UNSTABLE

The UNderstanding Severe Thunderstorms and Alberta Boundary Layers Experiment

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Scientific Overview

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AERI	Atmospheric Emitted Radiance Interferometer
AHP	Alberta Hail Project
AIMMS	Aircraft Integrated Meteorological Measurement System
AIRMET	Airman's Meteorological Information
ALHAS	Alberta Hail Studies
AMDAR	Aircraft Meteorological Data Reporting
AMMOS	Automated Mobile Meteorological Observation System
ATMOS	Automated Transportable Meteorological Observation System
BAQS-Met	Border Air Quality Study – Meteorological Measurements
CaPE	Convection and Precipitation/Electrification Experiment
CAPE	Convective Available Potential Energy
CBL	Convective Boundary Layer
CEOS	Centre for Earth Observation Science
CI	convective initiation
CIN	Convective Inhibition
CINDE	Convection Initiation and Downburst Experiment
CLASS	Canadian Land Surface Scheme
CLDN	Canadian Lightning Detection Network
CMAC-W	Canadian Meteorological Aviation Centre – West
CMOS	Canadian Meteorological and Oceanographic Society
CPSWRS	Cloud Physics and Severe Weather Research Section
CRD	Climate Research Division
EC	Environment Canada
ELBOW	Effects of Lake Breezes on Weather
ET	Evapotranspiration
FCA	Foothills Climate Array
FOPEX	Foothills Orographic Precipitation Experiment
GEM	Global Environmental Multiscale
GPS	Global Positioning System
HAL	Hydrometeorology and Arctic Lab
IHOP	International H_2O Project
IOD	Intensive Observation Day
IOP	Intensive Observation Period
LAM	Limited Area Model
LCL	Lifted Condensation Level
LFC	Level of free convection
LIMEX	Limestone Mountain Experiment
MARS	Mobile Atmospheric Research System
MOCISE	Mesoscale Observations of Convective Initiation and Supercell Experiment
MPC	Mountain-Plain Circulation
MRD	Meteorological Research Division
NALDN	North American Lightning Detection Network
NRC	National Research Council
NWP	Numerical Weather Prediction
OPP	Outcome Project Plan
PASPC	Prairie and Arctic Storm Prediction Centre
PI	Principal Investigator
PW	Precipitable Water
QC	Quality Control
RSD	Research Support Desk
SIGMET	Significant Meteorological Information
STEPS	Severe Thunderstorm Electrification and Precipitation Study
UAV	Unmanned Aerial Vehicle
UNSTABLE	Understanding Severe Thunderstorms and Alberta Boundary Layers Experiment
UTC	Coordinated Universal Time
VORTEX	Verification of the Origins of Rotation in Tornadoes Experiment
WMI	Weather Modification Incorporated

1. Executive Summary

The Alberta Foothills experience more thunderstorm days than any other region in the Canadian Prairie Provinces. Most storms developing there move eastward to affect the Edmonton – Calgary corridor, one of the most densely populated and fastest growing regions in Canada. Alberta has proven to be particularly susceptible to costly thunderstorm events, e.g., Public Safety and Emergency Preparedness Canada estimate that since 1981 more than 40 lives and $ 2.5 B have been lost due to severe storms.

Environment Canada researchers and other interested scientists from academia and the private sector have designed a field experiment in the Alberta Foothills to investigate atmospheric boundary layer (hereafter ABL) processes associated with convective initiation (hereafter CI) and severe thunderstorm development. The Understanding Severe Thunderstorms and Alberta Boundary Layers Experiment (UNSTABLE) will investigate the importance of ABL water vapour availability / stratification, mesoscale convergence boundaries, land surface and ABL interactions, and numerical modeling applications to the development of severe thunderstorms over the Alberta Foothills. Following a pilot experiment during the summer of 2008 to test and refine measurement strategies, UNSTABLE will take place from 1 June to 31 August 2011 with a three week intensive observation period planned during July. Measurements obtained through a high-resolution network of fixed and mobile surface, upper-air, and airborne instruments will be used together with measurements from existing platforms to better understand important mesoscale processes in this thunderstorm genesis zone.

The overall goals of UNSTABLE are:

- To better understand atmospheric processes leading to thunderstorm development over the Alberta Foothills (both prior to and during CI) with an aim to extend results to the rest of Canada
- To improve accuracy and lead time for severe thunderstorm watches and warnings
- To assess the Canadian GEM-LAM mesoscale model in resolving physical processes over the Alberta Foothills and its ability to provide useful numerical guidance for forecasting severe convection
- Through observational, case, and model studies refine current existing conceptual models describing CI and the development of severe thunderstorms over Alberta and the western prairies

To address these goals we have formulated the following three primary science questions:

1. What are the contributions of ABL processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?
2. What are the contributions of surface processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?
3. To what extent can high-resolution numerical weather prediction models contribute to forecasting the initiation and development of severe convective storms that originate in the Alberta foothills?

Associated with the above questions are a number of more specific sub-questions to be answered with data from UNSTABLE. Rationale for the project, extensive literature reviews, deliverables, and details on experimental design are included in this scientific overview document. An UNSTABLE operations plan is under development containing specifics related to instrument deployment, field logistics, etc.

2. Rationale for UNSTABLE

Rationale for the UNSTABLE project may be described in terms of impacts of summer severe weather in Alberta, forecast challenges for the Prairie and Arctic Storm Prediction Centre (PASPC), and the project's relationship to the results-based priorities of Environment Canada.

2.1 Socio-economic Impacts of Severe Weather in Alberta

The Canadian prairies are subject to a high frequency of thunderstorms and associated severe weather[1] during the summer months. Based on severe weather reports received by the Prairie and Arctic Storm Prediction Centre (PASPC), the prairies experience an average of 203 severe weather events each summer (McDonald and Dyck 2006). The average distribution of summer severe weather reports for each of the Prairie Provinces is shown in Table 1.

Table 1: Average number of summer severe weather reports for the Canadian Prairies during the period 1984 to 2006 based on reports collected by the Prairie and Arctic Storm Prediction Centre (McDonald and Dyck 2006). The numbers are rounded to integer values in the last row of the table accounting for the total of 203 events instead of 204.

Event Type	Alberta	Saskatchewan	Manitoba	Average for Prairies
Tornado	13	14	9	36
Hail	39	33	25	97
Wind	12	20	13	45
Rain	10	7	8	25
All Events	74	75	55	203

Areas of the prairies experiencing a high frequency of thunderstorms are evident in climatological lightning data from the Canadian Lightning Data Network (CLDN). A map of the mean number of days with at least one cloud-to-ground lightning flash detected between 1999 and 2006 (Burrows 2006, personal communication) shows that the Rocky Mountain Foothills region of Alberta experiences, on average, the most days with lightning (Figure 1). A secondary maximum of lightning activity extends through the far southern portions of Saskatchewan and Manitoba.

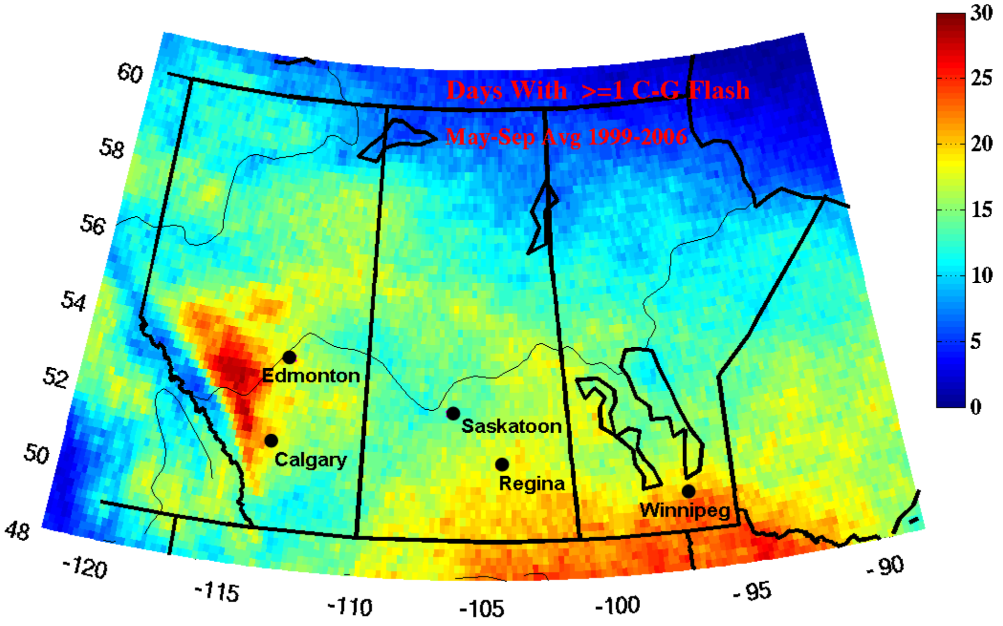

Figure 1: Climatological lightning activity over the Canadian Prairies showing the average number of days with at least one cloud to ground flash from 1999 to 2006 (Burrows 2006, personal communication).

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[1] Here, severe weather refers to the occurrence of tornadoes, hail with diameter 20 mm or greater , convective wind gusts of 90 kmh^{-1} or greater and/or convective rainfall amounts of 50 mm or greater in 1 hour.

Alberta has proven to be particularly susceptible to costly summer severe weather events. The most devastating event to date is the Edmonton F4 tornado and hailstorm of 31 July 1987 resulting in 27 lives lost and damage estimates in range of $660 m. Other costly severe weather events in Alberta are included in Table 2.

Table 2: List of the costliest Alberta summer severe weather events since 1980, all values taken from the Public Safety and Emergency Preparedness Canada Canadian Disaster Database[2]. Events in bold resulted in loss of life or at least $100 M estimated losses. Note that there has not been a major hailstorm in Calgary for 8 years while there were 2 in the 1980's and 7 in the 1990's.

Date	Location	Event	Estimated Damage	Deaths
11 July 2004	Edmonton	Hail	$ 74,000,000	
14 July 2000	**Pine Lake**	**Tornado/Hail**	**$ 30,477,000**	**12**
4-8 July 1998	Calgary	Hail	$ 65,258,000	
24-25 July 1996	Calgary	Hail	$ 87,877,000	
16-18 July 1996	**Calgary**	**Hail**	**$ 305,854,000**	
17 July 1995	Calgary	Hail	$ 74,559,000	
4 July 1995	Edmonton	Hail	$ 34,511,000	
18 June 1994	Southern Alberta	Hail	$ 30,969,000	
29 July 1993	Edmonton	Hail	$ 21,095,000	
1 September 1992	Edmonton	Hail	$ 22,522,000	
28 August 1992	Edmonton	Hail	$ 20,170,000	
31 July 1992	Calgary	Hail	$ 38,495,000	
7 September 1991	**Calgary**	**Hail**	**$ 884,595,000**	
3 July 1991	Red Deer	Hail	$ 40,387,000	
9 July 1990	Calgary	Hail	$ 22,028,000	
16 August 1988	Calgary	Hail	$ 61,024,000	
31 July 1987	**Edmonton**	**Tornado/Hail**	**$ 665,483,000**	**27**
28 July 1981	**Calgary**	**Hail**	**$ 288,414,000**	**2**
Total Estimated Cost			$ 2,767,718,000	41

The events noted above are all within the Edmonton to Calgary corridor which lies adjacent to, and just east of, the Alberta Foothills. Thunderstorms developing on the foothills tend to move with an eastward component of motion due to prevailing westerly winds aloft. Alberta contains 2 of Canada's 10 busiest airports (Calgary International 3rd and Edmonton International 7th, Transport Canada 2005) and the Edmonton to Calgary corridor is one of the most densely populated and fastest growing regions in Canada (Statistics Canada 2006 Census, see Figure 2). Given these facts, the potential for further risk to life and property in southern Alberta due to summer severe weather events is clear. Improved understanding of processes associated with the development of severe thunderstorms in the Alberta Foothills and application of that knowledge to operational forecast techniques will allow forecasters to maximize their ability to issue accurate and timely severe weather warnings and forecasts.

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[2] The Public Safety and Emergency Preparedness Canada Canadian Disaster Database is available online at: http://www.psepc-sppcc.gc.ca/res/em/cdd/search-en.asp . Dollar figures for events prior to 2001 have been adjusted to 1999 Canadian dollars.

