The Causes of Severe Convective Outbreaks in Alberta. Part II: Conceptual Model and Statistical Analysis

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(Manuscript received 4 December 1991, in final form 4 September 1992)

ABSTRACT

An intercomparison of all 11 Limestone Mountain Experiment case days provided the basis for a conceptual model of severe convective outbreaks in Alberta. It is proposed that most severe convective events result when upper-level cooling, associated with an advancing, synoptic-scale trough, occurs in phase with strong surface heating over the Alberta foothills. The deep destabilization over the elevated topography acts to amplify the mountain–plain circulation and to generate mesoscale upslope moisture transport. Concurrently, the surface synoptic pressure gradient gives rise to east-northeasterly winds that advect the moisture-rich air of the eastern plains into the lower branch of the mountain–plain circulation. In this manner, the plains moisture is permitted to reach the convectively active foothills through underrunning of the capping lid. The end product is the initiation of well-organized, severe convective storms that move eastward with the westerly component of the midtropospheric winds. A statistical analysis based on archived hail data furnished additional evidence for the key synoptic-scale features of the conceptual model.

1. Introduction

In Part I of this study (Smith and Yau 1993), we examined in detail one severe weather outbreak and two nonsevere events over Alberta. It was found that a joint meso–synoptic-scale interaction resulting in an upslope moisture transport was the key factor in initiating deep convection on the severe day. The absence of this interaction reduced the intensity of convection on the nonsevere days. In this paper, a comparison of all 11 Limestone Mountain Experiment (LIMEX-85) days is presented in section 2 and a conceptual model of severe convective outbreaks in Alberta is proposed in section 3. This model will be substantiated by a statistical analysis using climatological hail data in section 4. Conclusions, recommendations regarding forecasting, and suggestions for future research are given in section 5.

2. A comparison of LIMEX-85 case days

A brief comparison of all LIMEX-85 days is made to determine the generality of the mechanism for severe convective outbreaks found in Part I. As was done for 9, 11, and 17 July 1985, detailed analyses were prepared for the other eight case days. For reason of economy, they will not be shown. Instead, Table 1 has been assembled, which lists

1) 12-h 500-mb temperature tendency at Stony Plain (WSE; 1800 LDT),
2) 4-h surface temperature tendency at LMW (1200 LDT),
3) CAPE averaged over the LIMEX grid (1000 LDT),
4) 500-mb winds at ARM (1200 LDT),
5) upstream 500-mb height pattern (trough or ridge), and
6) afternoon surface wind direction at Edmonton International Airport (YEG).

The number of soundings, hail reports, and hail severity for each day are included. Parameters 1 and 2 identify the cooling aloft and strong surface heating over the foothills that is needed for amplification of the mountain–plain circulation. Parameter 3 is a measure of the bulk stability of the atmosphere over the LIMEX area after the period of maximum clear-sky surface heating in the foothills. Parameter 4 can be examined for the presence of strong southwesterly flow aloft. Parameter 5 is used to determine if the upper-level flow pattern was associated with large-scale ascent (upstream trough) or descent (upstream ridge). The afternoon surface wind direction at YEG (parameter 6) indicates whether the surface synoptic circulation gave rise to easterly or northeasterly flow over central Alberta. A

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TABLE 1. LIMEX-85 case-day comparison. The parameter N is the number of soundings. The letters R and T designate ridge and trough, respectively. Abbreviations NH, LH, MH, and SH denote no hail, light hail, moderate hail, and severe hail, respectively.

