmonton and Holden storms, whereas the Pine Lake storm had a northerly wind of 7 m s^{-1}. The Edmonton storm sounding had the highest Precipitable Water of 34 mm. The Holden storm had a Precipitable Water of 30 mm, while the Pine Lake storm was the driest at 23 mm. Dupilka and Reuter (2004) found that for Alberta a good correlation exists between the observed 24 hour maximum accumulated snowfall and the amount of atmospheric moisture in organized baroclinic weather systems. The Precipitable Water can certainly impose a limit on the convective precipitation in Alberta throughout the year (Reuter and Aktary 1995).

All three soundings had very high values for Convective Available Potential Energy (CAPE), exceeding 2200 J kg^{-1}. The Holden storm showed a CAPE that was about 25% or more greater than the other two. The mean 0-6 km wind shear (SHEAR) for the Edmonton and Holden storms was high (> 4 m s^{-1} km^{-1}). Rasmussen and Wilhelmson (1983) found that storm environment with CAPE values exceeding 2500 J kg^{-1} combined with SHEAR values exceeding 3.5 m s^{-1} km^{-1} often produced severe convection with tornadoes. The Bulk Richardson Number (BRN), defined as BRN = CAPE / (½ $SHEAR^2$), quantifies the ratio of the vertical component relative to the horizontal component of the kinetic energy. As the BRN number decreases, the multicell convection becomes better organized, and at small enough values, quasi-steady supercell convection may occur. According to Weisman and Klemp (1982, 1986), a storm environment with high CAPE value and a BRN value less than about 50, tends to cause the formation of a supercell storm, whereas a BRN larger than 50 tends to produce multicell storms. The BRN of all three storm environments was less than 50: Holden storm had BRN=42, the Pine Lake storm had BRN=18 and, the Edmonton storm BRN=13. Consistent with the Weisman and Klemp's criterion, all three soundings produced organized supercells. The maximum reported hail size diameters for the Edmonton and Holden storms were near 8-10 cm while the Pine Lake storm produced about 4 cm hail. This is likely a reflection of the higher CAPE and Precipitable Water values in the Edmonton and Holden storms.

4. DRYLINE ANALYSIS

As discussed in the introduction, the dry line is a synoptic-scale moisture front usually marked by the 12 °C isodrosotherm. For Central Alberta, the dryline tends to develop when the moist air originating in a southeast flow from the central United States meets the dry air flowing across the Rocky Mountains to the west (Knott and Taylor 2000). As an upper-level trough crosses the mountains, a strong low-level westerly flow develops along the foothills. The westerly flow is significantly drier than the moist southeast flow across the plains. This flow pattern causes a strengthening gradient in low level moisture along the foothills developing into a dryline. The dryline can exist in both quasi-stationary (quiescent) and synoptically active environments (Schaefer 1986). In the quiescent case the dryline lies nearly parallel to the mountains and its motion is largely determined by vertical mixing processes related to the diurnal cycle of heating of the moist and dry air mass. Under these conditions the dryline generally advances eastward during the day time as the dry air mixes with the moist boundary layer and then retreats westward during the evening (Schaefer 1974a,b). Within synoptically active environments, the dryline often extends southward from a surface low pressure system located along a synoptic-scale frontal zone, and therefore can be found much further to the east that in the quiescent case (Hane 2001; Hane et al. 2001). Motion of the dryline in this case is augmented by the motion of the low pressure system and the associated upper level trough's effect on horizontal and vertical wind motions. Very often, the dryline will develop an eastward bulge during synoptically active situations due to convective turbulent mixing of west winds in the dry air causing strong horizontal advection (Schaefer 1986).

Surface atmospheric moisture fields are not standard data available to the forecaster at a weather office. However, hourly humidity measurements are available for the Environment Canada weather stations (Fig. 1). We have used these measurements to plot dewpoint temperature contours for the Edmonton, Holden, and Pine Lake storms.