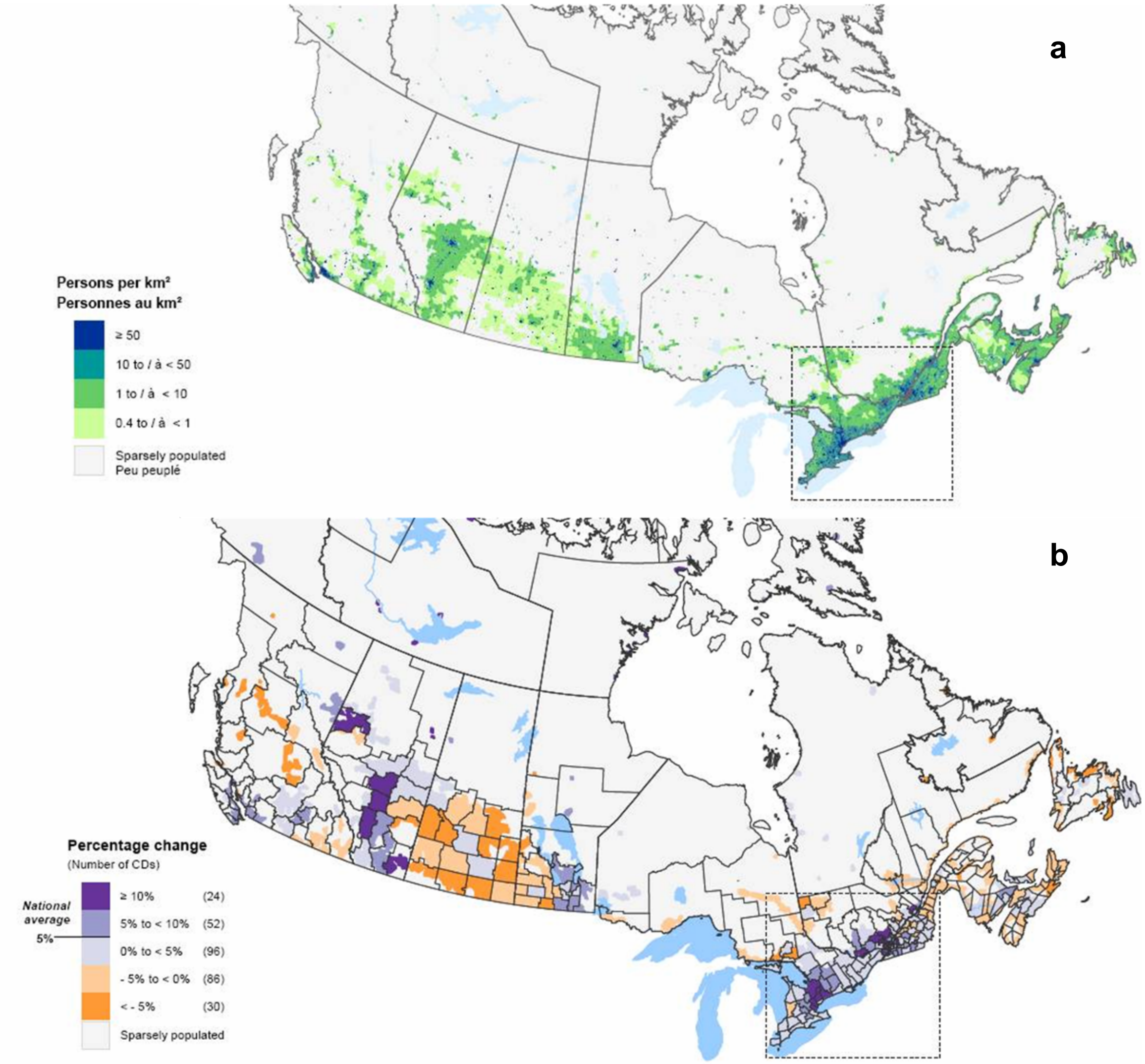

Figure 2: (a) Population density and (b), change in population from 2001 to 2006 over southern Canada from the Statistics Canada 2006 Canadian Census. The Edmonton – Calgary corridor is among the most densely populated and fastest growing regions in Canada.

2.2 Summer Severe Weather Forecast Challenges

The high frequency of thunderstorms and the socio-economic impacts of severe weather events in Alberta illustrate the need for accurate and timely severe thunderstorm watches and warnings in the region. Accurate forecasts of CI and thunderstorm severity generally require knowledge and understanding of the following:

- ABL structure and evolution, especially with respect to stratification of water vapour in the vertical
- Adequate conceptual models to describe processes leading to CI and the development of severe thunderstorms
- Mesoscale boundaries and circulations in the region of interest and their behaviour in association with CI
- Adequate in situ or remote sensing observations to resolve atmospheric characteristics and evolution associated with CI, especially with respect to mesoscale boundaries. In the absence of sufficient observations, techniques to infer important atmospheric characteristics and evolution given available observations.

- An understanding of important land-surface interactions with the convective ABL in the region of interest and their role in CI
- Performance of numerical models with respect to the above (e.g., strengths, weaknesses, systematic biases)

Water vapour availability can often be the limiting factor in the potential for severe thunderstorms in Alberta. Smith and Yau (1993b) showed climatological mean maximum dewpoint temperatures for July across the prairies for the period 1951-1980 (Figure 3) that highlight the drier conditions that become prevalent towards the western prairies. The gradient in dewpoint near the Alberta foothills is likely due in part to increasing terrain height but the presence of the dryline (e.g., Knott and Taylor 2000, Hill 2006), gradients in soil moisture, or evapotranspiration rates associated with transitions in vegetation types may also exert influence on regional dewpoint climatology.

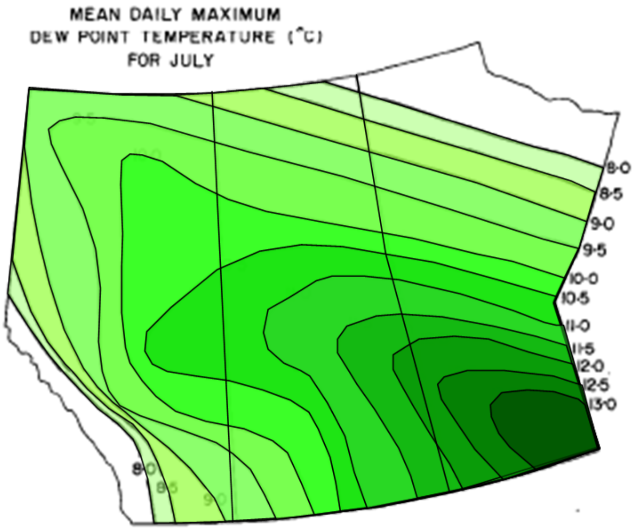

Figure 3: Climatological mean daily maximum dewpoint for July on the Canadian prairies for the period 1951-1980 (adapted from Smith and Yau 1993b).

Accurate estimates of convective instability require representative values of temperature and dewpoint (or mixing ratio) for a lifted parcel. The choice of a near-surface parcel (e.g., surface-based or with mean potential temperature and mixing ratio over some depth) has significant implications for estimates of thermodynamic instability (e.g., Bunkers et al. 2002). Craven et al. (2002) showed that a 100 hPa mean-layer parcel showed better correlation with observed convective cloud base heights than a surface-based parcel in the U.S. and suggested that the use of surface-based parcels often results in overestimates of convective instability. The selection of an appropriate temperature and mixing ratio for a near-surface parcel depends on knowledge of the thermal and moisture stratification above the surface. In Alberta, without moisture measurements on AMDAR soundings, profilers, or soundings over the foothills, forecasters often have little knowledge of moisture stratification and depth or, in some cases, of surface dewpoint. Since accurate convective forecasts are sensitive to observations of surface and ABL temperature and water vapour (e.g., Crook 1996) the ability of PASPC forecasters to issue timely and accurate forecasts of severe weather near the foothills may be limited. High spatial and temporal resolution measurements of water vapour at the surface and in the vertical are required to resolve and understand the structure and evolution of the ABL over this region prior to and during CI.

Conceptual models for CI and severe storm development are a critical element of the forecasting process (Johns and Doswell 1992, Joe et al. 1995). In regions with limited observational data, forecasters must apply conceptual models to available observations to infer active atmospheric processes of interest. In the case of the Alberta foothills, models for CI and severe thunderstorms are based largely on research that was conducted nearly two decades ago (e.g., Strong 1986, Smith and Yau 1993b). These studies link the synoptic upper-level flow and surface pressure patterns to the development of the capping lid and occurrence of a secondary circulation driven by differential heating known as the mountain-plain circulation (see section 3 for a more complete description of these studies). The resulting conceptual models are largely synoptic in scale and do not incorporate the presence of low-level convergence boundaries that are known to be important for CI (e.g., Ziegler and Rasmussen 1998, Weckwerth and Parsons 2006). In order to refine existing conceptual models for severe thunderstorm development over the Alberta foothills, ABL and near-surface processes must first be sampled and understood.

In recent years the dryline[3] has garnered increasing attention as a focus for CI over the Alberta foothills and has been shown to be an important factor in the development of tornadic supercells (e.g., Knott and Taylor 2000, Taylor 2001, 2004, Hill 2006). During the summer of 2000, the dryline was estimated to play a role in the development of severe thunderstorms on 13 of 23 severe weather days, accounting for 56% of the severe hail and tornado reports received by Environment Canada in Alberta for that year (Taylor 2004). The dryline in Alberta has been sampled using a line of closely spaced surface observations as well as with mobile humidity measurements (Hill 2006). However, the near dryline wind field near the surface and vertical profiles of temperature, humidity, and wind have not been sampled at all in Alberta.

The ability for forecasters to issue accurate warnings depends, in part, on the quality and quantity of surface, upper-air and remote sensing observational data available to them. Alberta contains only one upper air site (Stony Plain, approximately 40 km west of Edmonton) that is often not representative of conditions over the foothills, especially with respect to ABL moisture. Real time surface weather observations over the foothills are limited (Figure 4). A comparison of Figures 1 and 3 shows that the area of highest lightning frequency corresponds well to the area with the sparsest surface observations, in some cases over 100 km between stations. It should be noted that the stations at Jasper, Sask. River Crossing, Banff and Bow Valley are within the Rocky Mountains and do not necessarily represent conditions within the ABL over the foothills, therefore their use in thunderstorm forecasting is often limited.

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[3] In general terms, the dryline in Alberta is a boundary separating moist ABL air on the eastern slopes of the foothills and dry air subsiding in the lee of the Rocky Mountains. The dryline tends to form in Alberta due to a process similar to that of a Chinook and has been associated with CI and the development of severe thunderstorms both in Alberta and on the U.S. Great Plains.

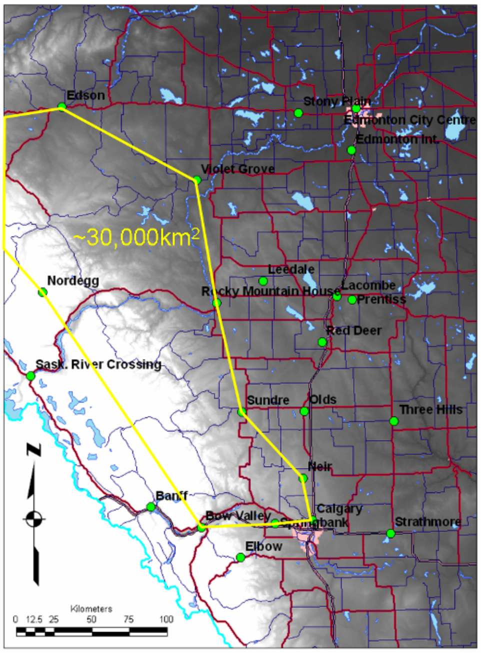

Figure 4: Hourly surface observation sites available to forecasters over the foothills region of Alberta. The main area of thunderstorm development is west of a line from Violet Grove to Calgary. The yellow polygon denotes an area of just over 30,000 km^2 within which there are no surface observations. This area also corresponds to the area with the highest occurrence of lightning days in Figure 1.

As a result of limited observational data, forecasters often must depend largely on their ability to interpolate observations in time and space. Processes leading to thunderstorm development often occur on small spatial and temporal scales (Weckwerth and Parsons 2006) limiting the applicability of distant observations due to displacement in space of the observations and rapid changes in ABL, or other, characteristics. To resolve and understand near-surface processes that may be important for CI and severe thunderstorms in the foothills region, a mesoscale network (hereafter mesonet) of surface, upper-air or profiler, and in situ airborne measurements is required.

Local evapotranspiration (hereafter ET) has been shown to be an important source of ABL water vapour on the Canadian Prairies (e.g., Raddatz 1998, Raddatz and Cummine 2003, Hanesiak et al. 2004). Forecasters at the PASPC have long recognized the importance of ET for thunderstorm development, especially as the frequency of thunderstorms decreases in conjunction with the heading[4] of crops and the fall harvest. An attempt to quantify ET contributions to ABL water vapour has been developed through an agrometeorological numerical model (Raddatz et al. 1996) run by Hydrometeorology and Arctic Lab staff in Winnipeg. Contributions from ET with respect to CI over the Alberta foothills are somewhat less certain. The eco-climatic regions of the Canadian Prairies are shown in Figure 5. Of particular interest is the change from Arid- through Subhumid- and Transitional Grasslands to Southern Cordilleran eco-climatic regions near the foothills (rectangle in Figure 5). Assuming sensible and latent heat flux rates vary with eco-climatic region (Raddatz and Noonan 2004) a persistent gradient in ET may exist in the vicinity of the foothills as shown for 1996 by Liu et al. (2003). Gradients in ET and soil moisture have been linked with local mesoscale circulations (e.g., land-land breezes) and CI (Hanesiak et al. 2004). Direct measurements of sensible and latent heat flux as well as soil moisture in this transition region would help characterize the impacts of soil moisture and ET on observed mesoscale

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[4] Heading refers to the development of the seed in cereal crops and is typically associated with a decrease in evapotranspiration.

boundaries and CI in the region. Measurements of this kind could also be used to validate the agrometeorological model in an effort to quantify ET effects for operational forecasters.