Case day	N	Number of hail reports/severity	WSE 500-mb 1800 LDT temperature tendency [°C (12 h)$^{-1}$]	LMW surface 1200 LDT temperature tendency [°C (4 h)$^{-1}$]	Area average 1000 LDT CAPE (J kg^{-1})	Upstream 500-mb pattern	ARM 500-mb 1200 LDT winds (deg, m s^{-1})	YEG afternoon surface wind
8 July	33	0/NH	+1.5	+11.6	−909	R	(288, 22)	NW
9 July	27	0/NH	+3.2	+15.6	−1225	R	(279, 13)	NW
10 July	57	6/LH	0.0	+10.9	−189	R	(264, 17)	W
11 July	68	228/SH	−3.0	+14.0	−664	T	(254, 19)	NE
12 July	47	72/MH	−2.8	+2.7	−1189	T	(236, 13)	NW
15 July	36	1/LH	+1.4	+6.8	−1022	R	(269, 20)	NW
16 July	61	25/LH	+3.2	+10.1	−528	R	(270, 14)	SW
17 July	30	63/MH	−1.8	+5.3	−1036	T	(283, 06)	NE
18 July	28	13/LH	+0.2	+13.0	−312	R	(292, 13)*	W
22 July	20	23/LH	−2.4	+6.0**	missing	T	(247, 17)*	NW
23 July	28	130/MH	−0.4	+5.0**	−284	T	(285, 11)	NE

* From AQF (ARM not available)
** Estimated

short description of the synoptic and mesoscale environments on each of the LIMEX days and how they were related to the observed convection can be found in Smith (1991).

Note that 8, 9, 10, 15, 16, and 18 July 1985 were all characterized by an upstream 500-mb ridge, a warming or neutral 500-mb temperature tendency, relatively strong surface heating in the foothills, a westerly component of the surface synoptic flow, and few or no hail reports.

Of the remaining days, 12, 17, 22, and 23 July 1985 were all distinguished by an upstream 500-mb trough, a cooling trend at 500 mb, weak surface heating in the foothills, and from 23 to 130 hail reports. An easterly component of the surface synoptic flow was observed on 17 and 23 July, while a westerly component existed on 12 and 22 July. Only on 11 July 1985 was an upstream 500-mb trough associated with cooling aloft, strong surface heating in the foothills, an easterly component of the surface synoptic flow, and more than 200 hail reports.

Of the six parameters listed in Table 1, two—area average CAPE at 1000 LDT and 500-mb winds at 1200 LDT—do not correlate well with the number of hail reports (severity of convection). For example, the CAPE on 11 July 1985 (-664 J kg^{-1}; 228 reports) is more negative than on 10 July (-189 J kg^{-1}; 6 reports), 16 July (-528 J kg^{-1}; 25 reports), 18 July (-312 J kg^{-1}; 13 reports), and 23 July (-284 J kg^{-1}; 130 reports). The strong southwesterly winds at 500 mb on 11 July 1985 (254°, 19 m s^{-1}; 228 reports) were also observed on 10 July (264°, 17 m s^{-1}; 6 reports), 12 July (236°, 13 m s^{-1}; 72 reports), and 22 July (247°, 17 m s^{-1}; 23 reports).

In the case of CAPE, the poor correlation is mostly a result of comparing values at one time only (1000 LDT). The afternoon CAPE on 11 July 1985 was larger than that of any other day. The same problem of comparing observations at a fixed time exists for the 500-mb wind, although the temporal variability is much smaller than for CAPE. It may be the case, however, that the speed and direction of the 500-mb wind is relatively unimportant in determining the severity of convection compared to other factors such as the phasing of upper-level cooling with strong surface heating (see also Reinelt 1970).

3. Conceptual model of severe convective outbreaks in Alberta

The evolution of both the synoptic and mesoscale environments accompanying a severe convective event usually takes place over the course of 2–3 days. This evolution can be described in terms of two separate stages, each lasting typically about one to two diurnal cycles.