The dryline analyses for the Pine Lake case is shown in Fig. 6 and Fig. 7. The grey area represents dewpoints of 12 °C and greater and "star" marks the location of Pine Lake. At 1300 UTC (Fig. 6a; the morning of the storm) there was evidence of a dewpoint gradient and dryline forming along the foothills in central Alberta. At this time Pine Lake was along the leading edge of the gradient (12 °C isodrosotherm). A bulge in dryline developed over southern Alberta as the drier westerly flow flowed across the mountains and surfaced east of the foothills in response to the eastward motion of the upper trough. Meanwhile an easterly flow in the low levels was bringing moist air into central Alberta. As the day progressed the dewpoint gradient intensified and the bulge continued to push eastward. By 1800 UTC (Fig. 6b) a stronger dewpoint gradient had formed along the foothills of central Alberta curving northeastward as a bulge continued to develop. The dryline was slightly south of Pine Lake at this time. The orientation of Pine Lake storm dryline differed from typical pattern observed over the southwestern U.S. (Rhea 1966, Schaefer 1986) where the dryline aligns parallel

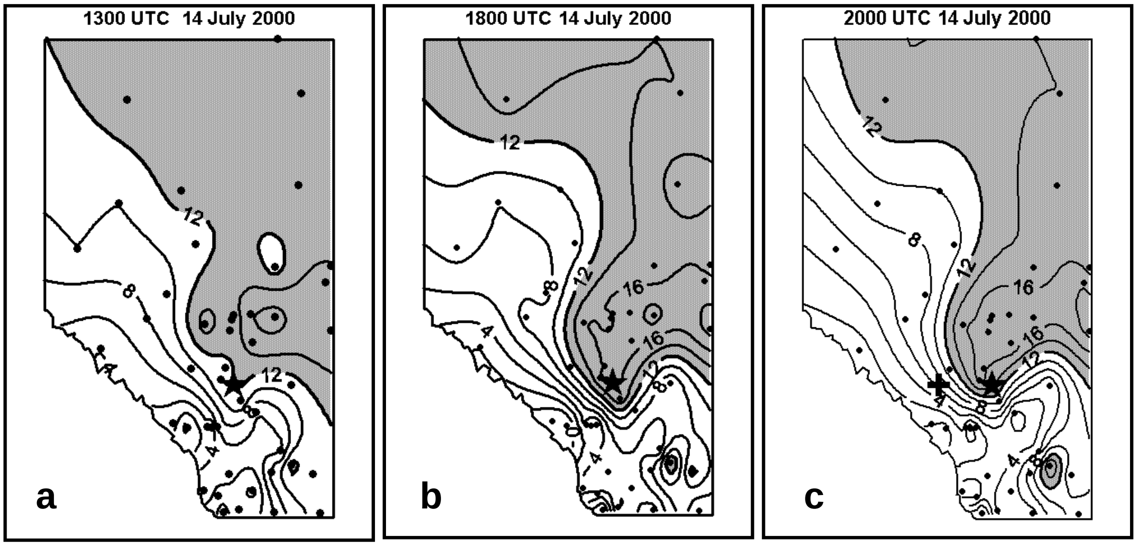

Fig. 6. Contour analysis of surface dewpoint temperatures for a) 13 UTC, b) 18 UTC, and c) 20 UTC 14 July 2000 (Pine Lake storm). Contours are drawn every 2 °C, with shading for T_d > 12 °C. Dots show dewpoint observations, the star shows the Pine Lake storm site, and the cross in c) marks the site of the storm that spawned the tornado.

to the mountains. By 2000 UTC (Fig. 6c) the dryline was well defined just east of the foothills into south-central Alberta and then curving sharply northeast. From 2100 UTC through 0000 UTC (Fig. 7a, b, c, d) the dryline remained quasi-stationary. The thunderstorm cell (indicated by a “cross”) which later spawned the F3 tornado developed and moved eastward along the dewpoint gradient. Due to the orientation of the dryline, the thunderstorm pushed into the area of higher dewpoints which enhanced the CAPE (due to a lower Level of Free Convection). At 0100 UTC the thunderstorm was over Pine Lake and spawned the tornado. The dryline had remained quasi-stationary in terms of intensity and location (Fig. 7e). At 0200 UTC, an hour after the tornado touched at Pine Lake, the dryline (Fig. 7f) dipped southward and the storm continued its track along the dryline. The dip may be due to the cyclonic winds to the rear of the storm center drawing moisture southward.

Knott and Taylor (2000) made a detailed analysis of the dryline for the Holden storm. The dry line pattern was similar to the Pine Lake case. In both cases the dewpoint gradient was strong along the foothills to near Red Deer (see Fig. 1 for locations) and then bulged eastward across central Alberta. Also, in both cases a supercell which spawned the tornado formed near the dryline.