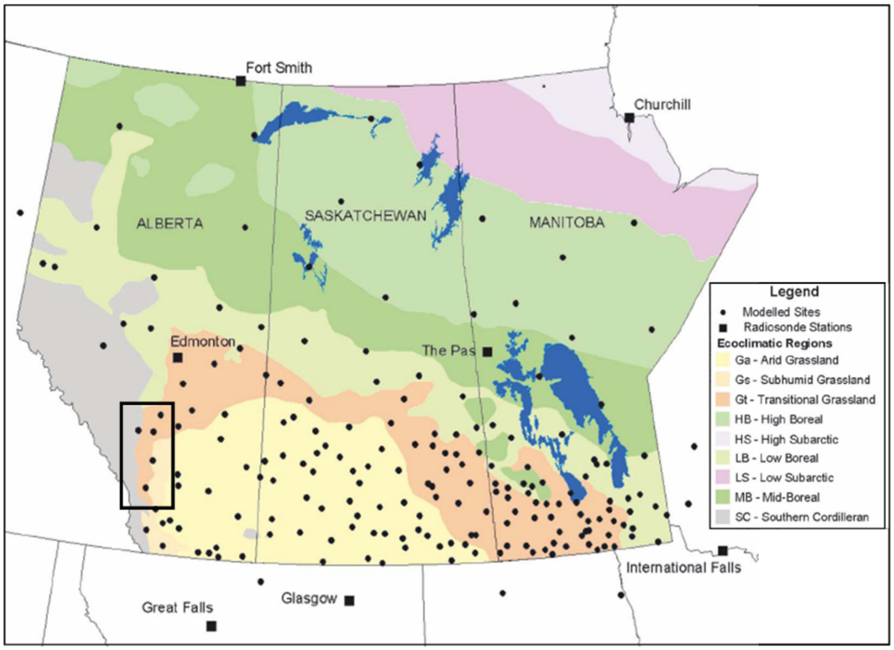


Figure 5: Eco-climatic regions of the Canadian Prairies along with Environment Canada radiosonde sites and sites at which the agrometeorological model is run (from Raddatz and Noonan 2004). The black rectangle indicated the area with significant changes in eco-climatic region described in the text.

Numerical model output is a necessary component of the modern storm prediction centre. PASPC forecasters use output from the Canadian Meteorological Centre's (CMC) Global Environmental Multiscale (GEM) Regional (REG) model as their primary operational numerical model. Recently, a high-resolution (2.5 km horizontal grid-spacing) version of the GEM-LAM (Limited Area Model) has been available to operational staff over specific geographical domains, for limited time periods, as an experimental tool. Informal evaluations of the GEM–LAM-2.5 during the 2006 convective season by the lead author, HAL, and PASPC staff suggest the model may have utility in characterizing the pre-storm environment including the formation of convergence lines in the foothills region. Further evaluations are required to assess the model's utility in forecasting timing and location of CI and mode of ensuing convection.

Understanding of the processes in the ABL related to CI is an ongoing area of research within the meteorological community. For PASPC forecasters, the lack of observations over the prime thunderstorm genesis region in Alberta limits their ability to anticipate the development of severe thunderstorms and issue warnings accordingly. Water vapour availability and depth is an especially critical factor in assessing the potential for severe thunderstorms over the western prairies. The forecast challenges described in this section point to the need for a field experiment to measure the spatial (in three dimensions) and temporal characteristics of the ABL over the foothills, especially with respect to water vapour distribution and vertical stratification and the development and evolution of mesoscale convergence lines (including the dryline). Results from UNSTABLE will improve understanding of how these factors contribute to CI and the development of severe thunderstorms thus allowing refinement of conceptual models and improving forecasters' ability to issue accurate and timely warnings.

2.3 Relationship to Environment Canada's Results-Based Structure

The UNSTABLE project is being designed in support of identified priorities of the Meteorological Service of Canada and Environment Canada. The project is directly related to no less than 10 Outcome Project Plans (OPPs) as identified in the most recent Environment Canada results-based structure. The OPPs of interest are given below along with a brief explanation of how UNSTABLE is related to them.

2. Weather and environmental predictions and services reduce risks and contribute to the well-being of Canadians

- **A**. Improved knowledge and information on weather and environmental conditions influences decision-making
    - **1**. Environmental monitoring allows EC to identify, analyse and predict weather, air, water and climate conditions
        - **2A1a** Atmospheric conditions near the surface are monitored
        - **2A1b** Atmospheric conditions aloft are monitored
        - **2A1f** Network planning management and standards ensures integrity of monitoring networks

Success of the UNSTABLE field campaign planned for July 2008 is reliant upon the quantity and quality of in situ measurements obtained. The UNSTABLE observation network is expected to consist of multiple data collection platforms for both surface and upper-air measurements. These include special weather stations supplemented by existing observation stations to form a mesonet of over 20 observation locations. In addition, at least one mobile mesonet station has been tested and will be deployed within the stationary mesonet for measurements with enhanced spatial and temporal resolution. Upper-air measurements will include multiple radiosonde locations, multiple profiling instruments, surface-based measurements of precipitable water using GPS technology, and a request has been submitted for the NRC Twin Otter aircraft for airborne measurements. One of the objectives of UNSTABLE is to assess the ability of the existing observation network to resolve the physical processes important for CI and to suggest adjustments to the network that may improve its utility in this regard.

- **2**. Science supports weather and environmental predictions and services, departmental decision making and policy development
    - **2A2a** Numerical Weather and Chemical Prediction contributes to understanding how to predict a future state, from minutes to seasons, of the atmosphere and the underlying surface conditions, using numerical models and methods developed to simulate the atmosphere and its coupling to chemistry
    - **2A2c** Cloud physics and severe weather research support understanding, detection and prediction of severe and high impact weather events
    - **2A2e** Water Cycle Prediction supports understanding and predictions of all phases of the water cycle with impacts on human and ecosystem health

One component of UNSTABLE is the evaluation of the GEM model, both the regional (15-km) and the LAM-2.5 configurations, in terms of its ability to predict CI over the Alberta foothills, in particular with respect to ABL water vapour and wind fields. Another important part of the project will be to examine in detail the utility of the current high-resolution model runs in terms of their usefulness to contributing to forecasting thunderstorms in Alberta.

In support of the hydrological modeling efforts within the Hydrometeorology and Arctic Lab, the dataset obtained from UNSTABLE can be used to evaluate ongoing efforts in coupling a version of the Canadian Land Surface Scheme (CLASS) with the operational GEM model. Measurements of precipitation, soil moisture and evapotranspiration would be valuable to the hydrology and hydrometeorology community in improvement of numerical parameterization of land-surface and ABL interactions.

- **B**. Canadians are informed of, and respond appropriately to, current and predicted environmental conditions

1. Environmental forecasts and warnings are produced to enable the public to take action to protect their safety, security and well being

  2B1a Weather warnings, forecasts and information for safety of Canadians and sound decision-making

  2B1f Canadians react effectively to hazardous events through better warning preparedness

An anticipated direct result from UNSTABLE is improved understanding of physical processes associated with CI and the development of severe thunderstorms over the Alberta foothills. Modification of existing conceptual models to incorporate the latest science and high resolution in situ measurements will enable forecasters to better understand and recognize the potential for severe thunderstorms in Alberta and improve their ability to issue timely and accurate watches and warnings. Improved understanding can also be transferred to Warning Preparedness Meteorologists and Emergency Management Organizations to incorporate into their plans.

2. Canadians are better informed through improved weather and environmental services and leveraged partnership opportunities

  2B2c Improved weather and Environmental services

3. Canadians benefit from the creation and use of meteorological and environmental information by EC and F/P/T partners, in support of programs of common interest

  2B3a Aviation weather services for NAV CANADA

Improved understanding of CI and severe thunderstorm development should result in improved severe weather watches and warnings as well as routine public forecasts. The potential exists for results to be incorporated into other publicly available products, web-based or otherwise, that could be developed within Environment Canada or as part of private sector weather services.

The aviation weather program of the Canadian Meteorological Aviation Centre – West (CMAC-W) is based in Edmonton and shares forecast office space with the PASPC. Thunderstorms are a major issue for both forecasters and the aviation community during the summer months on the Prairies. Improved knowledge gained from UNSTABLE and transferred to CMAC-W forecasters will have a direct impact on the production of the Graphical Area Forecast, quality of Terminal Aerodrome Forecasts at locations adjacent to the foothills (most notably Calgary and Edmonton International Airports), and improved anticipation of convective weather for AIRMETs and SIGMETs.

2.4 Summary of Rationale for UNSTABLE

The UNSTABLE project is being designed to address a number of issues that fall under the mandate of Environment Canada and have direct impacts on the Canadian public. The project rationale may be summarized as follows:

i. To mitigate the impacts of severe thunderstorms in Alberta by increasing our understanding of processes leading to their development thereby helping forecasters to issue more accurate and timely watches and warnings
ii. To better understand the structure and evolution of the ABL over the Alberta foothills, especially with respect to water vapour
iii. To refine existing conceptual models of severe thunderstorm development in Alberta by incorporating the latest science and high spatial and temporal resolution observations of convergence lines and other important boundaries or circulations
iv. To better understand the role and significance of the dryline and other boundaries for severe thunderstorm development and regional thunderstorm climatology
v. To assess the utility of the existing synoptic observation network in detecting mesoscale features important for CI and severe thunderstorm development over the Alberta foothills and make suggestions for improvements

vi. To better understand the role and impacts of evapotranspiration for CI and severe thunderstorm development over the Alberta foothills
vii. To evaluate the performance of regional and high-resolution numerical weather prediction over the Alberta foothills
viii. To contribute to the success of defined Outcome Projects within Environment Canada's results-based organizational structure

3. Literature Review

Here we present a review of research related to UNSTABLE objectives to put our work in context of other studies.

3.1 Selected Alberta Thunderstorm Research

Most of the thunderstorm-related research in Alberta has been associated with the Alberta Hail Studies (ALHAS) Project and/or the Alberta Hail Project (AHP) that extended from 1957 to 1985. Many hail-related studies resulted from the ALHAS and AHP data; here we will consider only Alberta studies related to CI and severe weather outbreaks, conceptual models and severe weather climatology.

To relate upper-air observations to the occurrence of severe hailstorms, Longley and Thompson (1965) constructed mean geopotential height and temperature maps (500 hPa and 850 hPa) at 0000 UTC and 1200 UTC for major, minor, and no-hail days using upper-air sounding data (Figures 6 and 7, see their paper for definitions). For major hail days they found a prominent upper trough was present over British Columbia, cooler 500 hPa temperatures and stronger thermal gradients, and stronger 500 hPa southwesterly flow over Alberta than for no hail days (Figure 6). At the 850 hPa level a trough deepening through the day and a well defined thermal ridge near the Alberta – Saskatchewan border was associated with major-hail days (Figure 7). Similar large-scale patterns continue to be observed by operational forecasters in association with severe hail outbreaks in Alberta. The question of evapotranspiration impacts on convection were also considered with the suggestion that reduced evapotranspiration in late August associated with the harvest may reduce the frequency of hail outbreaks late in the convective season.

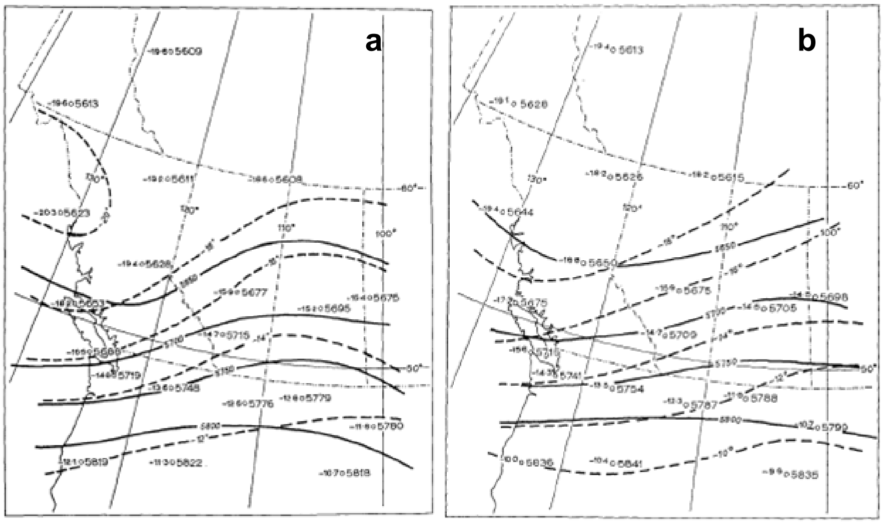


Figure 6: 500 hPa composite maps for (a) 1200 UTC, and (b), 0000 UTC on major hail days. Heights are in m (from Longley and Thompson 1965).

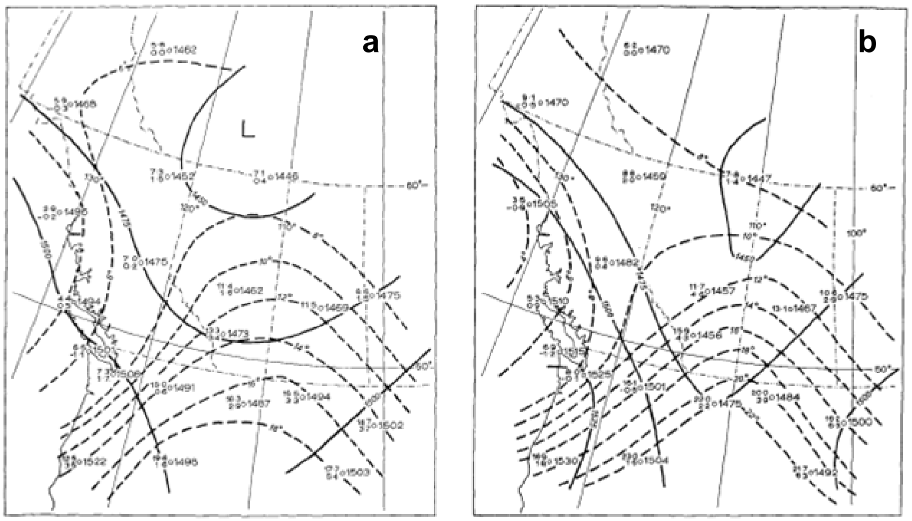


Figure 7: 850 hPa composite maps for (a) 1200 UTC, and (b), 0000 UTC on major hail days (from Longley and Thompson 1965).