a. Stage 1

Stage 1 is characterized by clear skies resulting from subsiding air ahead of an upper-level ridge. A strong inversion is present in the lower troposphere, which inhibits or "caps" deep convection. Strong morning surface heating in the Alberta foothills is sufficient to weaken significantly or to remove the inversion locally and initiate convection. The surface heating is also responsible for early pressure falls that induce shallow upslope flow near the foothills. Owing to upper-level warming and relatively strong stratification associated with the ridge, however, CAPE is minimal and the initial foothills convection remains relatively shallow (the level of neutral buoyancy ranging between 600 and 400 mb as opposed to 300–200 mb on severe days). As a result, the vertical and horizontal growth of the mountain–plain circulation produced by the thermally generated pressure falls proceeds slowly. The upslope flow does not commence east of the foothills, if it develops at all, until late in the afternoon, which is too late to advect any significant amount of moisture into the convectively active foothills region. Furthermore, the synoptic pressure gradient over the plains favors a westerly component of the surface winds that transports the moist plains air away from the foothills. Weak-to-moderate upper-level flow associated with the ridge and the lack of strong upslope flow result in weak to moderate vertical wind shear. On days during stage 1, therefore, convective activity over the plains is limited to cumulus, towering cumulus, and possibly isolated thunderstorms.

b. Stage 2

By 1200 LDT on a stage 2 day, the upper-level ridge has moved eastward, placing part or all of the foothills region downstream of the advancing trough (Fig. 1). Mostly clear skies prevail, although some altocumulus clouds may be present. Convection again occurs first over the foothills, but on this day, the strong surface heating and the cooling aloft, in the presence of weaker stratification, act to destabilize the atmosphere, allowing for large CAPE and deep convection (Fig. 2). Rapid vertical and horizontal growth of the mountain–plain circulation takes place, which generates mesoscale upslope moisture transport. The synoptic pressure gradient over the plains favors an easterly component of the surface winds that advects the moist plains air into the lower branch of the mountain–plain circulation.

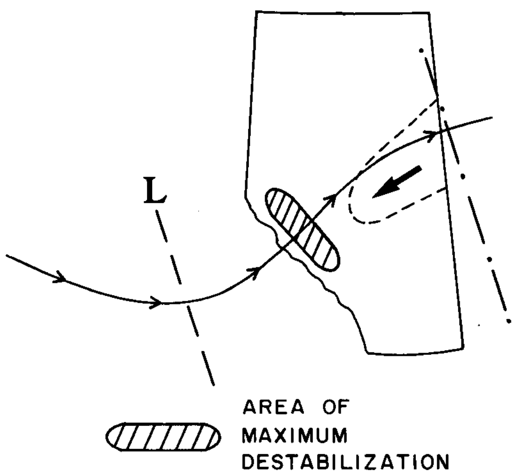

FIG. 1. Schematic diagram of synoptic-scale features present on days of severe convective outbreaks. Long-dash line indicates axis of 500-mb height and thermal troughs. Dash–dot line indicates axis of 500-mb height and thermal ridges. Thin connected arrows show core of maximum 500-mb winds. Short-dash line is surface moisture tongue. Thick arrow is surface synoptic flow. The area of maximum destabilization is located over the foothills where maximum upper-level cooling is superimposed over maximum surface heating.

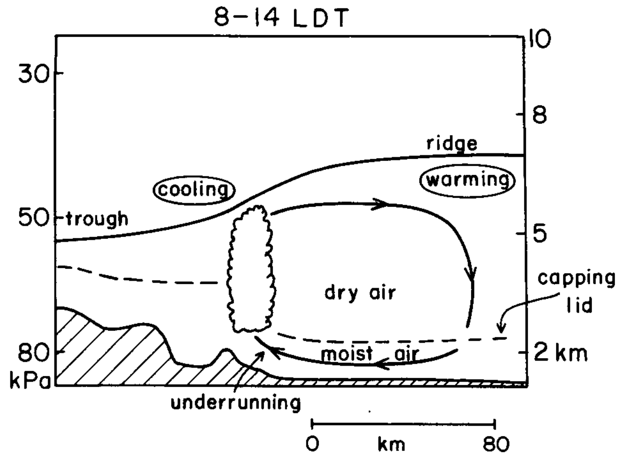

FIG. 2. Schematic vertical cross section for 0800–1400 LDT illustrating the amplified mountain–plain circulation and underrunning of the capping lid.

