

AN EXAMINATION OF THREE SEVERE CONVECTIVE STORMS THAT PRODUCED SIGNIFICANT TORNADOES IN CENTRAL ALBERTA

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Abstract

Three tornadic thunderstorms with F-scale damage ratings of F3 and F4 occurred in Alberta during the past 20 years. These events were: the Edmonton storm of 31 July 1987, the Holden storm of 29 July 1993, and the Pine Lake storm of 14 July 2000. A synoptic examination of these cases was made with an emphasis on the surface humidity fields. Proximity sounding profiles associated with each event were analyzed. The tracks of the three storms were examined and compared. The intent of this study is to document and compare synoptic and mesoscale patterns and parameters to a previously developed conceptual model of Alberta thunderstorm outbreaks, and to deduce meteorological parameters that can be applied operationally to aid forecasters in recognizing the possibility of such outbreaks.

It was found that all three storms developed within a baroclinic zone having bulk vertical wind shear values in excess of $4 \text{ m s}^{-1} \text{ km}^{-1}$. The Holden and Pine Lake storms were initiated and developed along well-defined surface drylines or moisture fronts. In contrast, the Edmonton storm environment showed no surface dryline as the atmospheric boundary layer was uniformly moist. The three cases showed differences in the vertical profiles of 12 hour temperature change: mainly mid-level cooling affected the Pine Lake storm, mid-level cooling combined with low-level warming below $\sim 850 \text{ mb}$ occurred with the Holden storm, while the Edmonton storm was affected by low-level warming below 750 mb with mid-level temperature change being small. In each case the thermodynamic vertical profile revealed a capping inversion and Convective Available Potential Energy (CAPE) exceeding 2200 J kg^{-1} . A comparison of the tracks of the thunderstorms showed that the Pine Lake and Holden storms moved with constant direction and speed. The Edmonton storm, however, made an abrupt change in direction and speed. Thus, extrapolation of thunderstorm movement would not have been a viable nowcasting technique in this case.

1. Introduction

The Rocky Mountains are an impressive north-south mountain barrier extending 2400 km from Yukon to New Mexico. A significant influence of the mountains is to cause a subsidence inversion that acts as a capping inversion for the build-up of Convective

Available Potential Energy (CAPE) in the Alberta region. The capping inversion is a common feature of 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 and found that, on average, 10 reported tornadoes occur over Alberta each summer. A major mandate of the Meteorological Service of Canada forecast offices is to issue timely warnings of severe storms so that appropriate safety measures can be taken. The forecasting of severe convective storms will become increasingly important as the populated areas of Alberta continue to expand.

This study focuses on the evolution of three severe convective storms that spawned tornadoes in Alberta. Three convective storm cases were chosen which had the most intense tornadoes recorded during 1983-2003. The cases were: the Edmonton storm of 31 July 1987 that resulted in 27 fatalities and 250 million dollars (Canadian) of property damage (Bullas and Wallace 1988; Charlton et al. 1998); the Holden storm of 29 July 1993 which destroyed several well constructed brick and mortar farm buildings (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 F4 on the Fujita F-scale (Fujita 1981). The detailed climatology of Alberta tornados compiled by Hage (1994, 2003) showed that the Edmonton tornado was the only F4 tornado observed in Alberta during recorded history. The Holden and the Pine Lake tornados were both rated F3. There were no other observed F3 tornadoes in Alberta during the period 1983-2003.

A synoptic examination of the three severe storms with an emphasis on the surface atmospheric moisture patterns was conducted. 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 and subsiding air ahead of an approaching

Table 1. A comparison between the Edmonton, Holden, and Pine Lake Tornadoes. The parameters are taken from the 0000 UTC proximity soundings and are described in the text.

	Edmonton	Holden	Pine Lake
Tornado F-scale value	F4	F3	F3
Maximum hail size (cm)	10	8	4
Number of fatalities	27	0	12
Insured property damage (\$Can million)	250	3	13
Start time of tornado track	2100 UTC 31 July 1987	0345 UTC 30 July 1993	0045 UTC 15 July 2000
End time of tornado track	2200 UTC 31 July 1987	0405 UTC 30 July 1993	0115 UTC 15 July 2000
500 mb wind speed (m s^{-1})	29	24	23
500 mb wind direction	170°	180°	220°
850 mb wind speed (m s^{-1})	9	1	7
850 mb wind direction	100°	150°	350°
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})	2420	3190	2250
Lifted Stability Index	-8.6	-8.8	-8.2
0-6 km bulk shear ($\text{m s}^{-1} \text{ km}^{-1}$)	5.2	5.0	4.3
0-3 km Storm Relative Helicity ($\text{m}^2 \text{ s}^{-2}$)	153	-2	199
Bulk Richardson Number	13	42	18

upper-level ridge, setting up the low-level capping inversion along the foothills. Upper-level warming and associated weak lapse rates contribute to a minimal amount of CAPE. Isolated shallow convection along the foothills may occur as the cap is eroded locally by daytime heating (Reuter and Nguyen 1993). Low-level synoptic pressure gradients cause a light westerly flow which transports moisture away from the foothills. Weak to moderate upper-level winds are associated with relatively weak vertical wind shear. Convective activity is limited to cumulus clouds and isolated thunderstorms along the foothills.

Stage 2 of the conceptual model begins when the upper-level ridge axis moves eastward and an upper level trough approaches the area. Convection again begins along the foothills during the day. However, strong cooling aloft and surface heating combine with the low-level moisture influx to steepen the lapse rate, resulting in 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 inversion. There is a continued buildup of latent energy through differential temperature change forming a "loaded gun" sounding (Miller 1972). Low-level heating combined with localized convergence overcome the capping inversion and more vigorous convective storms form along the foothills. These storms move eastward with mid-tropospheric westerlies. The strong mid-level westerly flow ahead of the advancing trough combines with the

intensifying low-level southeasterly flow to create strong vertical wind shear. The convection becomes organized into long-lasting multicell or supercell storms due to the strong vertical wind shear (Chisholm and Renick 1972). The focus of this 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 of 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; Johns and Doswell, 1992). Synoptic features for the three thunderstorm events will be compared to determine the validity of Smith and Yau's conceptual model.