A comprehensive summary of data collected from the ALHAS project was presented by Wojtiw (1975). There were found to be an average of 61.3 hail days each summer with 33% of those days in July. Climatological information on seasonal variation of hail days (Figure 8) and locations of the highest frequency of hail days were also included (Figure 9).

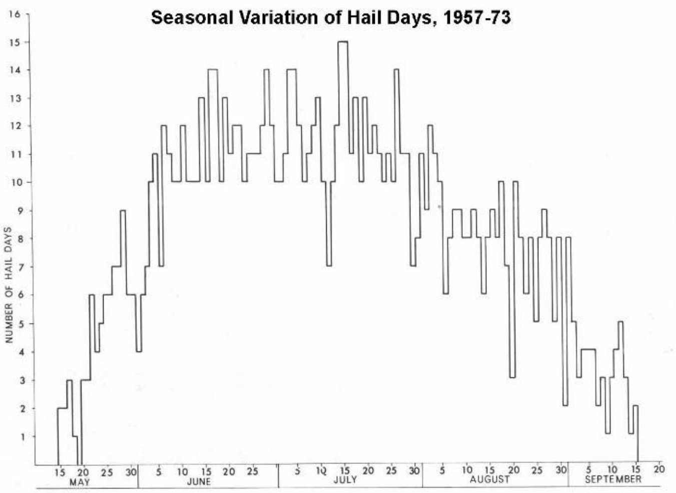


Figure 8: Seasonal variation of the number of hail days within the ALHAS study area from 1957 to 1973 (Wojtiw 1975).

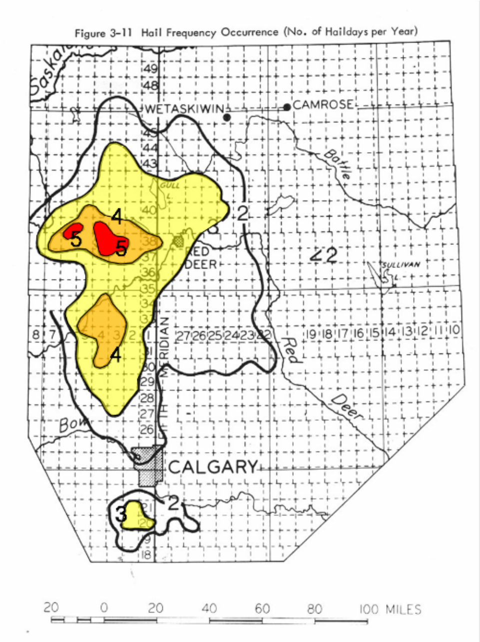


Figure 9: Spatial distribution of average number of hail days per year from ALHAS data (adapted from Wojtiw 1975). The location of the UNSTABLE mesonet is designed to capture the main genesis region of storms that produced the maxima of hail days west and southwest of Red Deer.

A conceptual model for severe thunderstorm outbreaks initiated in the foothills region of Alberta was proposed by Strong (1986), and later refined by Strong and Smith (2001). Following a period where Alberta lies under an upper-level ridge, the advancement of an upper trough, with accompanying southwesterly winds at mid levels, results in orographic subsidence and the development of a capping lid over the foothills. Radiative cooling under clear skies during the night strengthens the low-level inversion. As the day progresses, surface cyclogenesis is initiated over southern Alberta in response to the approaching upper trough. Differential heating over the foothills promotes upslope flow and water vapour is added to the air advecting toward the foothills due to evapotranspiration processes on the plains. Prior to the passage of the upper trough, orographic subsidence, and the capping lid, is maintained in the lee of the mountains. As the ABL over the higher terrain is heated, upslope flow allows moist air to underrun the capping lid and ascend to assist in weakening the capping lid from below. Synoptic-scale lift associated with the approaching upper trough contributes to further weakening of the capping lid and eventually storms develop over preferred areas where the lid has been weakened most rapidly. The process is summarized graphically in Figures 10 and 11. Strong verified his model against data collected during the Limestone Mountain Experiment – 1985 (LIMEX-85, Strong 1989). The LIMEX-85 observation network (Figure 12) consisted of upper-air soundings from 9 locations every two hours between 1400 UTC and 0000 UTC, 8 surface stations with 5-minute average parameter measurements, 13 forestry stations with twice daily observations and regular synoptic Environment Canada stations.

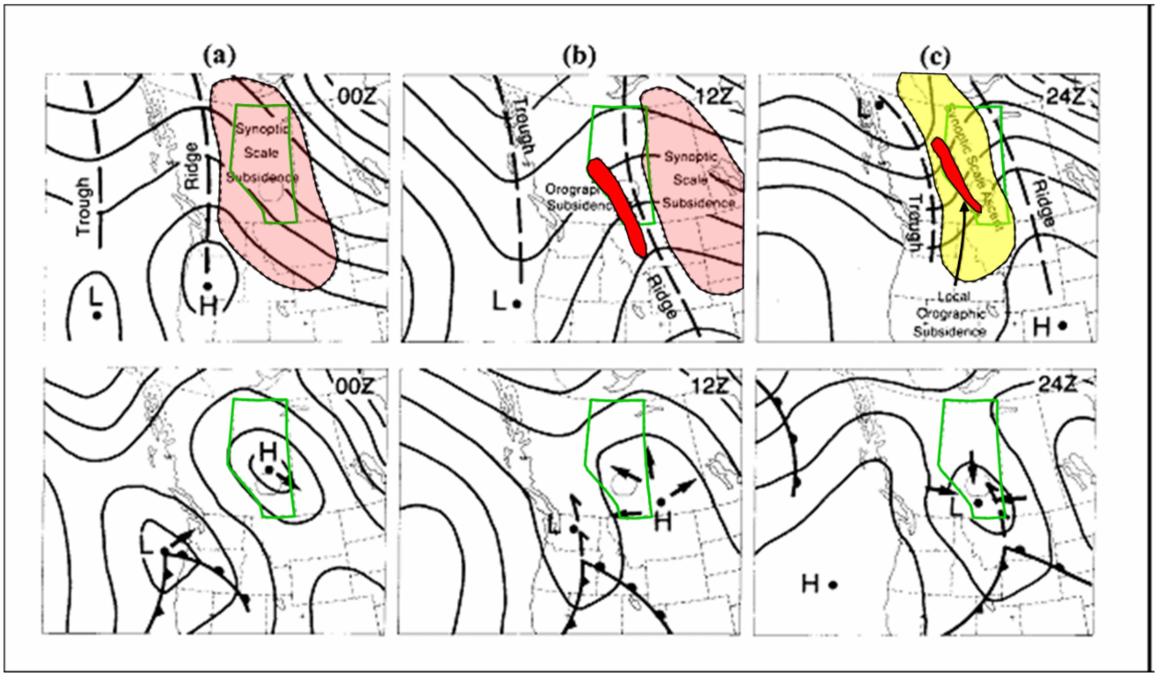


Figure 10: Graphical depiction of the conceptual model of Strong (1986) for severe thunderstorm outbreaks over Alberta. The top figures are the 500 hPa pattern and the lower figures are the associated surface pressure field at the noted time. Periods are late afternoon the day before the outbreak (a), the morning of the outbreak (b), and the late afternoon of the outbreak (c). Areas of large-scale subsidence are lightly shaded red, darker red indicates areas of local orographic subsidence, and the yellow area in (c) is associated with synoptic-scale ascent. The province of Alberta is outlined in green. Adapted from Strong and Smith (2001).

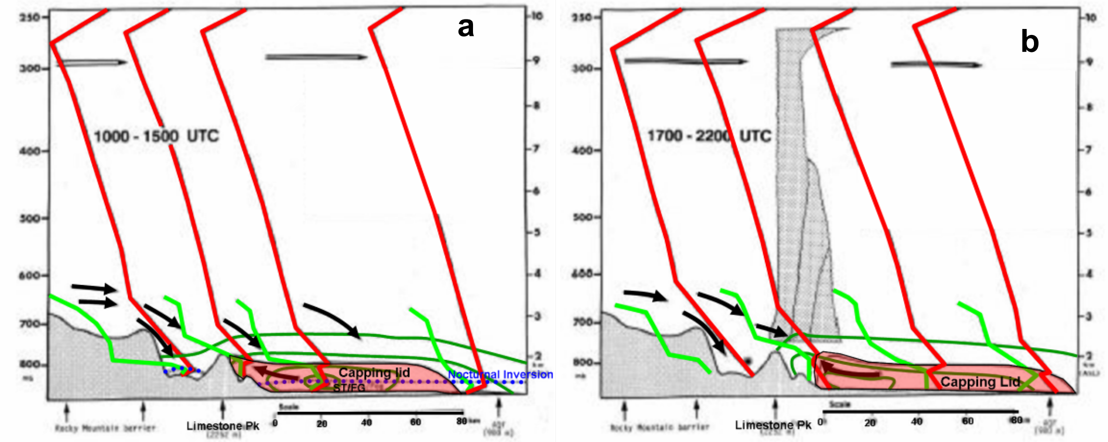


Figure 11: Vertical cross sections of Strong's (1986) conceptual model for (a) 1000 to 1500 UTC on the morning of the convective outbreak, and (b), 1700 to 2200 UTC on the afternoon of the outbreak. Vertical profiles of temperature are in red and of dewpoint in green. Dark green contours are of mixing ratio or dewpoint and red shaded area is the area under the capping lid. The dotted blue line in (a) is the height of the nocturnal inversion and black arrows indicate airflow. Adapted from Strong and Smith (2001).

Using a severe hail day from the LIMEX-85 data set (11 July 1985), Honch and Strong (1990) constructed vertical velocity fields prior to CI. They found general ascent east of the foothills and subsidence in the lee of the mountains supporting the conceptual model of Strong (1986). An additional finding of this study was a strong line of surface convergence associated with the development of convective clouds. One conclusion was that sources of lift associated with CI in the foothills were due, at least in part, to surface convergence and not entirely to orographic subsidence or circulations resulting from differential heating (i.e., the mountain-plain circulation).

Using the same LIMEX-85 dataset, Smith and Yau (1993a, b) investigated the relationship between synoptic and mesoscale processes and their role in the initiation of severe thunderstorms over the Alberta foothills. They suggested that the mountain-plain circulation (MPC), *"…may act in concert with the synoptic-scale pressure gradient to give rise to severe convection"*. Their study focussed on the role of the MPC, the significance of the synoptic setting of Longley and Thompson (1965), and where and when the capping lid is weakened or removed on severe weather outbreak days. Data from LIMEX-85 were analysed for days where a capping lid was observed.

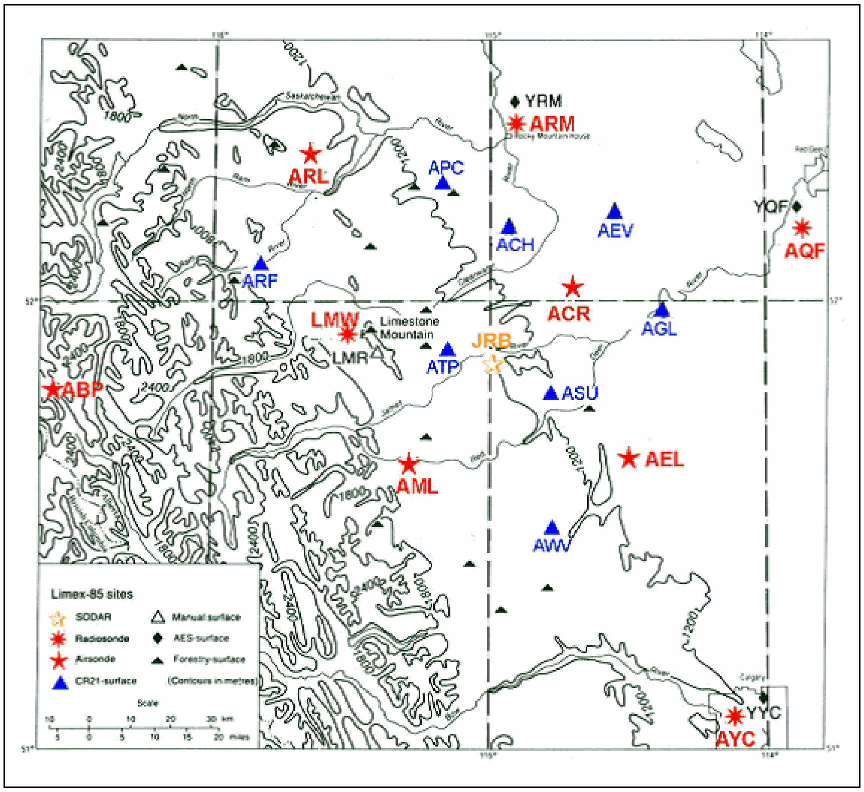


Figure 12: Map showing the LIMEX-85 study area (from Strong and Smith 2001).