This moisture-bearing upslope flow underruns the capping lid and reaches the foothills in time to reinforce the initial convection. The resulting vigorous convective storms move eastward with the westerly component of the midtropospheric winds. The primary role of the capping lid east of the foothills is to inhibit the formation of convective clouds whose updrafts would tend to deplete the moisture content of the upslope flow and whose shading effect would tend to reduce CAPE. The strong southwesterly flow ahead of the trough, in combination with the intensifying low-level upslope flow, provides an environment of large vertical wind shear for the growing storms. Aside from its destabilizing effect in cooling the upper levels, the dynamic lifting provided by the advancing trough aids in increasing and maintaining the strength of cumulonimbus updrafts.

c. Discussion

We wish to emphasize the phasing aspect of the conceptual model. Cooling aloft over the foothills must occur within the 0800–1400 LDT window in order for maximum destabilization (stage 2) to take place. Early passage of the upper-level trough tends to suppress the mountain–plain circulation by allowing for widespread convection, while late passage weakens its development through the subsidence warming of the ridge. In this model, therefore, improper phasing between the upper-level trough passage and low-level warming results in a direct transition from one stage 1 situation to another *without* a severe convective outbreak.

While quasigeostrophic theory indicates that the 500-mb trough upstream of Alberta would always be associated with a surface low in southern Alberta, in reality there are a number of different surface synoptic pressure fields that may yield the needed east-northeasterly flow over the plains on severe days. For this reason, we have explicitly avoided specifying any one pattern in our conceptual model. The importance of the southern low–northern high couplet observed on 11 July 1985 relative to other possible patterns is examined in section 4.

Although the most important part of the conceptual model (stage 2) is largely based on only one case day (11 July 1985), our analyses of two nonsevere days (9 and 17 July 1985) have shown that the physical arguments supporting it are well founded. Furthermore, the idea that a particular synoptic-scale flow pattern (upper-level trough, resolvable in the operational observing network) can permit a specific evolution of the mesoscale flow field (amplified mountain–plain circulation, not resolvable) can be readily incorporated into current severe weather forecasting procedures. In section 4, a statistical analysis based on archived hail data will be presented to further investigate the relationship between the key synoptic-scale features of our model and the severity of convection.

There would appear to be a conflict between our conceptual model, which places much importance on the role of the mountain–plain circulation, and Thyer's (1981) results. It is argued, however, that given the poor temporal and spatial resolution of Thyer's dataset (twice daily rawinsonde ascents from two stations over three summers), it is not surprising he could not find any correlation between the strength of the mountain–plain circulation and the occurrence of hail. Thyer himself hinted at this possibility by suggesting that, given suitable data, further investigation into the spatial extent of the mountain–plain circulation toward the east and the relation between its strength on individual days and the synoptic situation would be worthwhile.

The major synoptic features of Doswell's (1980) composite of severe weather in the High Plains of the United States and of Longley and Thompson's (1965) mean maps for major hail days in Alberta (i.e., a 500-mb height trough upstream with southwesterly winds of at least 10 m s^{-1} and an easterly component of surface winds arising from the synoptic pressure gradient) are also a part of our conceptual model. Unlike the image presented in these studies, however, our results for Alberta demonstrate that without the proper mesoscale forcing in the form of an amplified mountain–plain circulation, the above synoptic features represent only a necessary condition for the occurrence of severe convection and not a sufficient one.

4. Statistical analysis

a. *Introduction*

To date, high-resolution observations suitable for studying the mountain–plain circulation are limited to the 11 LIMEX-85 case days. Daily synoptic observations over many summers, however, represent a large dataset that can be used to examine the relationship between the synoptic circulation and the severity of convection. In this section, the results of a simple statistical analysis are reported using standard synoptic charts and archived hail data to further validate the synoptic features of our conceptual model of severe convective outbreaks.

b. *Dataset and method of analysis*

For this investigation the daily number of hail reports logged each summer (June, July, and August) were obtained for the years 1974–85. Each day was assigned a severity following the Smith and Yau (1987) classification. It was found that hail days make up 54% of all days in summer. The breakdown by severity is 5%, 9%, and 40% for severe, moderate, and light hail days, respectively. Thus, severe days make up 9% of all hail days, moderate 17%, and light 74%. No-hail days comprise 46% of all days in summer.