A focus of this storm analysis is the evolution of the surface moisture field. Schaefer (1986) suggested that a moisture front can at times trigger thunderstorm development. A moisture front, referred to as a dryline (Fujita 1958), often initiates and organizes spring and summer convection (Rhea 1966; Ziegler and Hane 1993). The typical criterion for a dryline is a surface dewpoint gradient of $10^\circ\text{C}/100 \text{ km}$ 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 as a "first guess" to locate the dryline position (Schaefer 1973). In the dry air, temperature soundings

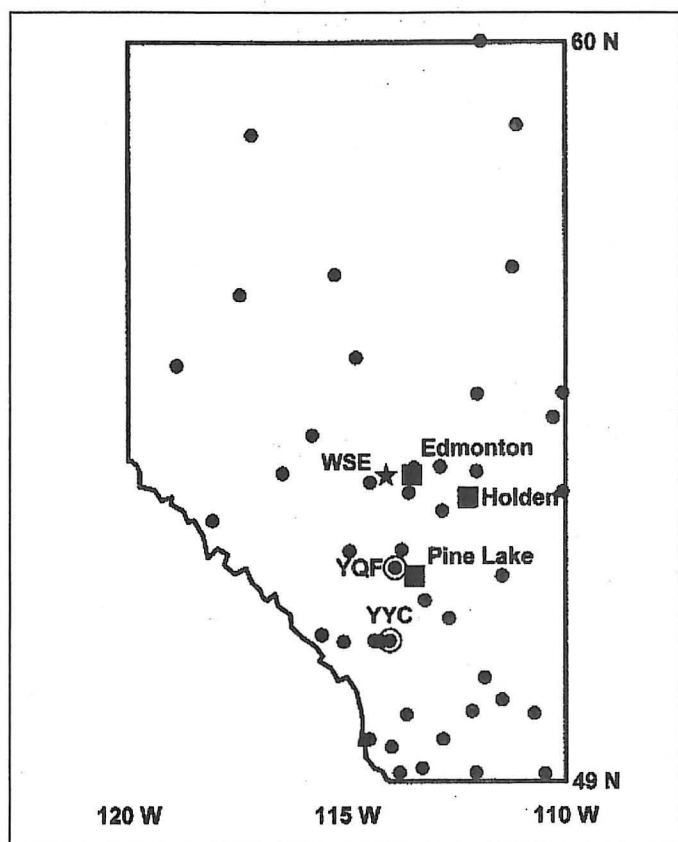


Fig. 1. Location of surface weather observing stations (dots) within the Province of Alberta. The squares show the sites of the Edmonton, Holden, and Pine Lake storms. The circles show the cities of Red Deer (YQF) and Calgary (YYC). The location of Stony Plain (WSE) upper air station is marked by the star.

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 inversion the air can be well-mixed, forming steep mid-level lapse rates. The capping lid allows for the buildup of 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 and Hane 1993). A diurnal variation of the moisture gradient often exists (Rhea 1966) with the afternoon gradient stronger than in the early morning.

This study also serves as a subject of a larger research project in which a database of tornadic and non-tornadic thunderstorm cases in central Alberta is being examined for such parameters as wind shear, helicity, and atmospheric moisture content. The aim of this project is the continuation of a long range goal (Brooks et al. 1994a) to explore whether synoptic scale parameters (e.g. vertical wind shear, precipitable water, and buoyancy) can be used to distinguish between the environments of tornadic thunderstorms and non-tornadic severe thunderstorms. A further goal is to determine if these parameters can be useful in discriminating between the F-scale values of tornadic events. Since numerical model prediction of individual thunder-

storms and tornadoes is likely to remain problematic (Brooks et al. 1992), identifying synoptic-scale features that may cause the outbreak of severe convection can be useful for forecasting severe thunderstorms. Here, we examine synoptic features associated with three severe thunderstorms which spawned tornadoes.

This study is organized in the following manner:

- First, we describe the synoptic environment associated with the three severe thunderstorm cases. Comparisons between the Smith and Yau conceptual model and the observed synoptic patterns are discussed.
- Next, we describe and analyse proximity soundings for each event. Similarities and differences between the Smith and Yau conceptual model and the observed soundings are presented.
- Then we analyse and describe the surface dew-point fields (dryline) for each event.
- Following this, we analyse the storm tracks for the three cases.
- Finally, we present a discussion of the results and suggest implementations for operational forecasting.

2. Synoptic Scale Storm Environment

Table 1 compares selected quantities of the three thunderstorms which spawned each of the tornadoes. The times for the tornadoes were: 2100–2200 UTC 31 July 1987 for the Edmonton Tornado, 0345–0405 UTC 30 July 1993 for the Holden Tornado, and 0045–0115 UTC 15 July 2000 for the Pine Lake Tornado. The 0000 UTC (corresponding to 1800 MDT) 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. Both the Holden and Pine Lake cases (Figs. 2c, e, respectively) had a long-wave trough over British Columbia. In the Holden case, the trough was oriented south-north through Vancouver Island. The Pine Lake case showed the trough along a more southwest-northeast line, with the southern portion over Vancouver Island, and the northern portion advancing into north-east British Columbia. In both cases, the long-wave ridge had advanced over Saskatchewan. Meanwhile, the Edmonton case (Fig. 2a) had a low center form over southern British Columbia and a high center located to the northwest. The Holden and Pine Lake patterns were 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 500 mb wind direction during the Edmonton and Holden storms was southerly while the Pine Lake case had a southwest direction.