Using the same severe hail day as Honch and Strong (1990), Smith and Yau (1993a) showed the capping lid was eroded by surface heating at a quicker rate over higher terrain (LMW in Figure 12) than closer to the plains (ARM in Figure 12). They suggested that the synoptic surface flow advected moisture into the lower branch of the MPC resulting in ABL water vapour being advected to higher elevations. Water vapour then underruns the capping lid to reach the area where the lid has been eroded by surface heating and helps initiate convection. The moist air underrunning in association with the MPC, when timed with upper-air destabilization, results in thunderstorm development.

Analyses of surface winds and dewpoint temperature at 1600 UTC and 1800 UTC on 11 July 1985 (Smith and Yau 1993a) show the formation of a well-defined convergence line associated with a strong moisture gradient (Figure 13). The presence of a line of convergence in this area was noted by Honch and Strong (1990). The area of deepest ABL depth at 16 UTC corresponds with the area of lowest dewpoints (see Figure 13a). The presence of a deep, well-mixed ABL in dry air adjacent to a strong moisture gradient accompanied by surface wind convergence and shallow, moist ABL, is analogous to accepted conceptual models of the dryline in the Great Plains of the United States (e.g., Ziegler and Rassmussen 1998). Similar dryline boundaries have been proposed in this area of Alberta by Taylor (2001) and sampled by Hill (2006). Moisture gradients across the boundary in Figure 13b are ~13 ˚C over 20 km (0.65 ˚Ckm^{-1}) between AML and AEL.

The true strength of the moisture gradient is unknown due to limited observing station density and lack of mobile measurements. Still, similar across-dryline moisture gradients have been sampled in field studies on the U.S. plains (e.g., Hane et al. 1993). Smith and Yau (1993a) focused on the upper-air analysis of the LIMEX data and, somewhat surprisingly, make no reference to the surface convergence line evident in their analysed fields.

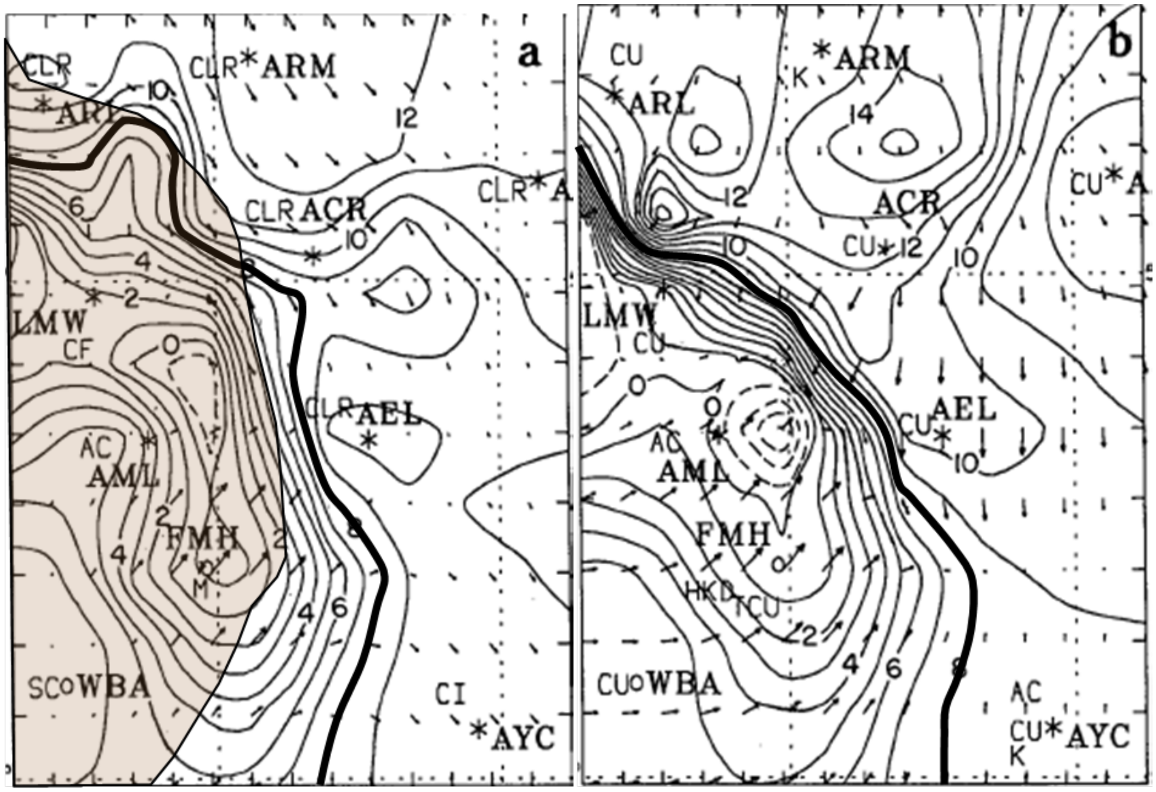
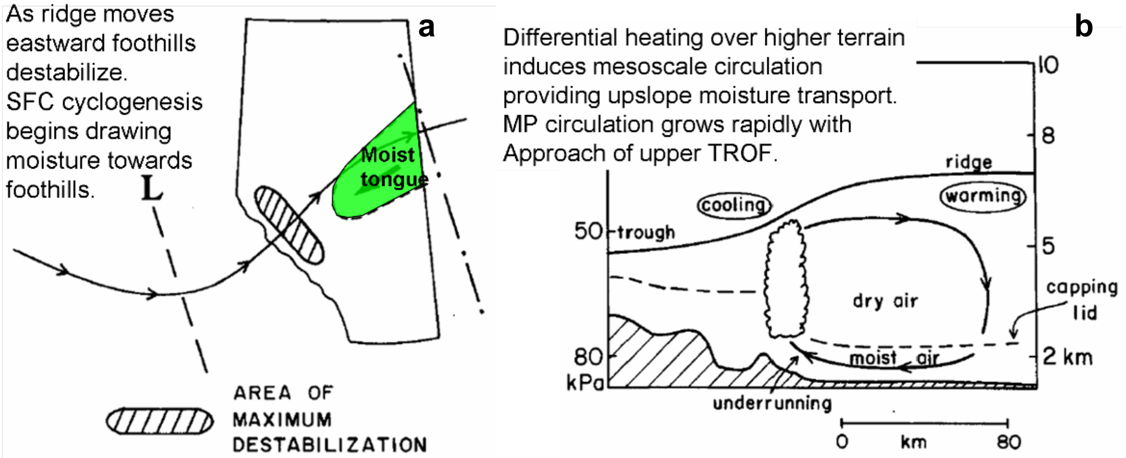


Figure 13: Analyses of surface dewpoint (contours) and surface wind (vectors) at (a) 1600 UTC, and (b) 1800 UTC. The ABL depth greater than 800 m at 1600 UTC is shown in brown shading in (a). Adapted from Smith and Yau 1993a.

Based on the case discussed above and with some comparison to other LIMEX-85 days, Smith and Yau (1993b) proposed a conceptual model for severe outbreaks over Alberta (see Figure 14). In the first stage, over a 1-2 day period most of Alberta is under the influence of an upper-level ridge with clear skies and a strong inversion in the lower troposphere inhibiting convection. While heating over the foothills may induce pressure falls and local upslope moisture transport, slow horizontal and vertical growth of the MPC and stability associated with the upper ridge results in only shallow convection if CI occurs at all. The second stage (duration of 1 day) is initiated with the eastward movement of the upper ridge allowing heating over the foothills to be accompanied by upper-level cooling. The MPC grows rapidly in extent, both horizontally and vertically, promoting upslope flow of ABL water vapour. With the approaching upper trough, the surface synoptic pattern favours advection of water vapour on the plains into the lower branch of the MPC near the foothills. Underrunning of ABL moisture occurs and convection is initiated where the cap has been weakened near the higher terrain of the western foothills. The phasing of the approach of the upper trough and differential heating over the foothills is critical in this model. Premature advancement of the upper trough results in widespread convective development and weakening of the MPC while delayed advancement of the trough results in large-scale subsidence inhibiting the growth of the MPC and development of deep convection.

The Smith and Yau (1993b) conceptual model conforms to the results of Longley and Thompson (1965), Strong (1986), and Strong and Smith (2001). The origin of the ABL water vapour that is transported to the foothills is not resolved with respect to local evapotranspiration or advection from the plains. There also remains some uncertainty of the origin of the capping lid, either as a result of large-scale subsidence or due to orographic subsidence as suggested by Strong (1986).


As ridge moves eastward foothills destabilize. SFC cyclogenesis begins drawing moisture towards foothills.

Differential heating over higher terrain induces mesoscale circulation providing upslope moisture transport. MP circulation grows rapidly with Approach of upper TROF.

Figure 14: Illustrations depicting Smith and Yau’s conceptual model for convective outbreaks in Alberta. In (a), the advancement of the upper trough allows destabilization over the Alberta foothills. A cross-sectional depiction of the mountain-plain circulation is shown in (b) (Adapted from Smith and Yau 1993b).

In considering the climatological potential for severe thunderstorms in Alberta, Taylor (1999) examined 31 years of summertime 0000 UTC soundings from Stony Plain. Mean daily values of thermodynamic-related sounding parameters (e.g., surface-based CAPE, precipitable water, maximum temperature and dewpoint) follow a seasonal cycle, with little day-to-day variability, and reach maximum values in July. Surface to 500 hPa temperature differences suggest that the troposphere over Alberta is conditionally unstable throughout the summer months. Mean daily values of surface to 6 km mean wind shear exhibit significant daily variability and peak in September. The peaks in instability and surface to 6 km shear are slightly ‘out of phase’ with the strongest shears and typically occur approximately two months after the peak in CAPE and surface dewpoint. Taylor (1999) concluded that a six week period between 1 July and 15 August is the climatologically optimal time window for severe thunderstorms in Alberta. These results are supported by those of Wojtiw (1975), McDonald and Dyck (2006), and others indicating that the frequency of severe weather events in Alberta peaks in July.

The importance of the dryline for severe thunderstorms in Alberta was first proposed by Knott and Taylor (2000). In a review of the severe weather outbreak of 29 July 1993 (numerous severe hail, damaging wind, and tornado events, one of which rated F3) they showed that the dryline was associated with the development of what would become a tornadic supercell. Time series of observed surface dewpoint temperature and wind direction associated with dryline passage (Figure 15) were shown for Calgary (YYC), Sundre (WAV), and Red Deer (YQF). At each station, dryline passage was associated with a rapid decrease in dewpoint temperature and veering of the winds from southeasterly to southwesterly. Maximum 1 h decreases in dewpoint associated with dryline passage were 6.1 ˚C and 7.7 ˚C for YYC and WAV, respectively.

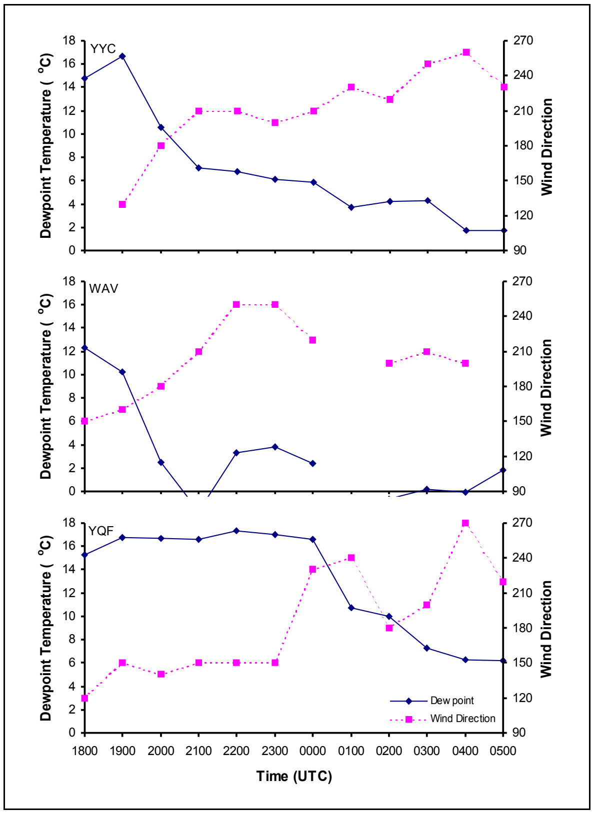


Figure 15: Time series of surface dewpoint temperature and wind direction for Calgary (YYC), Sundre (WAV), and Red Deer (YQF) associated with dryline passage on 29 July 1993. Dryline passage was associated with rapid decreases in dewpoint temperature and veering of the surface winds from southeasterly to southwesterly (from Knott and Taylor 2000).

Isochrones of dryline position were also shown by Knott and Taylor (2000) as analysed from hourly surface dewpoint and wind fields (Figure 16). The southern portions of the dryline were observed to bulge toward the east with time. Dryline bulging has been associated with vertical mixing of mid-level momentum to the surface resulting is rapid dry advection and dryline motion (e.g., Schaefer 1986). Similar dryline bulges associated with other severe thunderstorm events have since been observed in Alberta (Taylor 2001, 2004).

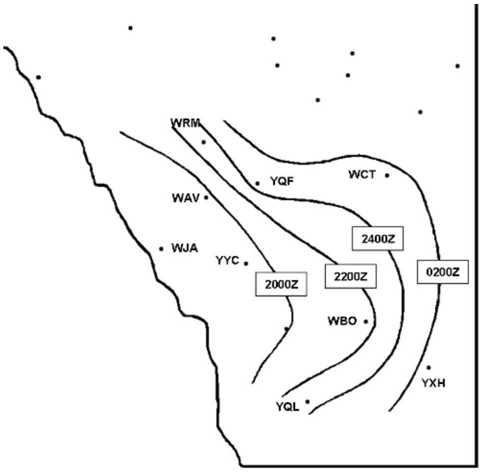


Figure 16: Dryline position at noted times on 29 July 1993 (Knott and Taylor 2000).