The surface dewpoint analyses for the Edmonton storm are shown in Fig. 8. The “star” marks the location of the city of Edmonton. At 1800 UTC 31 July 1987 the humidity field showed very moist conditions prevailing over all of central Alberta. Dewpoints varied from 14 °C in the west to 18 °C and greater in the east (Fig. 8a). There was no evidence of a defined dewpoint gradient and corresponding dry line. The 1900 UTC and 2000 UTC surface dewpoint patterns (Fig. 8b, c) show little change in the field. Only some weak drying is evident along the foothills. At 2100 UTC, the time of the tornado touchdown, (Fig. 8d) the dewpoints in the Edmonton area were quite uniform near 18°C. At 2200 UTC, the time of the tornado dissipation, (Fig. 8e) a dewpoint gradient developed over southern Alberta, still well to the south of Edmonton. The gradient was increasing slightly in the Edmonton area, but not enough to suggest the formation of a surface dryline in that area. The 12 °C isodrosotherm was well south of Edmonton. At 2300 UTC (Fig. 8f) the drier air continued to push across southern Alberta where the dewpoint gradient was continuing to strengthen. Meanwhile, only a slight increase in the gradient occurred across central Alberta. The 12 °C isodrosotherm remained well south of Edmonton.

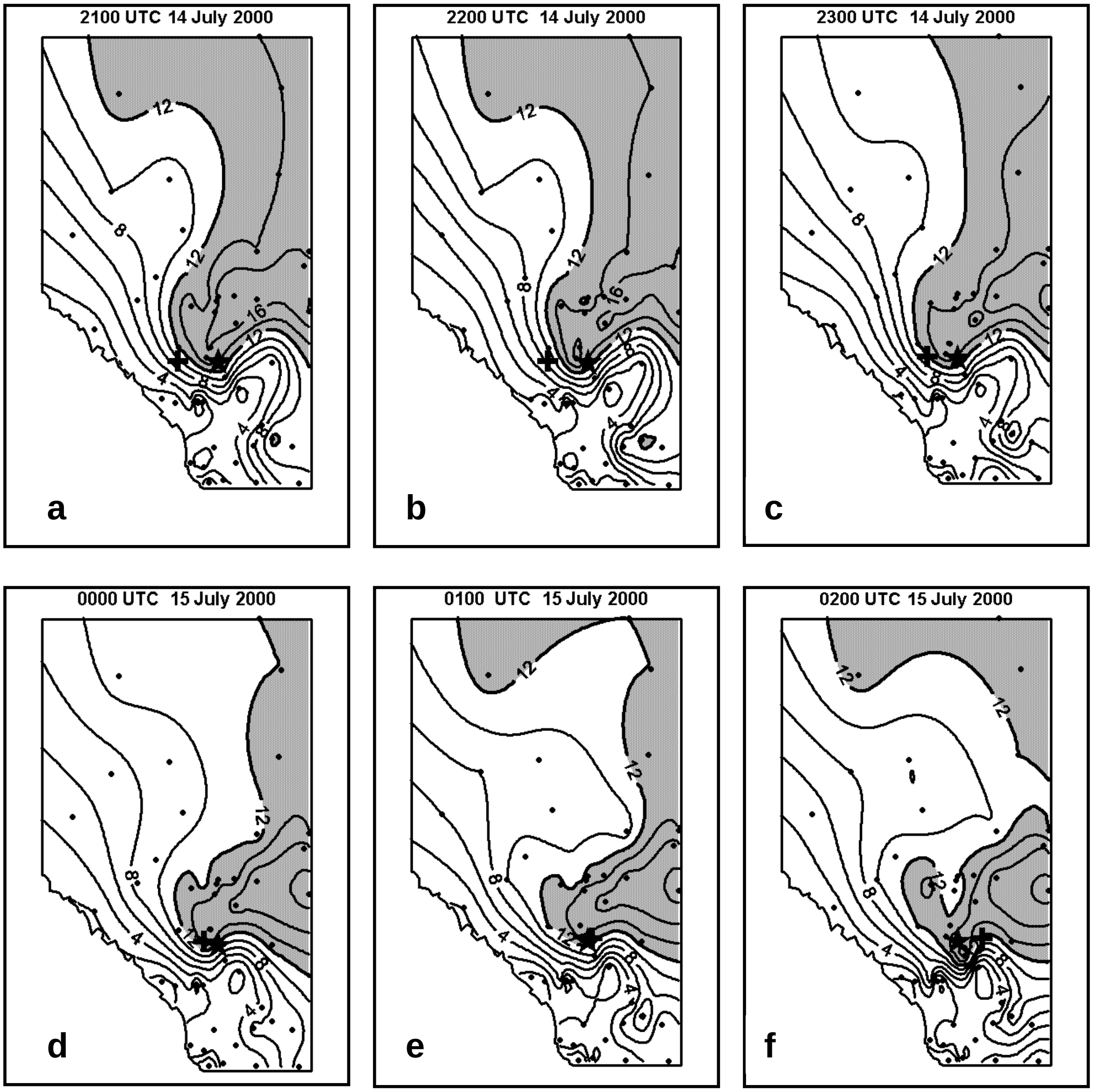

Fig. 7. Hourly evolution of the surface dewpoint field for the Pine Lake storm from 21 UTC 14 July to 02 UTC 15 July 2000. Contours are drawn every 2 °C, with shading for T_d > 12 °C. The cross marks the storm which spawned the tornado.

Fig 9 compares the evolution of the dewpoints at the cities of Edmonton, Red Deer and Calgary for the three storm cases. Edmonton, Red Deer and Calgary are aligned north-south (see Fig. 1) roughly [perpendicular to the moving dryline. The shaded zone indicates the time interval when the tornado touched the surface. The Edmonton storm (Fig. 9a) shows fairly uniform dewpoints at all locations until near the time of the tornado. The three locations were in the moist air away from the dryline (12 °C dewpoint). The dry air began to surface at Calgary (about 300 km south of Edmonton) during the tornado while dewpoints remained high at the other two locations. Only well after the tornado did dewpoints decrease at Edmonton and Red Deer. The Holden case dryline (Fig 9b) advanced northward through Calgary at about 1900 UTC, then Red Deer at about 0000 UTC and finally Edmonton near 0300 UTC, which was about an hour before the tornado