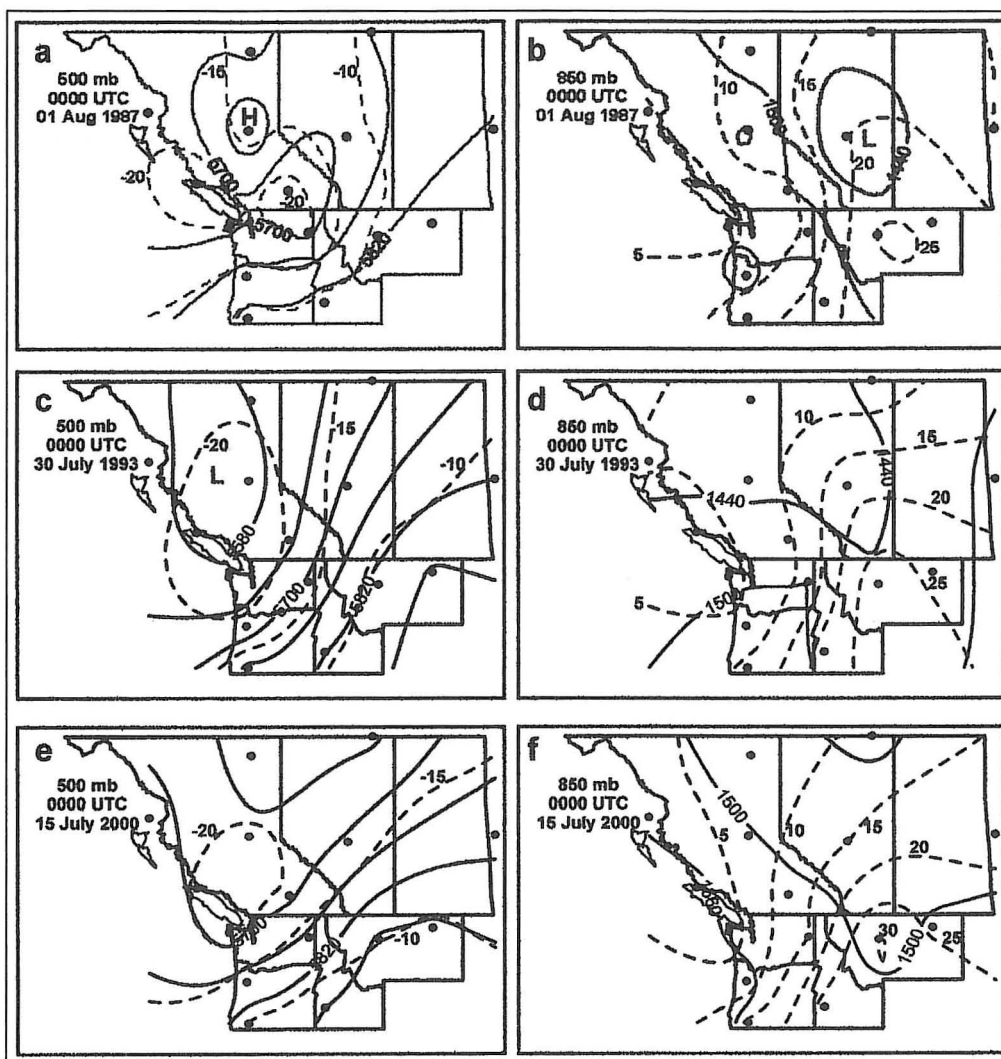


Fig. 2. 500 mb and 850 mb height contour maps at 0000 UTC for the Edmonton tornado (top panel), Holden tornado (middle panel), and Pine Lake tornado (bottom). Geo-potential heights (solid) are contoured every 60 m, isotherms (dashed) are contoured every 5°C.

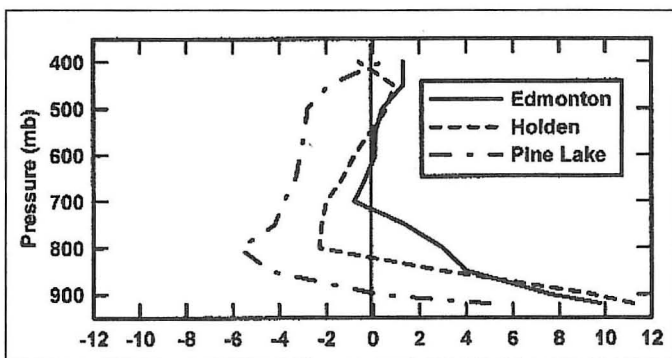


Fig. 3. Vertical profile of the 12-h temperature change (ΔT) from 1200 UTC to 0000 UTC for the three tornado cases.

At 850 mb a trough was over central Alberta for both the Edmonton (Fig. 2b) and Holden storms (Fig. 2d). This feature would promote a low-level (below ~850 mb) 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). Similar to the 850 mb pattern, the surface pattern for the Edmonton and Holden (Knott and Taylor 2000) storms both showed a low pressure center just east of Edmonton. Meanwhile, the Pine Lake storm had a surface low pressure center in western Saskatchewan.

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. The values of ΔT are calculated from actual (where possible) and interpolated sounding temperatures at the surface, and then at intervals of 50 mb beginning at 900 mb. Figure 3 indicates that the Edmonton storm profile showed warming ($\Delta T > 0$) throughout most of the column. Only a narrow region from about 750 to 650 mb showed minimal cooling

(< 1°C). The warming is most pronounced below 850 mb suggesting that diabatic heating played a large role in the destabilization process. The Smith and Yau conceptual model suggests that mid-upper-level cooling is a significant contributor to destabilization, implying that the Edmonton storm differed somewhat from their model. The Holden storm showed significant warming below about 800 mb (the surface warmed by about 11°C), coupled with cooling of the low to mid-levels from about 800 to 550 mb. The strongest cooling occurred near 800 mb (–2°C) with steadily decreasing cooling above to 450 mb. The Pine Lake profile showed warming only in a shallow near surface layer (from the surface to about 900 mb) and cooling at all levels above. Similar to the Holden case, the largest cooling occurred near 800 mb (–6°C). Except for a near ground layer, the whole column cooled with height. The Holden and Pine Lake cases are more consistent with the conceptual model of Smith and Yau which has mid-level cooling initiated by an advancing trough, while the low-levels are warmed through day-time heating.

3. Sounding Analysis

Sounding data from the upper air station at Stony Plain (WSE) Alberta (53.55° N, 114.10° W; Fig. 1) were used for this study (Stony Plain is the only upper air station in Alberta). The sounding data are available on a CD-ROM archive of *Rawinsonde Data of North America 1946-1992*, and on-line (1992 to present) produced by the National Climate Data Center (NDCD) and the Forecast Systems Laboratory (FSL). RAOB software from Environmental Research Services was used to calculate various convective parameters.

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 air mass that the convection forms within (Brooks et al. 1994a). It is recognized that there are important concerns with respect to what constitutes a representative sounding. There cannot be complete confidence that the WSE sounding actually represents the environmental conditions in which the storms developed. Buoyancy, especially, is sensitive to the low-level temperature and dewpoint. For environmental parameters such as CAPE, numerical cloud modeling by Brooks et al. (1994b) shows that the effects of convection can cause changes in these parameters on the space and time scale comparable to the development of thunderstorms. Markowski et al. (1998) concluded that major variations in environmental sounding parameters can occur over time and space scales comparable to the duration of thunderstorm development. Markowski also found that shear values from about 500 m to 6 km were fairly uniform over large distances, suggesting that shear parameters derived from proximity soundings could be very robust and not as subject to local variations as other parameters such as CAPE.

The following approach was used to synthesize the WSE sounding for the three tornadic storm cases. Low-level adjustments to the temperature and dewpoint were performed on both the 1200 UTC and 0000 UTC.