In a review of three tornado events in Alberta, Dupilka (2004) compared the synoptic patterns associated with the events to the conceptual model of Smith and Yau (1993b). He found that all three events were consistent with the proposed model and capping lids were observed on 1200 UTC Stony Plain soundings. The dryline was considered as a potential focus for CI and confirmed earlier findings by Knott and Taylor (2000) and Taylor (2001) that initiation of F3 tornadic storms on 29 July 1993 and 14 July 2000 were associated with the dryline. With respect to the Pine Lake storm on 14 July 2000 (see Table 2), results from a modeling study by Erfani et al. (2003) were used to support the role of the dryline in the initiation of the storm.

The most recent and detailed observations of the dryline in Alberta have been presented by Hill (2006) in which seven drylines were identified in July and August of 2003 and 2004. Five of those drylines were associated with thunderstorm development and one with severe hail. Drylines were sampled using a high resolution line of surface observing stations (Smith 2005) and mobile measurements of pressure, temperature and humidity. Gradients in mixing ratio sampled across the dryline ranged from 0.9 to 4.3 g kg^{-1} km^{-1} and compare well with those from other studies (Table 3).

Table 3: Comparison of dryline associated mixing ratio gradients from recent dryline studies in Alberta and the U.S. plains.

Observed Mixing Ratio Gradient	Reference
0.9-4.3 g kg^{-1} km^{-1}	Hill 2006
1.6 $gkg^{-1}km^{-1}$	Ziegler and Hane 1993
0.6-1.1 $gkg^{-1}km^{-1}$	Atkins et al. 1998
0.53-16.2 $gkg^{-1}km^{-1}$	Pietrycha and Rasmussen 2004

The above cited Alberta storm studies follow a progression from large-scale synoptic pattern studies to investigation of small-scale boundaries that are important for CI over the foothills. The foci of the investigations have evolved with scientific understanding of processes important for CI in general and with technology available to measure them. The studies by Longley and Thompson (1965), Strong (1986), Strong and Honch (1990), Smith and Yau (1993a, b), Knott and Taylor (2000) and Hill (2006) have provided a basis of understanding of how the large-scale circulation can be important for mesoscale processes (e.g., the mountain-plain circulation) and features (e.g., the dryline) associated with CI over the Alberta foothills. They have also shown that in order to increase our understanding of CI in the foothills, measurements with high spatial and temporal resolution are required.

The most detailed field experiment associated with thunderstorms over the foothills to date in Alberta is LIMEX-85. LIMEX-85 focussed on upper-air analysis and it would be difficult to duplicate the spatial and temporal resolution of the fixed sounding location grid used in that study. As shown by Honch and Strong (1990), Knott and Taylor (2000) and Hill (2006), small-scale boundaries at the surface are now known to be significant for CI over the Alberta foothills. Indeed, current research associated with CI (e.g., Weckwerth and Parsons 2006) points to the necessity for improved understanding of small-scale convergence lines, their formation, evolution, and interactions in order to maximize skill in forecasting, nowcasting, and issuing severe weather watches and warnings. The work of Hill (2006) has shown the necessity of in situ high resolution measurements to sample such boundaries. In order to fully understand the processes involved, a richer dataset including mobile measurements of atmospheric state variables (including wind speed and direction) is required via a high resolution surface mesonet of stations, mobile measurements, upper-air soundings and/or profilers, and measurements above the surface using aircraft.

3.2 ABL Water Vapour and Convergence Related to CI

The sensitivity of the initiation of deep moist convection to surface and ABL characteristics and associated processes has been investigated in numerous studies with respect to ABL water vapour (e.g., Mueller et al. 1993, Crook 1996, Weckwerth et al. 1996, Weckwerth 2000, Craven et al. 2002, Weckwerth and Parsons 2006), and convergence lines (e.g., Wilson and Schreiber 1986, Wilson et al. 1992, Wilson and Mueller 1993, Wilson and Roberts 2006). Results from these studies suggest that ABL moisture and convergence processes are intrinsically linked. Moreover, in order for forecasts of CI to improve, we must further our understanding of, and ability to measure, ABL characteristics related to these processes on small spatial and temporal scales.

Upper-air sounding climatology over central Alberta indicates that the atmosphere is conditionally unstable on most days during the summer months (Taylor 1999). Similar conditions exist in summer over the High Plains of the U.S. highlighting the importance of ABL variability for the initiation or inhibition of thunderstorm development (Mueller et al. 1993). Observational (e.g., Mueller et al. 1993) and modeling (e.g., Crook 1996) studies have indicated that variations of surface mixing ratio and potential temperature of 1 g kg^{-1} and 1 ˚C, respectively, can be the difference between no deep moist convection and intense thunderstorms. In spatial terms, Fabry (2006) estimated that, on average, 0.25 gm^{-3} changes in specific humidity occur on scales of 12 km in the parallel wind direction and 5 km in the across-wind direction over the Texas Panhandle. Spatial and temporal variations of these magnitudes are not resolved with existing, synoptic-scale, observation networks (Mueller et al. 1993, Crook 1996). To complicate matters, surface moisture variability may not be indicative of moisture variability near the top of the convective ABL due to mixing by convective thermals with dry air above the ABL as observed during IHOP_2002 (Fabry 2006).

The depth of available water vapour in the ABL has also been shown to have a critical impact on CI (e.g., Mueller et al. 1993, Weckwerth et al. 1996, Weckwerth 2000). Soundings released in an area where thunderstorms developed (so-called proximity soundings) have been shown to be unrepresentative of the thunderstorm environment due to ABL moisture considerations. Weckwerth (2000) showed that modification of proximity soundings was required using ABL aircraft measurements for the soundings to reflect the pre-storm environment when horizontal convective rolls were observed. Even under unstable conditions associated with a moving convergence line (without a capping lid); CI has been observed not to occur under conditions of shallow ABL moisture (Mueller et al. 1993). McCaul and Cohen (2002) showed that given environments with sufficient CAPE and deep wind shear for severe storm development, those with deeper ABL moisture were more conducive to severe storms.

Forecasts of atmospheric stability are also very sensitive to ABL characteristics. Variations in mixing ratio of 1 g kg^{-1} have been shown to have 2.5 times the impact of 1 ˚C variation in surface potential temperature on calculations of CAPE (Crook 1996). In considering moisture depth, the use of a surface-based parcel for stability estimates over a mean parcel layer of some depth has been shown to overestimate CAPE (Bunkers et al. 2002) and underestimate observed convective-cloud bases (Craven et al. 2002). Convective inhibition (CIN), a critical factor for CI, was shown by Crook (1996) to be more sensitive to changes in surface temperature than mixing ratio. Also considering CIN, Fabry (2006) suggested that on spatial scales less than about 20 km, moisture variability has a greater impact on CIN values while at larger scales, temperature variability is more important. When using sounding data to nowcast CI, Mueller et al. (1993) found that, while under stable conditions storms tended not to develop, with potentially unstable profiles storms did not always form when ABL moisture was shallow. When they did their intensity was not correlated with sounding-derived measurements of stability. Variations of surface water vapour have been shown to impact updraft strength in model simulations (e.g., Crook 1996). Clearly, knowledge of surface and ABL temperature and moisture are needed for forecasters to successfully anticipate thunderstorm development and intensity.

Low-level convergence zones have long been associated with development of deep moist convection (e.g., Ulanski and Garstang 1978, Purdom 1982, Achtemeier 1983, Wilson and Schreiber 1986) and the strength and depth of lifting along convergence lines is known to be important for CI and maintenance of existing thunderstorms (e.g. Wilson et al. 1992, Crook and Klemp 2000, Weckwerth and Parsons 2006). Using satellite observations, Purdom and Marcus

(1982) found that 73% of afternoon thunderstorms in the southeastern US were due to intersecting convergence lines. From 418 storms observed (with reflectivity of at least 30 dBZ) during the 1984 convective season in Colorado, Wilson and Schreiber (1986) found 80% of those storms were associated with radar-observed convergence lines. In considering only storms that reached 60 dBZ or more the percentage rises to 95% suggesting that more intense storms are more often triggered by ABL convergence lines. Lake-breeze boundaries in Southern Ontario have been shown to influence the timing and location of CI (e.g., Sills 1998, King and Sills 1998, Sills et al. 2002) and severe thunderstorm climatology in that region (King et al. 2003). Observed convergence lines have also been shown to be important for severe weather and tornado development on the U. S. Great Plains (e.g., Markowski et al. 1998), in Australia (Sills et al. 2004), Southern Ontario (Sills and King 2000, King et al. 2003), and Alberta (Knott and Taylor 2000, Taylor 2004).

Preferred regions for CI were identified by Wilson and Mueller (1993) to include the intersection of horizontal convective rolls and stationary boundaries, collisions between moving and stationary boundaries, and where moving boundaries pass beneath a field of cumulus clouds. These convergent areas can often be observed via Doppler radar as fine lines of enhanced reflectivity (Wilson and Schreiber 1986). Wilson et al. (1992) showed that a quasi-stationary convergence line was associated with local deepening of ABL water vapour leading to CI and that convergence lines tend to modify the environment with about 10 km to either side of the line.

The impact of ABL convergence on the potential for CI is not limited to near-surface effects. Secondary circulations have been shown to be associated with ABL convergence lines and to influence whether or not deep moist convection can be initiated (e.g., Wilson et al. 1992, Ziegler and Rasmussen 1998, Crook 2000, Weckwerth and Parsons 2006). Divergence associated with these circulations can offset the effects of low-level convergence and inhibit CI if it occurs below the LFC (Wilson et al. 1992, Crook 1996). The importance for lifted parcels to reach their LFC prior to leaving the influence of dryline-associated convergence was highlighted by Ziegler and Rasmussen (1998). Updrafts associated with low-level convergence should be more erect and penetrate to higher levels if vertical shear on either side of the line is equal in magnitude (Rotunno et al. 1988). This effect was shown using observational data by Markowski et al. (2006). Vertical shear below cloud base can act to tilt parcel updrafts and delay or inhibit convection as shown in both observational and modeling studies (e.g., Wilson et al. 1992, Mueller et al. 1993, Crook 1996, 2000). Measurements of thermodynamic and kinematic fields necessary to resolve these effects require simultaneous use of surface, sounding or profiling, and aircraft measurements.

The importance of ABL convergence lines in the lee of the Rocky Mountains in Alberta has only recently garnered formal attention. Investigating the significance of the dryline for Western Canadian Prairie severe thunderstorms, Taylor (2004) found that during the summer of 2000 36% of severe weather days[5] had storms associated with observed drylines. Severe weather reports from these storms accounted for 56% of all the severe weather reports received from Alberta during that summer. The importance of the dryline in Alberta has been investigated by Hill (2006) and, though not discussed in their papers, a dryline-like convergence boundary is evident in the earlier analyses of Smith and Yau (1993a).

The dryline has been recognized as an important convergence line for CI and the development of severe thunderstorms for over forty years (e.g., Rhea 1966, Schaefer 1974, 1986, Ziegler and Hane 1993, Ziegler and Rasmussen 1998, Pietrycha and Rasmussen 2004, Cai et al. 2006). The dryline defines a sharp moisture boundary between a hot, deeply-mixed ABL (generally to the west) and a cooler, moist, and capped ABL (to the east) and develops frequently over the Plains of the U.S. (e.g., Hoch and Markowski 2005). Dryline development is typically associated with the convergence of moist Gulf of Mexico air and dry air originating from the plateau regions of Mexico and the southwest U.S. (Cai et al. 2006). Dryline-associated circulations have been described

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[5] In his study the criteria for a severe weather day was at least 3 reports of 20 mm hail and / or at least 1 report of 30 mm hail and / or at least one report of a tornado.

(Ziegler et al. 1997) as being thermally direct secondary circulations that are frontogenetic and primarily solenoidally forced. Convergence and associated lift at the dryline boundary provides a focus for the development of (often severe) thunderstorms.

The dryline on the western Canadian Prairies has been observed to form in Alberta in the lee of the Rocky Mountains. It has been proposed that dryline genesis in this region is mainly in response to the convergence of subsident air associated with upper-level south-westerly flow with moist air resident on the western Prairies (Taylor 2001, 2004, Hill 2006). This conceptual model is similar that described by Schreiber-Abshire and Rodi (1991) for the origin of a mesoscale convergence boundary in north-eastern Colorado utilizing a conceptual model described by Banta (1984, 1986). Detailed measurements of the dryline in Alberta, both at the surface and aloft, are required to relate its formation and observed characteristics to those of the dryline observed in the U.S.