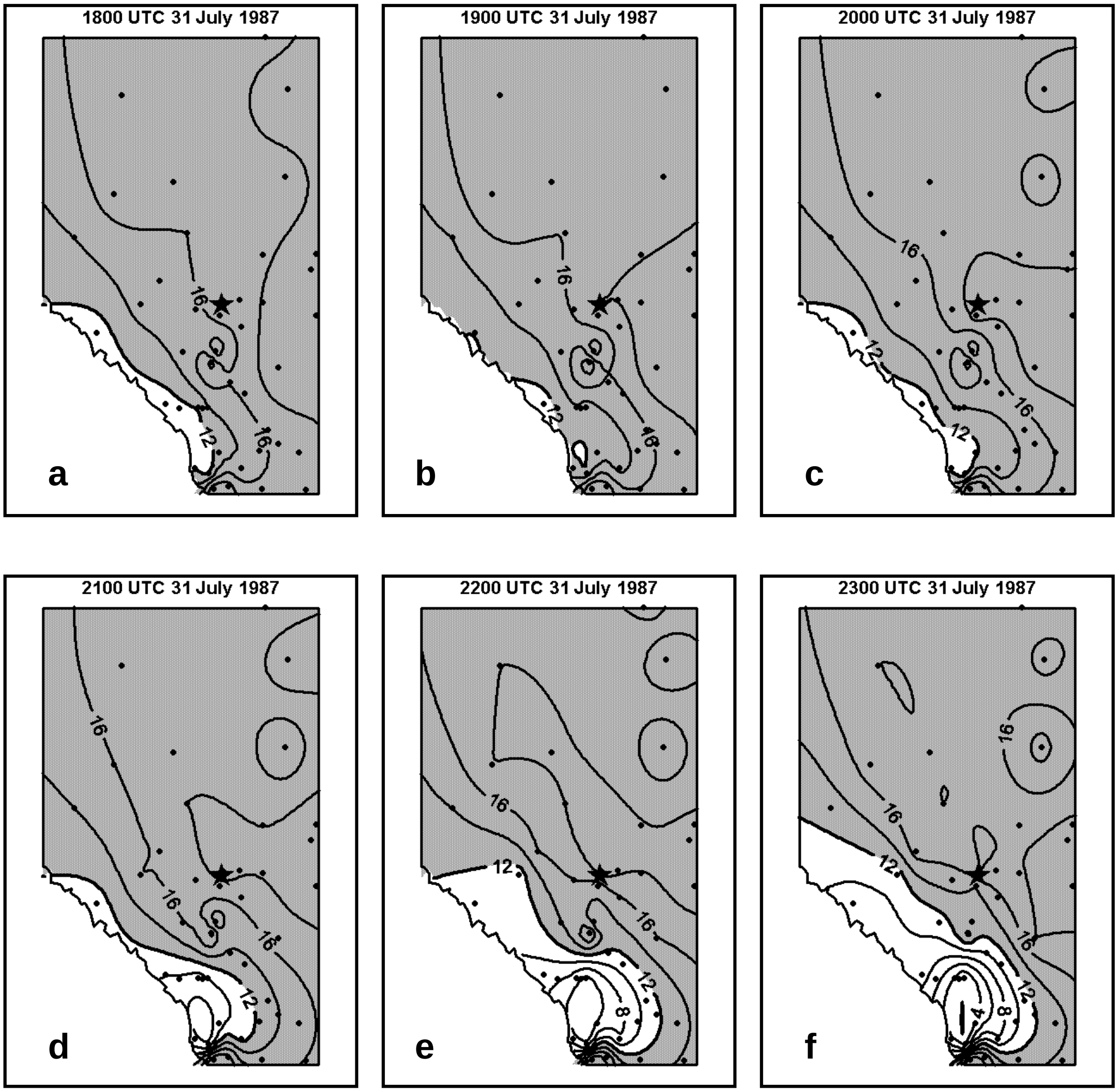

Fig. 8. Hourly evolution of the surface dewpoint field for the Edmonton storm from 18 UTC to 23 UTC 31 July 1987. Contours are drawn every 2 °C, with shading for T_d > 12 °C. The star marks the city of Edmonton.

touchdown. The Pine Lake event (Fig. 9c) showed a quasi-stationary dewpoint regime for most of the duration. Dewpoints at Calgary remained the lowest in the dry air south of the dryline. The dryline remained south of Red Deer until after the tornado. Meanwhile, at Edmonton, the drier air actually began edging into the area from the north (see Fig. 7) as the moist tongue of air across east-central Alberta decreased in extent.

5. STORM TRACKS