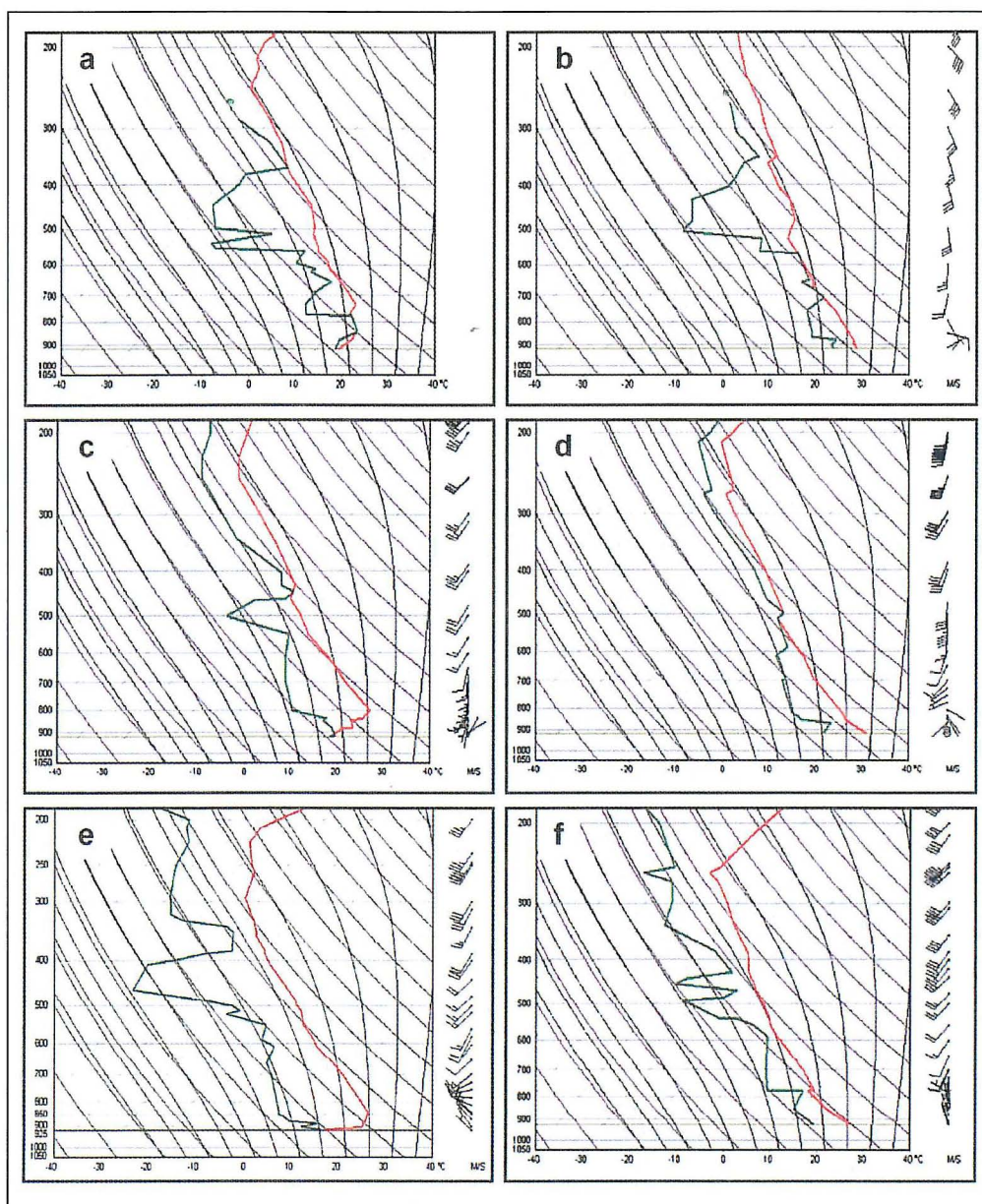


Fig. 4. Adjusted Skew T-log p diagrams for the Edmonton tornado (top panel), the Holden tornado (middle panel), and the Pine Lake tornado (bottom panel) for a), c), and e) 1200 UTC (morning of the events); b), d), and f) 0000 UTC (evening of the events). Wind vectors (in m s^{-1}) are shown at selected pressure levels at the right of each sounding.

Surface winds were not adjusted. The local surface temperatures and dewpoints for each storm were obtained from the nearest neighbouring weather reporting sites: for the Edmonton and Holden cases the Edmonton city site (YXD) was used; and for the Pine Lake Red Deer (YQF) was used (see Fig. 1). The temperature profile was adjusted (if necessary) below 850 mb to ensure that a dry adiabatic lapse rate was not exceeded. The dewpoint values above the surface were not modified for the Edmonton and Holden storms. For the Pine Lake event, however, the 900 mb dewpoint temperature was increased by 2°C to smooth a large decrease between the adjusted surface and the non-adjusted dewpoints below 850 mb.

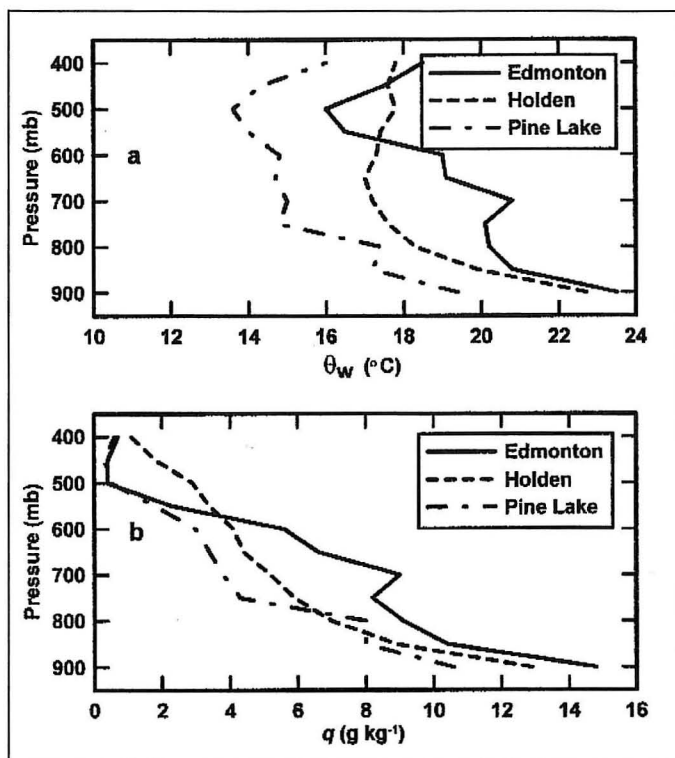


Fig. 5. Vertical soundings at 0000 UTC of a) wet-bulb potential temperature (θ_w in $^{\circ}\text{C}$), b) vapor mixing ratio (q in g kg^{-1}) for the Edmonton, Holden, and Pine Lake storms.

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 inversions were evident at 850 mb and 730 mb. The lower capping inversion was consistent with the conceptual model of a pre-thunderstorm environment; however, the second cap could add even more to the buildup of CAPE. Overcoming both caps by surface heating alone would require the surface temperature to reach 30°C (86°F). Above the two capping inversions there was a drier layer. The wind data sampled by the balloon 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 inversion located at about 800 mb. This single cap is more typical of the conceptual model. Overcoming this cap by surface heating alone would require a temperature of about 30°C , similar to the Edmonton case. The Holden pre-storm environment was noticeably drier compared to the Edmonton tornado storm case. For the Holden case, the air was close to saturation only near the surface. The observed wind profile showed a weak southerly flow in the low-levels below the capping inversion. The flow became stronger above the cap and veered slightly to the southwest at mid-levels (above ~650 mb). The wind profile had similarities to the conceptual thunderstorm model of Smith and Yau; however, the amount of veering in the low-levels was very minimal.

The 1200 UTC sounding for the Pine Lake storm environment is depicted in Fig. 4e. A capping inversion was evident at about 850 mb, but the inversion was weaker than the Holden case. The surface temperature would have to reach 27°C to break the capping inversion by surface heating alone. The Pine Lake sounding was the driest of the three cases, showing no layers with saturated air. Winds were light northwest near the surface, backing to southwest in the mid-levels. This wind profile is not consistent with the Smith and Yau model of low-level veering winds at 1200 UTC.