In order to get a simple estimate of the temporal variability of the hail statistics, the above percentages were recomputed using six randomly selected years (1974, 1975, 1977, 1979, 1980, and 1985). Hail was found to occur on 56% of all days in summer (SH 5%, MH 9%, and LH 42%). The close agreement between the 6-yr and 12-yr results suggests that the long-term temporal variability of hailfall is not large.

The 12-yr percentages were also computed separately for the northern and southern halves of area B in an effort to examine the spatial variability of the statistics. It was found that hail occurred on 44% of all days (SH 5%, MH 9%, and LH 30%) in the northern half and on 43% of all days in the southern half (SH 5%, MH 6%, and LH 32%). It is evident that reducing the observational area by a factor of two has the effect of increasing the number of no-hail days at the expense of the light hail days. The nearly identical results for the two halves, however, indicate that there is no long-term bias toward enhanced hail occurrence in either half.

In order to study the validity of our conceptual model, archived operational 1200 UTC (0600 LDT) surface and 500-mb analyses for the severe hail and no-hail days from 1974–85 were scrutinized to determine 1) the upstream 500-mb height pattern, 2) the 500-mb winds at Stony Plain, 3) the surface gradient wind direction in central Alberta, and 4) the surface pressure pattern.

Following our proposed model, severe days should be characterized by an upstream 500-mb trough with southwesterly winds and an easterly component of the surface gradient wind. Although a particular surface pressure pattern was not specified in the model, those considered were 1) a high over northern Alberta coupled with a low over southern Alberta (HL; see 11 July

TABLE 2. Percentage of severe and no-hail days with upstream 500-mb height trough (ridge).

500-mb height pattern	Severe hail (%)	No hail (%)
Trough	94	29
Ridge	6	71

TABLE 4. Percentage of severe and no-hail days with 1200 UTC (0600 LDT), 500-mb wind speed $\geq$ (<) 10 m s^{-1} at WSE.

500-mb wind speed (m s^{-1})	Severe hail (%)	No-hail (%)
$\geq$10 m s^{-1}	81	67
<10 m s^{-1}	19	33

1985) and 2) a low extending into northern Alberta with no corresponding high (L). For most no-hail days, one would expect to find a 500-mb ridge upstream with northwesterly winds and a westerly component of the gradient wind at the surface. The following surface pressure patterns were examined on no-hail days: 1) a low in northern Alberta, a high in central Alberta, and a second low in southern Alberta (LHL; see 9 July 1985); 2) a low in northern Alberta and a high in central Alberta (LH); 3) a high in central Alberta and a low in southern Alberta (HL); and 4) a low alone (L) or a high alone (H).

The sample size of severe hail days was 52. Since early June and late August in Alberta can be quite cold and unrepresentative of summertime conditions, only the no-hail days occurring in July of the selected years were considered. The no-hail sample size was 147.

c. *Results*

It is clear from Table 2 that an upstream 500-mb height trough is associated with nearly all severe hail events. An upstream ridge is present on about three-quarters of all no-hail days.

Table 3 demonstrates the predominance (63%) of southwesterly winds at 500 mb on severe hail days associated with the upstream upper-level trough. The wind direction aloft on no-hail days appears to be more variable, with northwesterly winds occurring most often (45%).

Surprisingly, 500-mb wind speeds of at least 10 m s^{-1} seem to occur only slightly more often on severe days than no-hail days (81% compared to 67%; Table 4).

As one would expect, the variability in wind direction is considerably greater at the surface than 500 mb on both severe and no-hail days (Table 5). Nevertheless, on severe days, a distinct preference can be seen for wind directions that would act to transport moisture from the eastern plains to the foothills [northeast (54%) and east (17%)]. On no-hail days, surface winds that would transport moisture eastwards away from the foothills are favored [northwest (50%), west (23%), and southwest (17%)]. The relatively high percentages for north and northwest winds on severe days (10% and 11%) probably represent the cases where synoptic gradient evolves during the course of the day, giving rise to easterly or northeasterly flow only after 0600 LDT (see 11 July 1985).