Storm track positions were obtained using both ground observations and radar data for the Holden (Knott and Taylor 2000) and Pine Lake (Joe and Dudley 2000) thunderstorms. Observations and archived reports (Charlton, et al. 1998) were used to track the Edmonton storm.
A plot of the hourly positions of the thunderstorm cells which spawned the three tornadoes is shown in Fig. 10. The Edmonton storm sequence began

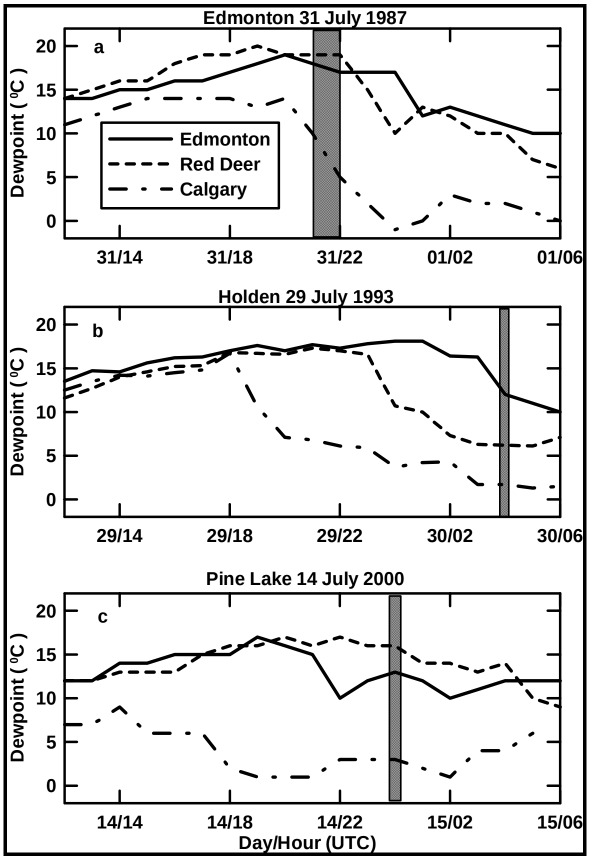

Fig. 9. Evolution of surface dewpoint temperatures (in °C) recorded at Edmonton (solid), Red Deer (short dashed), and Calgary (long dashed) airports for the a) Edmonton, b) Holden, and c) Pine Lake storm events. The shaded zones indicate the approximate duration of each tornado.

at 1900 UTC 31 July 1987 and ended at 0000 UTC 01 August 1987 The Holden storm plot is from 0100 UTC 29 July to 0400 UTC 30 August 1993. The Pine Lake plot is from 2000 UTC 14 July to 0200 UTC 15 July 2000.