The 0000 UTC sounding for the Edmonton tornado (Fig. 4b) depicts environmental conditions about two hours after the tornado had dissipated, but with the thunderstorm still active. The low-level temperatures and dewpoints were adjusted to the nearest observed values of surface temperature (25°C) and dewpoint (19°C). There were several degrees of warming from the surface to about 730 mb. This low-level warming has contributed to eliminating the caps. There was also drying from 870 to about 790 mb. There was very little temperature change above 700 mb. The winds in the low-levels were light easterly which may have continued to advect moist air near the surface. However, there was drying from 850 to 800 mb even though winds in that layer were easterly. Above 800 mb, winds veered to southerly. A near saturated layer developed from 700 mb to about 550 mb. Due to the development of thunderstorms several hours prior to the 0000 UTC sounding that tracked to the south of WSE, there may have been some contamination of the sounding from the thunderstorm itself due to the mid-level southerly flow. Additionally, synoptic scale advection may have contributed to the increased moisture in the mid-levels; however, winds above 550 mb were southerly with little change in the moisture profile. This wind profile appeared slightly different than the conceptual model which would suggest a drying southwest flow throughout the mid-levels.

The 0000 UTC sounding for the Holden storm (Fig. 4d.) showed increased moisture throughout most of the column (below 450 mb). Similar to the Edmonton storm, a nearly saturated layer developed from 600 to 500 mb. The sounding remained moist well above 500 mb. In this case there were thunderstorms in the vicinity of WSE prior to the Holden storm which may have modified the sounding. Winds in the low-levels became quite light and generally southerly while winds in the 600 to 500 mb layer increased by an average of about 18 m s^{-1} and backed from southwest to south.

The 0000 UTC sounding for the Pine Lake storm is shown in Fig. 4f. 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 may not have been the main factor in breaking the capping inversion. Moisture increased significantly below 500 mb. This was especially evident in the low-level layer from ~875 to 790 mb where dewpoints increased by $8\text{--}10^{\circ}\text{C}$. Winds in the mid-levels remained quite strong from the southwest throughout the day, consistent with the Smith and Yau

model. However, even though the southwest flow in mid-levels persisted, the moisture through that level actually increased.

Profiles of 0000 UTC wet-bulb potential temperature (θ_w) and mixing ratio (q) are shown in Fig. 5. The values of θ_w and q are determined from actual (where possible) and interpolated sounding values of temperature and dewpoint at intervals of 50 mb beginning at 900 mb. Figure 5a compares the 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. The Holden storm showed a trend toward a neutral profile from 800 to 650 mb, becoming stable above 650 mb. The Pine Lake profile had a stable layer from 850 to 800 mb, then unstable to 750 mb. There was a rather deep neutral layer from 750 to 600 mb. The Edmonton case showed a significant stable layer between 750 and 700 mb, becoming unstable above to 500 mb. The Edmonton storm had much larger θ_w values in the lower and mid-levels (800–600 mb) than the other two, with the Pine Lake θ_w values being consistently smallest. The q profiles (Fig. 5b) show the Edmonton storm consistently having the greatest moisture from the 900 to 600 mb than the other two soundings.

Table 1 compares values from the 0000 UTC adjusted proximity soundings for the three events. The Edmonton tornado was the highest rated (F4) on the Fujita damage scale. The 500 mb 12-h temperature changes showed a slight warming in the Edmonton and Holden storm cases, while the Pine Lake storm environment cooled by about 3°C. At 850 mb the 12-h temperature changes showed warming of 3–4°C during the Edmonton and Holden storms, unlike the Pine Lake event which cooled by about 4°C. The 850 mb wind was 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 (PW) of 34 mm, similar to the Holden storm (30 mm), while the Pine Lake storm was the driest at 23 mm. The amount of Precipitable Water can act as a threshold for convective precipitation in Alberta (Reuter and Aktary 1995). Djurić (1994, pp. 86) notes that values of PW ≥ 25 mm are conducive to the development of thunderstorms in the southwestern United States.

CAPE was calculated using the virtual temperature for the ascent curve of the surface-based parcel. The 0000 UTC soundings all had very high values for CAPE, exceeding 2200 J kg⁻¹. The Holden storm showed a CAPE that was about 25% greater than the other two. Supercell storms are often associated with CAPE values exceeding ~2500 J kg⁻¹ (Rasmussen and Wilhelmson 1983; Rasmussen and Blanchard 1998; Rasmussen 2003). The 0000 UTC sounding 0–6 km bulk wind shear (SHEAR) for the Edmonton and Holden storms was high (≥ 5 m s⁻¹ km⁻¹) while the Pine Lake storm had a slightly lower SHEAR (4.3 m s⁻¹ km⁻¹). Observational and modeling studies of SHEAR show that environments with values of roughly 2.5–4.0

m s⁻¹ km⁻¹ are necessary to support supercells (Weisman and Klemp 1982; Bunkers 2002; Thompson et al. 2003).

Storm-Relative Helicity (SRH) is defined for a layer of depth h as (Davies-Jones et al. 1990):

$$\text{SRH} = - \int_0^h \mathbf{k} \cdot (\mathbf{V} - \mathbf{c}) \times \frac{\partial \mathbf{V}}{\partial z} dz \quad (1)$$

where \mathbf{V} is the horizontal velocity and \mathbf{c} is the storm's velocity. The depth h is typically chosen as 1 to 3 km. One can visualize SRH as minus twice the area swept out by the hodograph with the origin at the storm motion location. The 0000 UTC sounding, 0–3 km SRH, was calculated using Bunkers' method (Bunkers et al. 2000) to estimate storm velocity. As shown in Table 1, values of SRH were 153 m² s⁻² for the Edmonton storm, near zero (–2 m² s⁻²) for the Holden storm, and 199 m² s⁻² for the Pine Lake storm. The low SRH value for the Holden case is indicative of the light winds in the low-levels (Fig. 4d). The 0–3 km SRH values of the three storms are all lower than the median value of 223 m² s⁻² for F2–F4 tornadoes in the U.S. found by Thompson et al. (2003).