3.3 Land Surface - ABL Interactions and Mesoscale Circulations Related to CI and Severe Thunderstorms[6]

The importance of land surface and atmosphere interactions for CI and severe thunderstorms was introduced in section 2.2. Water vapour availability and depth near the surface can be a limiting factor for development and intensity of surface-based thunderstorms (e.g., Weckwerth 2000, McCaul and Cohen 2002). ABL water vapour over a specific location (in the absence of precipitation) arises from some combination of; evaporation of surface water (including the near surface soil layer and precipitation intercepted by vegetation), transpiration of water vapour by vegetation from the soil root zone, or horizontal advection of water vapour from a 'distant' source. Determining relative contributions of these moisture sources from standard meteorological observations (e.g., relative humidity or dewpoint) however, is difficult. Numerous observational (e.g., Rabin et al. 1990, Mahrt et al. 1994, Hanesiak et al. 2004, Doran et al. 1995) and modeling (e.g., Lynn et al. 1998, Weaver and Avissar 2001, Trier et al. 2004) studies have stressed the importance of soil moisture and evapotranspiration for contributions to ABL water vapour and the development of mesoscale circulations associated with CI and severe thunderstorms.

Soil moisture controls the partitioning of turbulent sensible and latent heat fluxes from the land surface to the ABL in response to absorbed solar radiation (Entekhabi et al. 1996). These fluxes in turn influence the thermal and moisture profiles, depth, and evolution of the ABL on a given day (Pielke 2001). Radiation absorbed by dry soils is readily converted to sensible heat so that over dry areas sensible heat flux dominates, the depth of the ABL grows rapidly, and dry air from above the ABL is entrained to lower levels. Over moist soils absorbed radiation is predominately converted into latent heat, the ABL depth increases more slowly, and water vapour is added to low levels through evaporation. The ratio of sensible heat flux to latent heat flux is defined as the Bowen ratio (Pielke 2001). Lowering of the Bowen ratio has been shown to be associated with an increase in potential for moist deep convection (Segal et al. 1995). Distributions of soil moisture influence the location and timing of CI through local modification of ABL thermodynamics resulting in changes in LCL and LFC height, CAPE, CIN, and timing of convective cloud formation (e.g., Colby 1984, Lanicci et al. 1987, Georgescu et al. 2003, Hanesiak et al. 2004). Soil moisture gradients have also been correlated with the development of the dryline and associated CI (e.g., Sun and Wu 1992, Trier et al. 2004).

Evapotranspiration (ET) is recognized as an important source of ABL water vapour for the development of deep moist convection (e.g., Raddatz 1998, Raddatz and Cummine 2003) and moisture recycling through convective precipitation (Raddatz 2000) on the Canadian prairies. Raddatz (1993) estimated that regions of the Canadian prairies can experience increases in ABL mixing ratio of 4-8 gkg^{-1} per day due to ET (assuming a 1000 m ABL depth), results that are supported by Segal et al. (1995). Under quiescent conditions it is reasonable to assume there could be greater contributions to ABL moisture from 'local' ET than from horizontal advection

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[6] The literature review compiled in this section was assisted by an excellent, but unpublished, review on these issues conducted by Brimelow (2006, personal communication) at the University of Manitoba.

(e.g., Cheresnick and Basara, 2005). Johns et al. (2000) suggest that ET processes may be associated with pre-storm environments associated with violent tornadoes and Raddatz and Cummine (2003) related seasonal crop phenology and associated ET with the seasonal pattern of tornado days. ABL water vapour contributions from ET have been found to be more strongly correlated with root-zone soil moisture than surface or near surface soil moisture (e.g., Basara and Crawford 2002, Hanesiak et al. 2004). This implies that ET – convective precipitation feedbacks occur on both intra- and inter-seasonal timescales (e.g., Hanesiak et al. 2004) in addition to immediately following a heavy precipitation event (e.g., Wai and Smith 1998).

The Alberta Foothills lie within an eco-climatic transition zone between Southern Cordilleran to the west and Prairie Grasslands to the east (see Figure 5). The Grassland eco-climatic zone on the Canadian prairies is made up of ~50% field crops and ~25% native grasses (Raddatz 2003). Of primary importance is a predominance of Spring Wheat and annual field crops with similar properties that are the main contributors to ET in the region (Raddatz 2005). In a modeling study McPherson and Stensrud (2005) showed that Spring Wheat can result in higher latent heat fluxes (and lower sensible heat fluxes) than native grasses. The result was higher mixing ratios and a shallower ABL above and downstream of the crops. The conversion from native grasses to agricultural crops on the Canadian Prairies has been linked to an increase in the potential for deep convection due to increased latent heat flux (Raddatz 1998). In contrast to the high ET rates over the prairies, the predominantly coniferous (over higher terrain) and mixed forests in the foothills region are known to be associated with relatively low latent heat flux when compared to prairie crops and grasses. Thus, even under conditions with spatially homogeneous soil moisture content there potentially exists then a gradient in latent heat fluxes (and hence ABL moisture contributions) from the prairies to the east to the mountains to the west due to vegetation differences.

Analogous to the sea-breeze phenomenon, surface heterogeneities in soil moisture, land use, vegetation, water cover, and topography (among other factors) can result in generation of thermally-direct, solenoidal mesoscale circulations (e.g., Segal and Arritt 1992, Segal et al. 1998, Lee and Kimura 2001). Terrain-induced upslope flow and the mountain-plain circulation were discussed in section 3.1, for further details the reader is referred to the work of Banta (1984a, b), Benjamin and Carlson (1986), Wolyn and McKee (1994), and Tian and Parker (2002). Numerous observational (e.g., Rabin et al. 1990, Mahrt et al. 1994, Doran et al. 1995) and modeling (e.g., Chen and Avissar 1994(a, b), Li and Avissar 1994, Lynn et al. 1995, Wetzel et al. 1996, Avissar and Schmidt 1998) studies have investigated the effects of land surface heterogeneities, generation of mesoscale circulations, and the resulting effects on cumulus convection. Segal and Arritt (1992) reviewed how horizontal pressure gradients resulting from these effects can be strong enough to generate organized circulations. Such circulations can enhance the potential for CI by;

- generating horizontal advection of low-level moisture from areas with lower Bowen ratio to an adjacent area with higher Bowen ratio, favouring earlier development of convective clouds
- providing an axis of moisture convergence thus locally increasing and deepening ABL water vapour to increase CAPE and reduce CIN thus promoting CI; and,
- by providing an axis of mass convergence and resulting vertical motion that may, either through interaction with other boundaries or, independently under quiescent conditions, promote near-surface parcels in reaching their LFC.

3.4 High-Resolution Numerical Modelling of Alberta Thunderstorms

There have been relatively few high-resolution modelling studies of convective storms in Alberta. With Canada's large area and limitations in computational resources, the focus of NWP by the Canadian Meteorological Centre has generally been on the prediction of larger scale weather systems. Furthermore, the sparsity of observations has tended to discourage researchers studying deep convection from performing detailed modelling studies in Alberta. However, with increasing computer power and with high-resolution 3D modelling being more affordable, there have been a few recent modelling studies. On 14 July 2000, there was a very severe convective outbreak in central Alberta, generally referred to as the Pine Lake storm. This case followed, in many ways, conceptual models for severe Alberta thunderstorms. The convection initiated in the mid-afternoon in the foothills, east of Red Deer, and propagated eastward. There were periods of hail, with golf ball to softball-sized hail observed at the ground and the storm produced an F-3 tornado near Pine Lake, approximately 20 km south-east of Red Deer. The accumulated precipitation, estimated from reflectivity from the WMI radar, indicates the track of the storm, shown in Figure 17. This storm was strongly forced by upper-level dynamics, was long-lived, and was well-observed by the WMI radar, making it an excellent candidate for numerical modelling studies.

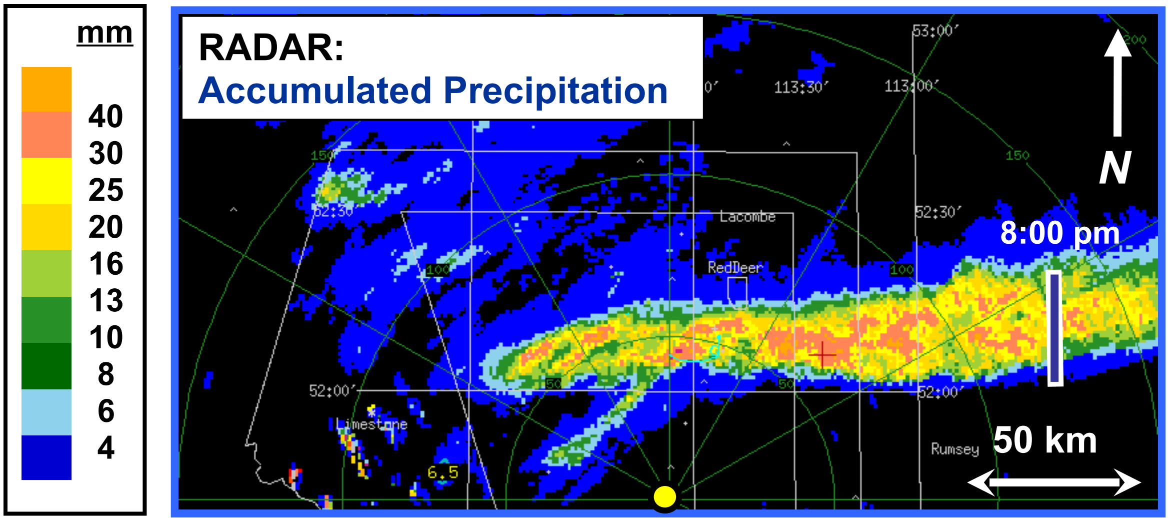

Figure 17: Accumulated precipitation from 0600 UTC 14 July to 0527 UTC 15 July 2000 estimated from the WMI radar (location indicated by yellow circle).

Erfani et al. (2003) simulated this case using the GEM forecast model (see Côté et al., 1998 for model description). The model was initialized using the 24-km CMC regional analysis at 1200 UTC 14 July 2000. The simulation used was the non-hydrostatic variable-resolution global version of the GEM, with a horizontal grid-spacing of 4-km in the central Alberta region. The 18-h accumulated precipitation from the model is shown in Figure 18. The simulated convection was initiated along the foothills in the mid-afternoon, similar to the observed convection. The model produced two main storm tracks, with similarities to the observed track of the Pine Lake storm. It was thus demonstrated that it was possible to simulate convection that resembled the observations using a model configuration similar to the operational set-up at that time.

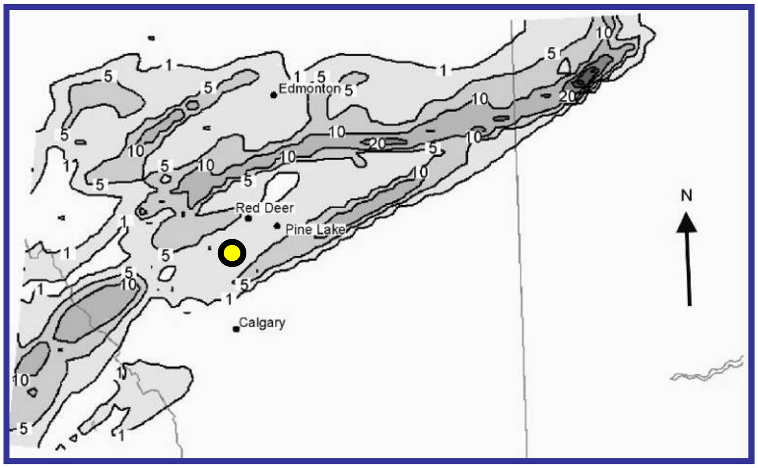

Figure 18: Accumulated precipitation (mm) from (1200 UTC 14 July 2000 to 0600 UTC 15 July 2000) produced a 4-km (global, variable resolution) GEM. Yellow circle indicates location of the WMI radar. Adapted from Erfani et al. (2003).

The same case was also investigated in a modelling study by Milbrandt and Yau (2006a, b) using the Canadian MC2 mesoscale model, which is a non-hydrostatic limited-area model (Benoit et al., 1997). The same CMC regional analysis used by Erfani et al. (2003) was used to initialize the model. The MC2 simulations, however, used a strategy of self-nesting (similar to the current nesting strategy of the current GEM-LAM-2.5), first running the model over a large domain with a 12-km grid-spacing, and then successively nesting to 3-km and then to 1-km grids. The 6-h accumulated precipitation from the 1-km simulation is shown in Figure 19. The MC2 simulations were, in several respects, similar to the 4-km GEM simulation. The 3-km MC2 precipitation pattern (not shown) was very similar to the pattern in Figure 18. For the 1-km MC2 grid, the two simulated storm tracks were also similar in locations. (Note, the grid orientations in Figs. 18 and 19 are not the same; the southern MC2 storm track in Figure 19 is actually very similar to the southern-most GEM storm track in Figure 18. Also, the 1-km MC2 simulation ends at 0200 UTC 15 July.) As with the GEM simulation, the storm tracks simulated by the MC2 had some similarities to the observed tracks, but also some distinct differences in location and orientation.