Table 6 shows that the northern high–southern low surface pressure couplet observed on 11 July 1985 is indeed the most common pattern on severe hail days (HL, 62%). A single low was associated with 33% of all days. Some other pattern accounted for the remaining 15%.

In Table 7, the pattern most often observed for no-hail days is northern low–central high–southern low (LHL, 36%). The other significant patterns are LH (24%), H (17%), and L (12%). Clearly, the presence of a low in southern Alberta is a common occurrence on both severe (95%, HL and L) and no-hail days (41%, LHL and HL). Overall, these results confirm the basic synoptic settings of stage 1 (weak, isolated convection) and stage 2 (severe convective outbreak) of our proposed model. Most important, the need for a westerly component of synoptic surface wind on days during stage 1 and an easterly component on days during stage 2 is substantiated.

It is also apparent from the above findings that most days of severe convective outbreaks are characterized by one particular synoptic setting. For the operational forecaster, it is important to know if this setting is unique to days of severe convection or if it can also be found on other days. To tackle this question, the correlation between the 500-mb height and 1000–500-mb thickness pattern and the hail severity has been investigated. Two height patterns [upstream height trough

TABLE 3. Percentage of severe and no-hail days with a particular 1200 UTC (0600 LDT), 500-mb wind direction at WSE.

	500-mb wind direction (%)							
	North	Northeast	East	Southeast	South	Southwest	West	Northwest
Severe	0	0	0	4	8	63	13	12
No hail	3	3	1	1	2	28	17	45

TABLE 5. Percentage of severe and no-hail days with a particular 1200 UTC (0600 LDT), surface gradient wind direction in central Alberta.

	Surface gradient wind direction (%)							
	North	Northeast	East	Southeast	South	Southwest	West	Northwest
Severe	10	54	17	4	0	4	0	11
No hail	5	1	1	1	2	17	23	50

(UHT) and upstream height ridge (UHR)] and four thickness patterns [thickness trough aloft[1] (TTA), thickness ridge aloft (TRA), upstream thickness trough (UTT), and upstream thickness ridge (UTR)] have been considered. Each day was tagged by its hail severity and the 500-mb height and 1000–500-mb thickness pattern, determined subjectively from archived operational analyses (1981–85). Of the 259 days considered, 16 were classified as SH, 39 as MH, 123 as LH, and 81 as NH. In total, 140 were tagged UHT and 122 UHR. The breakdown for TTA, TRA, UTT, and UTR was 43, 122, 46, and 48, respectively. The large number of TRA days is most likely due to strong surface heating present over Alberta during the summer months, which often builds and maintains a thickness ridge. The six synoptic patterns were first correlated with the four severities separately. For the purpose of comparing with our conceptual model, only the results for severe hail are presented. The first six entries in Table 8 are the correlation coefficients and 95% confidence intervals.

The UTT is more strongly correlated to the occurrence of severe hail than the UHT (0.84 compared with 0.49). During the summer in Alberta, temperature advection in the lower troposphere is generally weak so that the passage of a 1000–500-mb thickness trough is usually indicative of cooling at 500 mb. A thickness trough upstream of central Alberta usually places the foothills beneath the region of steepest thickness gradient or, assuming the normal eastward migration of troughs, the region of strongest upper-level cooling. Therefore, the large positive correlation coefficient for UTT lends support to our hypothesis for the need for upper-level cooling on days of severe convection. The 0.49 correlation for UHT points out that while an upstream height trough is a feature common to most severe hail days, it can also be observed on other days and probably would be a poor predictor of severe convection.

The above calculations were repeated, looking at the correlation between a given hail severity and a particular joint, height, and thickness pattern. The last four entries in Table 8 are the results for severe hail and the UHT. A correlation coefficient of 0.92 for (UHT/UTT) indicates that while an upstream height trough alone is only moderately correlated with severe hail, when accompanied by an upstream thickness trough it is highly correlated (little confidence can be placed in a correlation coefficient of 0.63 for UHT/UTR because the sample size was too small). It would seem that if the passage of the upper-level height trough over Alberta is not in phase with the passage of the upper-level thermal trough, a severe convective outbreak is unlikely. This is consistent with Longley and Thompson's (1965) mean 500-mb map for major hail days and with our conceptual model.