The Bulk Richardson Number (BRN), defined as $\text{BRN} = \text{CAPE} / (1/2 U^2)$ (where U represents the difference between the density weighted mean winds in the 0–6 km and 0–500 m layers) quantifies the ratio of the vertical component relative to the horizontal component of the kinetic energy. As the BRN decreases, 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 a high CAPE value and a BRN value less than about 50, increases the likelihood of a supercell storm, whereas a BRN larger than 50 tends to be associated with multicell storms. The BRN of all three storm environments was less than 50. Edmonton, Holden and Pine Lake storms had BRN values of 13, 42, 18 respectively. Consistent with the Weisman and Klemp's criterion and verified by Thompson et al. (2003), all three soundings produced organized supercells. However, the degree to which CAPE and BRN can distinguish between supercell and non-supercell environments is still not clear. Rasmussen and Blanchard (1998) found that their BRN values did not discriminate well between supercell and non-supercell environments. Turcotte and Vigneux (1987) found that a combination of CAPE and shear could discriminate well between environments with severe and non-severe thunderstorms. CAPE alone does not appear to distinguish between environments associated with tornadic and non-tornadic storms (e.g. Trucotte and Vigneux 1987; Brooks et al. 1994a; Monteverdi et al. 2003). The Lifted Index (LI) values of the three events were very similar (about –8). Blanchard (1998) suggests that the LI may be better than CAPE alone as a measure of the buoyancy characteristics of the environment. In this sense, it is interesting that the buoyancy environments of the

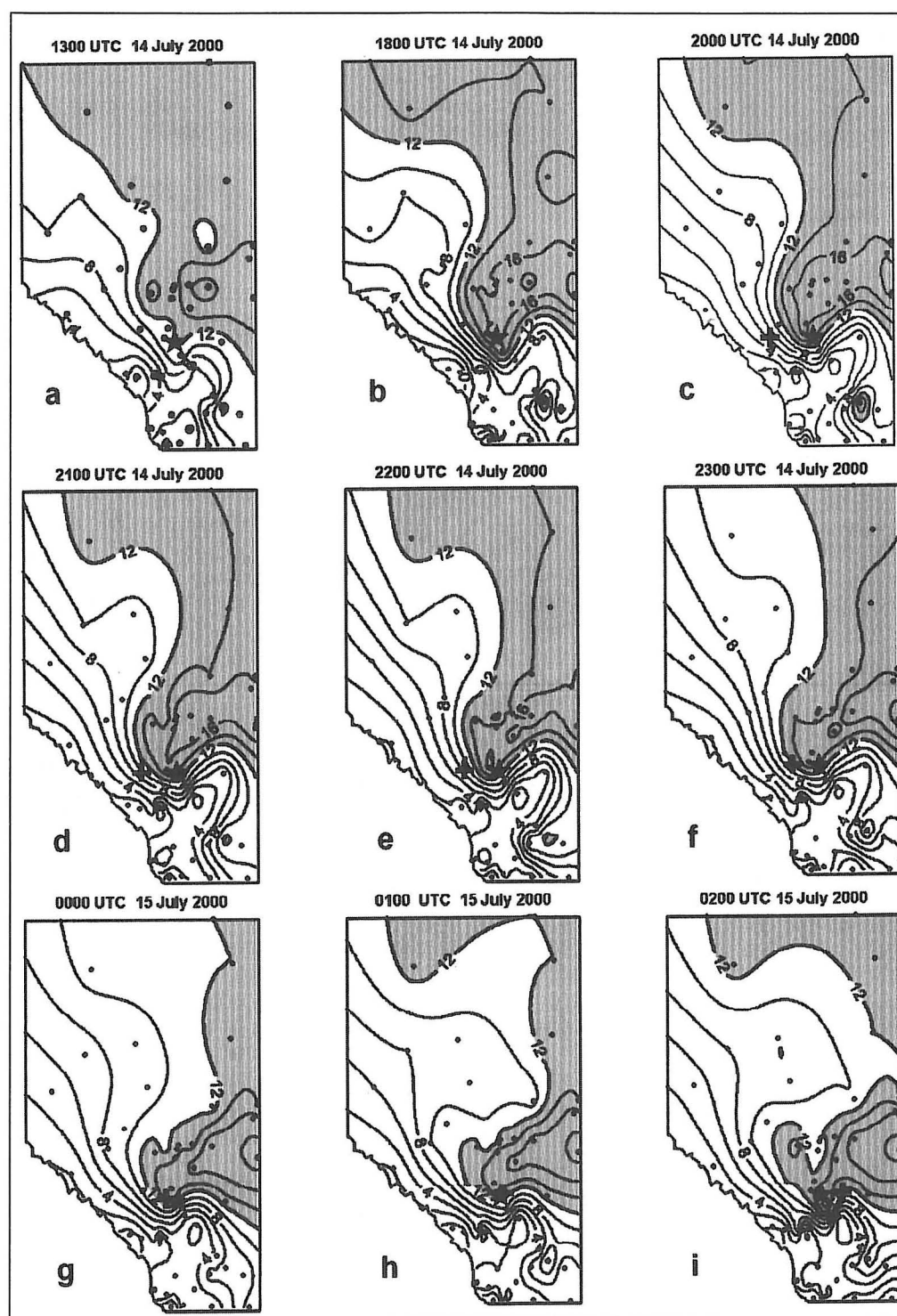


Fig. 6. Contour analysis of surface dewpoint temperatures for the Pine Lake storm from 1300 UTC 14 July 2000 to 0200 UTC 15 July 2000. Contours are drawn every 2°C, with shading for $T_d > 12^\circ\text{C}$. Dots show dewpoint observations, the star shows the Pine Lake storm site, and the cross marks the storm.

three storms were perhaps more similar than suggested by CAPE alone. 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 PW values in the Edmonton and Holden storms.

4. Dryline Analysis

In 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 from the west (Knott and Taylor 2000). As an upper-level trough crosses the mountains, a strong low-level westerly downslope flow develops along the foothills of the Rocky Mountains. 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 that often develops 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 masses. 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 1974). 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 than in the quiescent case (Hane et al. 2001, 2002).

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 turbulent mixing of subsiding west winds in the dry air (Schaefer 1986).

Some surface atmospheric moisture fields (e.g. mixing ratio) are not standard data available to the fore-

caster at a weather office. However, hourly dewpoint measurements are routinely 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.

Surface dewpoint analyses for the Pine Lake case are shown in Fig. 6. 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, the leading edge of the gradient (12°C isodrosotherm) was near Pine Lake. A bulge in the dryline developed over southern Alberta as the drier westerly air flowed across the mountains and reached the surface east of the foothills in response to the eastward motion of the upper trough. Meanwhile, an easterly flow in the low-levels was advecting 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 which curved northeastward as a dryline bulge continued to develop. The dryline was slightly south of Pine Lake at this time. The orientation of the Pine Lake storm dryline differed from typical pattern observed over the U.S. (Rhea 1966; Schaefer 1986) where the dryline aligns parallel to the mountains. By 2000 UTC (Fig. 6c), the dryline was well defined along the foothills into south-central Alberta and then curved sharply northeast. From 2100 UTC through 0000 UTC (Fig. 6d, e, f, g), the dryline remained quasi-stationary. The thunderstorm (indicated by a "cross") which later spawned the F3 tornado, developed and moved eastward. Due to the orientation of the dryline, the thunderstorm moved into the area of higher dewpoints which enhanced the CAPE. 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. 6h). At 0200 UTC, an hour after the tornado occurred at Pine Lake, the dryline (Fig. 6i) dipped southward and the storm continued its track along the dryline.