The thunderstorm which produced the Edmonton tornado developed along the foothills in the early afternoon (1900 UTC) and then moved eastward at about 40 km h^{-1} (Wallace 1987; Charlton et. al. 1998). Once the cell neared the southern edge of the city of Edmonton it made a sharp turn to the north. The northward track of the storm may be related to the southerly winds observed at mid-levels. There was no Doppler radar at observations sampled prior 1992. The first reporting of a tornado occurred just south of the city of Edmonton at about 2100 UTC (Wallace 1987; Bullas and Wallace 1988). The storm then continued to intensify with the tornado reaching category F4 as it crossed the eastern outskirts of Edmonton between about 2100 and 2200 UTC. The tornado was on the ground for slightly over an hour, from its touchdown south of Edmonton to its dissipation just northeast of Edmonton, stretching a damage path of nearly 40 km. The tornado had an average speed of 35 km h^{-1} (Wallace 1987).

The Holden storm also began near the foothills in the early evening (0100 UTC). This storm moved fairly consistently northeast with a speed of about 50 to 60 km h^{-1} (Knott and Taylor 2000). In this case the 0000 UTC 500 mb wind was south at 29 m s^{-1} which indicated the thunderstorm was moving well to the right of the upper wind. A right moving storm is a common feature of a supercell (e.g. Weisman and Klemp 1986). The estimated path length of the tornado was 17 km.

The Pine Lake supercell storm also had a straight track similar to the Holden storm. case. Both storms were generated along the foothills and then tracked eastward with a speed of about 50 km h^{-1} (Joe and Dudley 2000). The 0000 UTC 500 mb wind for this case was southwest 23 m s^{-1}. As with the Holden storm, the track of the Pine Lake storm was to the right of the upper wind.

6. GEM MODEL SIMULATION OF THE PINE LAKE STORM

The Global Environmental Multiscale (GEM) numerical weather prediction model is used for operational forecasting in Canada. Erfani et al (2002) used this model with a very fine spatial resolution to simulate the evolution of the Pine Lake storm. The non-hydrostatic model had a resolution of 4 km and utilized a detailed microphysical package. As documented by Erfani et al., this high spatial resolution allowed for much better reproduction of the observed storm track. The simulated evolution of the surface dewpoint field closely resembled the synoptic observation. The model output at 2100 UTC 14 July 2000 (Fig 15a in Erfani at al.) created a strong gradient across central Alberta with a bulge to the east similar to Fig 7a. The strongest gradient on both the model and observations occurred to the south of Pine Lake. However, the model gradient was weaker than observed. Also the bulge of drier air pushed further north across the eastern parts of Alberta than the model forecast. The result was a much stronger gradient to the east of Pine Lake than predicted by the model. The GEM model simulations suggest that there was surface wind convergence close to the dryline and this convergence supported the storm development.