[1] The word *aloft*, in this instance, signifies directly above central Alberta.

5. Conclusions

In this study, we have set out to understand the interactions between the mountain–plain and synoptic-scale circulations on days when severe convection is initiated over central Alberta. Three detailed case day analyses for the LIMEX-85 mesoscale field experiment, a brief comparison of all 11 of the LIMEX-85 case days, and a statistical analysis relating the synoptic circulation to the severity of hail have led to the following conclusions.

1) Under generally clear sky conditions, cumulus convection begins over the Alberta foothills, where the capping lid is quickly eroded by strong surface heating.

2) Most severe convective outbreaks appear to occur when cooling aloft, associated with an approaching synoptic-scale, upper-level trough, is *in phase* with strong surface heating over the foothills. The surface synoptic pressure gradient provides for east-northeasterly winds over the plains that transport moist plains air toward the foothills and into the lower branch of the mountain–plain circulation. Such a configuration

TABLE 6. Percentage of severe days with a particular 1200 UTC (0600 LDT) mean sea level pressure pattern: HL—northern high-southern low, L—low alone.

Mean sea level pressure pattern on severe hail days (%)		
HL	L	Other
62	33	15

TABLE 7. Percentage of no-hail days with a particular 1200 UTC (0600 LDT), mean sea level pressure pattern: LHL—northern low-central high-southern low, LH—northern low-central high, HL—central high-southern low, L—low alone, H—high alone.

Mean sea level pressure pattern on no-hail days					
LHL	LH	HL	L	H	Other
36	24	5	12	17	6

brings about localized, deep destabilization, which gives rise to strong upslope moisture transport.

3) The mountain–plain circulation is ineffective in initiating severe convection when subsidence warming associated with an upstream ridge inhibits its growth, and the surface synoptic pressure gradient provides for northwesterly, westerly, or southwesterly winds over the plains. Under these conditions, the plains moisture is advected away from the foothills, so that by the time the thermally induced upslope flow has developed, its moisture content has been depleted to the point of being unable to support severe convection.

In regard to improved prediction of severe weather, the presence of an upstream 500-mb height and thermal trough with southwesterly winds of at least 10 m s^{-1} and an east-northeasterly surface gradient wind direction would indicate the potential for a severe convective outbreak in central Alberta even if the 1200 UTC (0600 LDT) soundings do not exhibit large CAPE. The surface dewpoint temperature and wind fields could be monitored for the presence of moist, capped upslope flow in order to determine the time and location of convective triggering, as well as to estimate the afternoon CAPE. Persistent overcast conditions over the foothills would signal a diminished potential for severe storms even if the large-scale flow pattern is favorable.

TABLE 8. Correlation coefficients for a given 500-mb height and/or 1000–500-mb thickness pattern and severe hail.

Height–thickness pattern	Correlation coefficient and 95% confidence interval
UTT	0.84 [0.73, 0.91]
UTR	−0.53 [−0.71, 0.28]
TTA	−0.68 [−0.82, −0.48]
TRA	0.18 [0.00, 0.34]
UHT	0.49 [0.36, 0.61]
UHR	−0.49 [−0.62, −0.34]
UHT/UTT	0.92 [0.85, 0.95]
UHT/UTR	0.63 [0.00, 0.91]
UHT/TTA	−0.56 [−0.78, −0.22]
UHT/TRA	0.00 [−0.29, 0.18]

Our conceptual model of severe convective outbreaks represents a significant first step toward understanding how the mesoscale and synoptic-scale processes interact to initiate severe convection in Alberta. It also provides an excellent observational study to which numerical modeling simulations may be compared. Three-dimensional simulations using numerical models with realistic topography could be used to investigate the breakdown of the capping lid and the effects of upper-level temperature tendency, low-level moisture, cloud cover, and wind shear on the development of the mountain–plain circulation.