Knott and Taylor (2000) made a detailed analysis of the dryline for the Holden storm. The dry line pattern

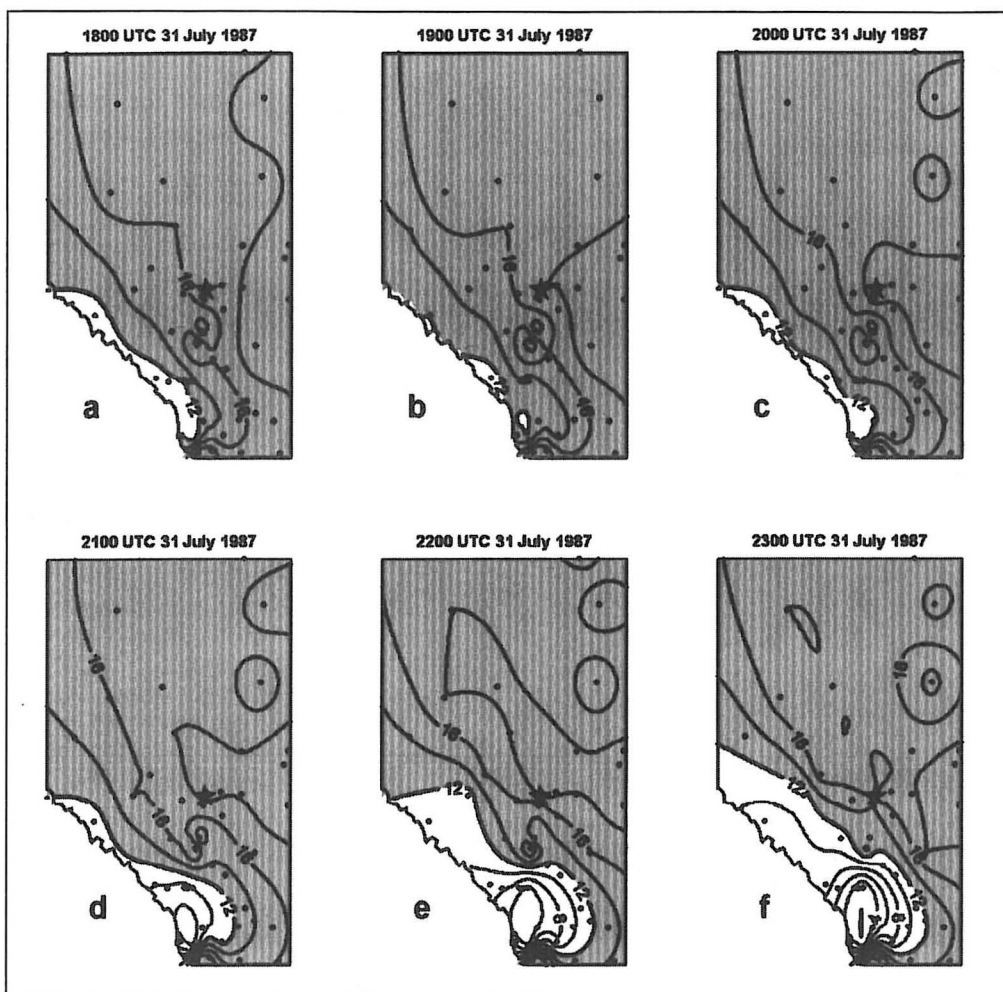


Fig. 7. Hourly evolution of the surface dewpoint field for the Edmonton storm from 18 UTC to 23 UTC 31 July 1987. Contours are drawn every 2°C , with shading for $T_d > 12^{\circ}\text{C}$. The star marks the city of Edmonton.

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. 7. The "star" marks the location of the city of Edmonton. At 1800 UTC 31 July 1987, the dewpoint field showed very moist conditions prevailing over nearly all of central Alberta. Dewpoints varied from 14°C in the west to 18°C and greater in the east (Fig. 7a). There was no evidence of a dewpoint gradient and corresponding dry line. The 1900 UTC and 2000 UTC surface dewpoint patterns (Fig. 7b, 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. 7d), the dewpoints in the Edmonton area were quite uniform near 18°C . By 2200 UTC, the time of the tornado dissipation (Fig. 7e), a dewpoint gradient had 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 forma-

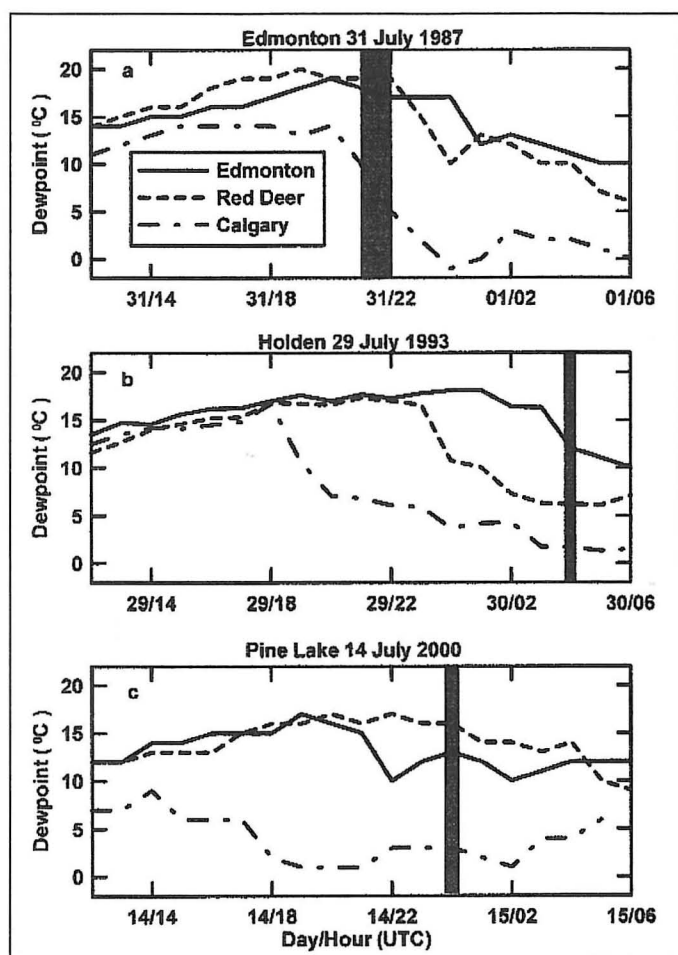


Fig. 8. Evolution of surface dewpoint temperatures (in °C) recorded at Edmonton (solid), Red Deer (short dashed), and Calgary (long dashed) airports for the a) Edmonton, b) Holden, and c) Pine Lake storm events. The shaded zones indicate the approximate duration of each tornado.

tion of a surface dryline as defined by Schaefer (1973). The 12°C isodrosotherm was well south of Edmonton. At 2300 UTC (Fig. 7f), 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.