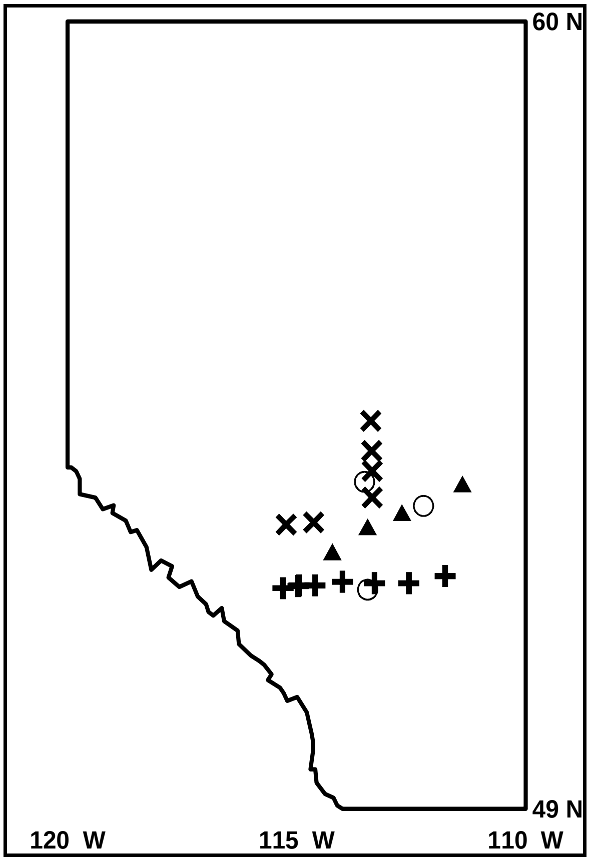

Fig. 10. Thunderstorm tracks plotted every hour for the Edmonton storm (19 – 00 UTC), the Holden storm (01 – 04 UTC), and the Pine Lake storm (20 - 02 UTC). The three circles mark the locations of the tornado sites (see Fig. 2).

The observational data set of surface wind measurements is too sparse to identify surface convergence zones for the Pine Lake storm environment. However, the build-up and maintenance of the strong surface dewpoint temperature gradient was clearly recognizable from the surface station network. The 4 km resolution simulation of the Pine Lake storms suggests that the kinematic pattern of convergence line (that affects the supercell storm development) is associated with the evolution of the dryline.

7. CONCLUSIONS AND IMPLICATIONS FOR FORECASTING

During the last 20 years only three tornadoes occurred with intensities of F3 and F4. The synoptic conditions, the proximity sounding, the surface moisture fields, and storm tracks were analyzed to determine the similarities and differences of the contributing factors. The emphasis was on those observations available at the local forecast office that must issue storm warnings. Our analysis revealed the following major points:

1) All three storms agreed with the evolution of the synoptic flow of the Smith-Yau (1993a, b) conceptual model of Alberta thunderstorm development.

2) All three storms had a pronounced low-level capping lid that allowed for the build-up of huge amounts of Convective Available Potential Energy (CAPE) exceeding 2200 J kg^{-1}.

3) All three storms developed in a baroclinic zone with significant 0-6 km wind shear exceeding 4 m s^{-1} km^{-1}. The Bulk Richardson Number (BRN) of the three storms were 42 (Holden), 18 (Pine Lake) and 13 (Edmonton). These low BRN values agree with the Weisman and Klemp (1982) and Rasmussen and Wilhelmson (1983) criterion for the formation of long-lasting supercells.

4) The build-up of CAPE was caused by differential advection of temperature at various altitudes. In two cases (Edmonton and Holden), the temperature lapse rate increased by strong low-level warm air advection. In contrast, for the Pine Lake storm strong cold air advection at mid and upper levels intensified the latent instability.

5) In all three cases the storms developed in very high humidity conditions for Alberta with surface dewpoint temperatures exceeding 13 °C. The Pine Lake and the Holden storms developed at a dry line (moisture front). High resolution numerical simulations of the Pine Lake case confirm that the dry line was collocated with a line of surface convergence that triggered and sustained the thunderstorm development.

6) The Edmonton storm environment did not depict a surface dryline; instead the boundary layer air was extremely humid with spatial uniformity. Thus the presence of a surface dryline may not be a necessary feature for the formation of thunderstorms.

7) For the Pine Lake and the Holden storms, simple extrapolation of the current storm motion would have been useful for nowcasting their storm

tracks. These storms continued to move on a straight track with uniform cruising speed. In contrast, the Edmonton storm moved steadily eastwards for some time, then suddenly made an abrupt turn towards the north and passed over the city of Edmonton. For this case, nowcasting the storm motion would have been impossible with the available data.

In conclusion, we want to discuss some implications of these findings. We feel that it would be very useful for the operational forecaster to have access to hourly contoured surface moisture field and to follow the development and movement of a drylines. Drylines provide valuable clues about the location of low-level convergence zones that would trigger and maintain convective outbreaks. However, while surface dewpoint gradients provide information about the magnitude of the surface convergence, they do not quantify the depth of the convergence layer. Xin and Reuter (1996) found that the intensity of the convective triggering depended markedly on both the magnitude and depth of the convergence. A vertical profile of convergence estimated from Doppler radar wind measurements would be needed to determine the depth of the convergence layer. In addition to real-time moisture fields it would be useful to have three-hourly soundings of thermodynamic and wind observations. Remote sensing may be a viable option for a cost effective data profile collection. Lastly, simple extrapolation of storm tracks is not always viable and other nowcasting techniques should be explored for Alberta storms.

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