There are several outstanding questions concerning severe convection in Alberta that are beyond the scope of this study. One of the most important of these is, What is the principal moisture source for convection in Alberta? Figure 3, which displays contours of climatological (1951–80) mean maximum daily dewpoint temperature for July, suggests that a tongue of modified maritime tropical air, which enters the Prairie Provinces in southern Manitoba and extends westward into east-central Alberta, is the most likely source. McKay and Lowe (1960) believed, however, that an important fraction of the low-level moisture must originate from evapotranspiration. Potential moisture sources for evapotranspiration include lakes, marshes, river valleys, foothills, forests, and irrigated fields. One possible method to identify source regions for the long-range transport of moisture into Alberta would be to carry out isentropic trajectory analysis (e.g., Carlson and Ludlum 1968) for each of the LIMEX-85 days.

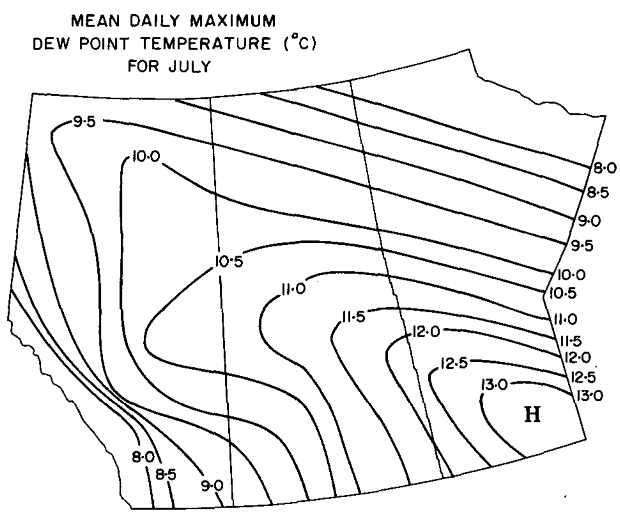

FIG. 3. Mean daily maximum dewpoint temperature for July in the Canadian prairies. Provinces from left to right: Alberta, Saskatchewan, and Manitoba. Contour interval is 0.5°C.

The contribution of evapotranspiration to the total moisture content of the low-level air in Alberta could be quantified by comparing field measurements of evaporation with values resulting from numerical model simulations.

Another important outstanding question is, What causes the formation of the capping lid in Alberta? Strong (1986) felt that the lid is a subsidence inversion enhanced locally near the foothills by orography. Considering the presence of an upper-level ridge prior to severe-outbreak days, some contribution of large-scale subsidence to lid formation is likely. The possibility that the lid may be partly due to advection of an elevated mixed layer (see Carlson et al. 1983) into central Alberta, however, has not been investigated. Over the escarpment of northeastern South Africa, Garstang et al. (1987) found that the lid forms by subsidence and is later enhanced by advection of the elevated mixed layer from the Highveld. There is also evidence in the LIMEX-85 data that lid formation in Alberta may be partly the result of radiative cooling at the surface. Comprehensive analysis of LIMEX sounding data should be carried out to determine the importance of these various processes.

The Alberta mountain–plain circulation is another example of a wide class of mesoscale solenoidal circulations that appear to play a fundamental role in the initiation of severe convection (see Schaefer 1987). For Alberta, we have identified upper-level cooling associated with a synoptic-scale trough as a key factor in permitting such a circulation to amplify. It is of interest to know if such cooling is also operating in other areas (e.g., the central plains of the United States) where differential surface heating and a favorable surface synoptic circulation induce underrunning and the subsequent triggering of severe convection. Such knowledge is vital in determining the best utilization of current and future observing systems for the forecast of severe weather.

Acknowledgments. The authors are very grateful to Dr. G. Strong and the Alberta Research Council for supplying us with the LIMEX-85 dataset. Comments by two anonymous reviewers led to significant improvements in the organization and presentation of the manuscript. This research was supported by the National Science and Engineering Research Council and the Atmospheric Environment Service of Canada. We thank Ms. U. Seidenfuss for aid in preparation of the figures.

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