Figure 8 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 dryline position. The shaded zone indicates the time interval when the tornado formed. The Edmonton storm (Fig. 8a) 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 (roughly marked by the 12°C isodrosotherm). The dry air advected into 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. 8b) 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 touchdown. The Pine Lake event (Fig. 8c) 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. 6) as the moist tongue of air across east-central Alberta decreased in extent.

Erfani et al. (2002) used a fine scale version of the Global Environmental Multiscale (GEM) model to simulate the Pine Lake storm. The simulated evolution of the surface dewpoint field closely resembled the synoptic observation. The model output at 2100 UTC 14 July 2000 in Erfani et al. (2002) (Fig. 15a), created a strong gradient across central Alberta with a bulge to the east similar to Fig. 6a. The strongest gradient on both the model and observations occurred to the south of Pine Lake. The model simulations suggest that there was surface wind convergence close to the dryline, and this convergence supported the storm development. 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.

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. 9.

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 reason for the abrupt change in direction is not clear. It may be due, in part, to the southerly mid-level wind. This does not, however, explain why the storm was moving eastward before the directional shift. There were no archived radar observations sampled prior 1992 and we cannot be certain that the storm did not split. 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 lasted for slightly over an hour, from its touchdown south of Edmonton to its dissipation just northeast of Edmonton, producing 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 0-6 km mean wind shear vector. 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. 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. Conclusions and Implications for Forecasting

During the last 20 years only three tornadoes have been recorded with F-scale ratings of F3 or F4 in Alberta. The synoptic conditions, the proximity sounding, the surface moisture fields, and storm tracks were examined to determine similarities and differences of contributing factors. The emphasis was on those observations available at the local forecast office that must issue storm warnings. Our analysis revealed the following points:

All three cases had a pronounced low-level capping inversion that allowed for the build-up of large amounts of Convective Available Potential Energy (CAPE) exceeding 2200 J kg⁻¹. This is in agreement with the Smith-Yau model.

All three storms developed in a thermal baroclinic zone with significant 0-6 km bulk 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), Rasmussen and Wilhelmson (1983) and Thompson et al. (2003) criterion for the formation of long-lasting supercells.

The build-up of CAPE was caused, in large part, by differential temperature changes at various altitudes. In two cases (Edmonton and Holden), the temperature lapse rate increased by strong low-level warming likely due to diabatic heating. In contrast, for the Pine Lake storm strong cooling at low and mid-levels intensified the latent instability with only a shallow layer near the surface experiencing warming. The Holden and Pine Lake storms showed cooling aloft, compatible with the Smith-Yau model, while the Edmonton storm showed warming throughout most all of the column, which appears contrary to the model. It is interesting to note the Holden and Pine Lake cases showed the greatest cooling near the 800 mb level. From discussions with operational forecasters at the Alberta weather office, we have been informed that cooling at the lower levels (~850-700 mb) is often a strong indicator that anticipated significant convection is imminent. We speculate that, while upper-level cooling is important to increase the buoyancy potential, low-level cooling (850-700 mb) is a major component for breaking the cap and releasing the latent instability.

In all three cases the storms developed in very high humidity conditions for Alberta with surface dewpoint

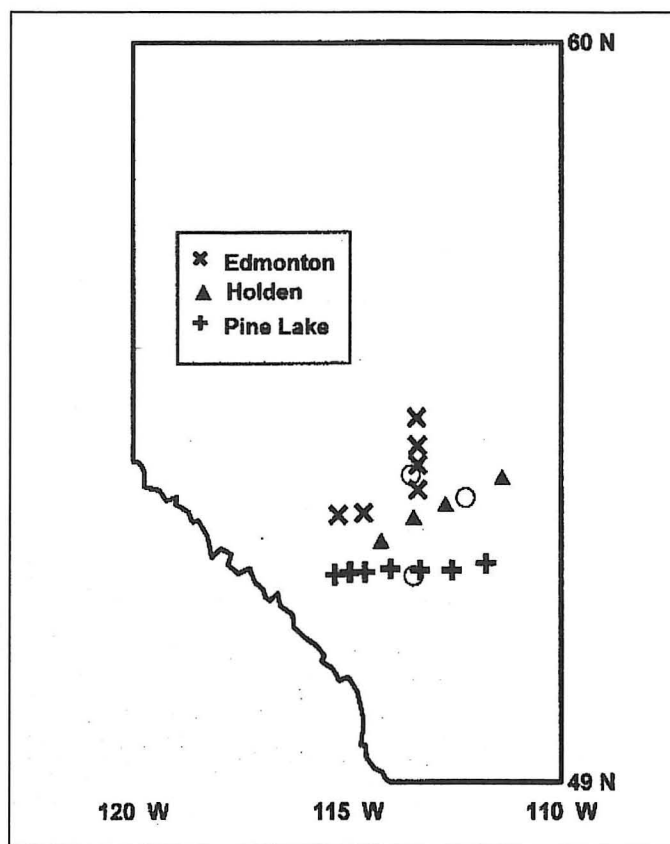


Fig. 9. Storm tracks plotted every hour for the Edmonton storm (1900 UTC 31 July 1987 to 0000 UTC 01 August 1987), the Holden storm (0100 UTC 30 July 1993 to 0400 UTC 30 July 1993), and the Pine Lake storm (2000 UTC 14 July 2000 to 0200 UTC 15 July 2000). The three circles mark the locations of the tornado sites (see Fig. 1).

temperatures exceeding 13°C. The Pine Lake and the Holden storms developed at a dry line (moisture front).

The Edmonton storm environment did not depict a surface dryline; instead, the boundary layer air was extremely humid with spatial uniformity. Thus, Alberta forecasters should keep in mind that the presence of a surface dryline may not be a necessary feature for the formation of thunderstorms.

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 nearly uniform 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.

Finally, we want to discuss some implications of these findings as they relate to forecasting in Alberta. Conceptual models are an important tool for forecasters to gain a relatively quick overview for the likelihood of severe convection. However, prototypes of atmospheric processes must be combined with an ingredients based approach in order to properly assess the full potential for thunderstorm development. In our study there were some features of the storms which agreed

with the Smith and Yau (1993a, b) conceptual model of Alberta thunderstorm development, while other aspects appeared contrary to the model. Operational forecasters should receive ongoing training of the current theories and research about thunderstorm and tornado development in order to properly apply the ingredients approach. Forecasters should also have access to hourly contoured surface moisture fields to follow the development and movement of drylines. Drylines provide valuable clues about the location of low-level convergence zones that could trigger and maintain convective outbreaks. However, while surface dewpoint gradients can, at times, provide information about the magnitude of the surface convergence or presence of a cap, 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 (Xin and Reuter 1998). In addition to real-time moisture fields, it would be useful to have three hourly soundings of thermodynamic and wind observations. Remote sensing of fields such as wind and moisture may be a viable option for a cost effective data profile collection. Lastly, simple extrapolation of storm tracks is not always viable and other now-casting techniques should be explored for Alberta storms.

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