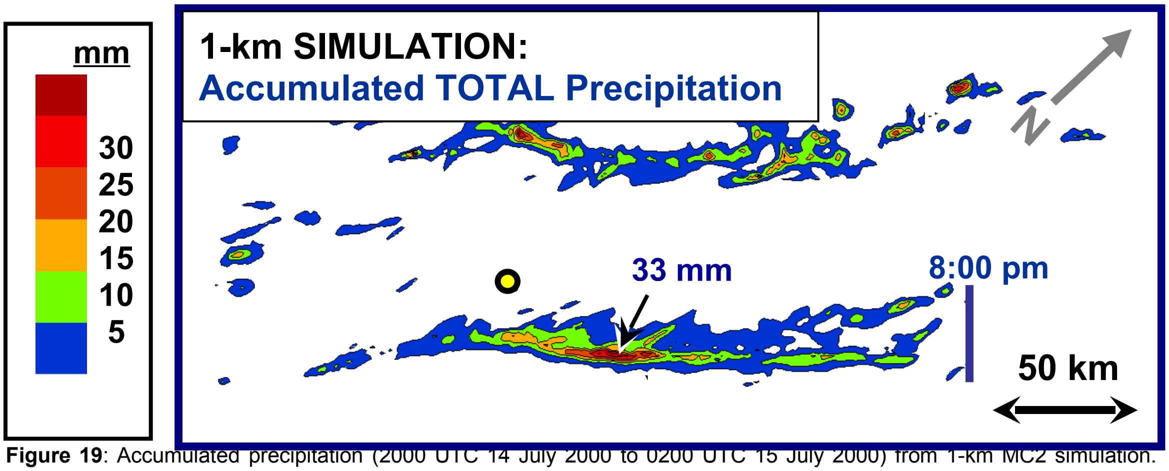

Figure 19: Accumulated precipitation (2000 UTC 14 July 2000 to 0200 UTC 15 July 2000) from 1-km MC2 simulation. Yellow circle indicates location of the WMI radar. From Milbrandt and Yau (2006a).

Despite these differences, the instantaneous storm structures in the 1-km simulations were remarkably similar to the observed storm. Figure 20 shows vertical and horizontal cross-sections of radar reflectivity (from the WMI radar) of the Pine Lake storm and corresponding cross-sections of simulated reflectivity from the storm in the MC2 (from the southern track) at the same time. The model storm resembles the observed storm in considerable detail, exhibiting a pronounced weak echo region and overhang with the correct spatial scale. In Figure 21, the supercell characteristics of both the observed and modelled storm are evident. In the 2-km radar CAPPI (Figure 21a), a distinct hook echo pattern is apparent, indicating the presence of a strong mesocyclone (e.g. Lemon and Doswell, 1979). The simulated storm shows a similar hook echo (Figure 21b), which results from sedimenting hail and rain on the rear flank of the main updraft, wrapping around as it falls through the cyclonically rotating air.

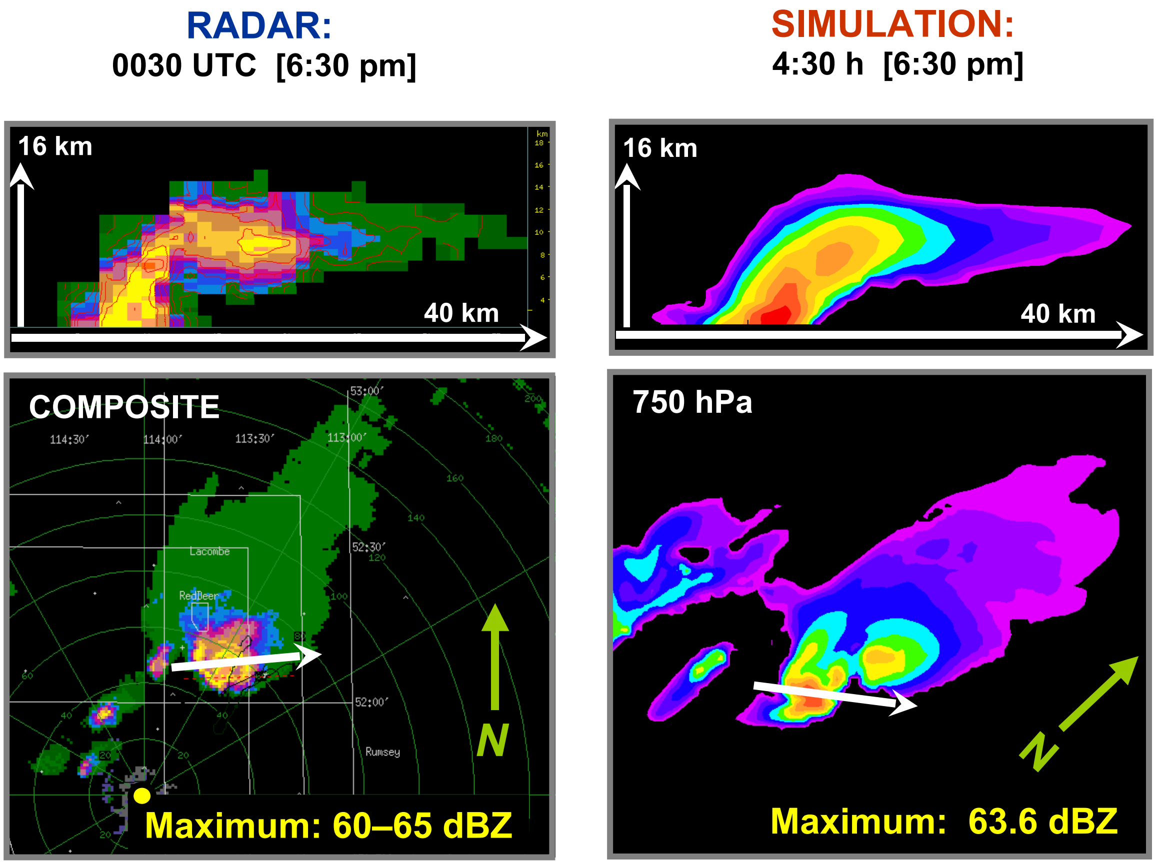

Figure 20: Vertical (top) and horizontal (bottom) cross-sections of observed (left) and simulated (right) radar reflectivity at 0030 UTC 15 July 2000. Adapted from Milbrandt and Yau (2006a).

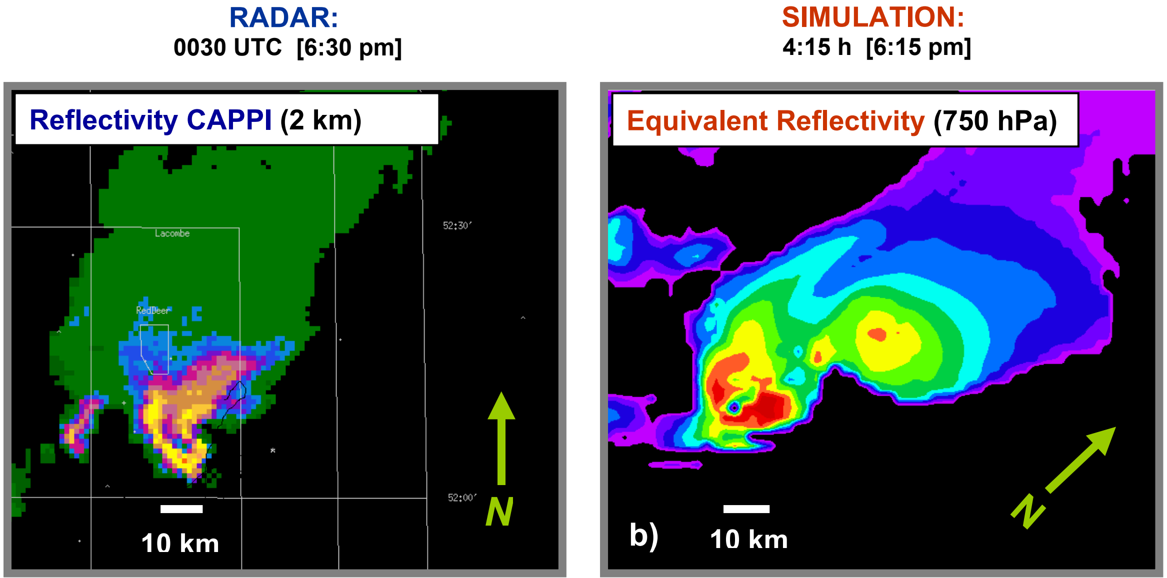

Figure 21: (a) Reflectivity CAPPI at 2 km from WMI radar at 0030 UTC 15 July 2000, and (b) 700 hPa equivalent reflectivity from 1-km MC2 simulation at 0015 UTC 15 July 2000. From Milbrandt and Yau (2006a).

In Milbrandt and Yau (2006b), the sensitivity to aspects of the cloud microphysics parameterization to the simulation of the Pine Lake case was investigated. Specifically, the treatment of the hydrometeor size distributions in the Milbrandt-Yau cloud scheme was varied. Instantaneous horizontal (700 hPa) cross-sections of the reflectivity from hail (the major contributor to the total reflectivity at this level) from different sensitivity runs. Simulations using single-moment and double-moment configurations of the scheme are shown in Figure 22. (A single-[double]-moment bulk scheme is one in which one [two] moment(s) of the size distribution function are prognosed independently.) The double-moment simulation produces a more realistic storm structure than the single-moment run and exhibits less variability. In contrast, the single-moment simulation shows a much different type of convection. One of the reasons for the variability in the simulations was that the magnitude of the wind shear vector between the surface and 400 hPa was on the order of 20 m s^{-1}, which is considered to be barely sufficient to support supercell development (Weisman and Klemp, 1984). Thus, changes to the microphysical assumptions, which can lead to stronger (or weaker) cold pools, can result in storms that are more multicellular in nature (as in Figure 22a). The sensitivity in these simulations illustrates the importance of having sufficiently sophisticated physical parameterizations in the model when the resolution is high enough to resolve individual thunderstorms.

These studies suggest that there is indeed some potential skill for high-resolution mesoscale models – and thus for operational NWP models – at explicitly predicting severe convection that originates in the Alberta foothills. They also illustrate the challenge in objectively defining a “success” in terms of accurately simulating (or forecasting) the observed correction. In neither the GEM nor MC2 simulations did the simulated storm tracks match the observed track. Standard skill scores such as the threat score, which severely punishes forecasts whose field locations are incorrect, would imply that these simulations were very poor. Subjectively, however, the models appear to demonstrate some skill. In fact, the northward bias in the (southern) storm tracks is likely due to a bias in the large-scale model wind fields. For the 1-km MC2 simulation, the propagation of the southern storm *relative* to the steering level flow (~ 700 hPa) was actually very close to the observed, though this is not evident from just examining the precipitation patterns. Furthermore, the storm structure and convective mode were very similar to the observed convection. Once cannot say that *the* Pine Lake storm was accurately simulated – that is, the specific storm – but clearly the overall *nature* of the observed convection was simulated with skill. Thus, there certainly appears to be potential value for high resolution numerical forecasts for the prediction of severe convection in Alberta, but there is a great need to define the meaning of a “success” in order to properly evaluate the general skill of the model(s) and to identify its strengths and weakness as a forecast tool.

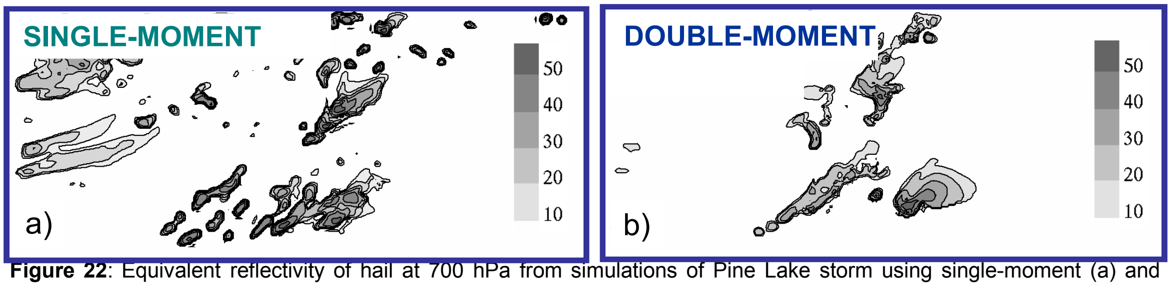

Figure 22: Equivalent reflectivity of hail at 700 hPa from simulations of Pine Lake storm using single-moment (a) and double-moment (b) configurations of the Milbrandt-Yau cloud microphysics scheme. Adapted from Milbrandt and Yau (2006b).

3.5 Other Field Experiments Related to CI and Severe Thunderstorms

UNSTABLE is a unique opportunity to study the initiation and development of severe thunderstorms over the Alberta Foothills. No study of similar magnitude has been conducted in the region for over 20 years. UNSTABLE will utilize the latest in technology and scientific understanding to answer specific science questions related to CI and severe thunderstorms in this region. Further, UNSTABLE is unique in its location relative to the Rocky Mountains, unlike most field experiments in the U.S., UNSTABLE will investigate the direct impact of this terrain barrier on severe thunderstorm development and evolution. In addition, it would appear that genesis of the dryline in Alberta is through a different mechanism (i.e., driven by ‘dry air advection’) than that widely accepted for the U.S. Plains. To put our work in context, brief descriptions of some other field experiments with objectives related to those of UNSTABLE are included.

LIMEX-80, LIMEX-85 (1980, 1985, Alberta Foothills)
LIMEX-80 and LIMEX-85 focused on pre-storm capping lids and lid breakdown leading to CI, respectively (Strong and Smith 2001). The latter experiment was longer, utilized a more extensive array of observations (as described in section 3.2), and was focused on a similar region of the foothills as UNSTABLE. The LIMEX experiments focussed largely on upper-air measurements and synoptic-scale processes. While some surface convergence boundaries were resolved in the data, they were not investigated explicitly. While it is unlikely that UNSTABLE will employ the number of radiosonde sites that were used in LIMEX-85, the inclusion of a larger suite of fixed and mobile profiling instruments and higher resolution mesonet will provide more detailed observations of pre-storm and storm initiation processes in the region.

CINDE (1987, Colorado)
The Convection Initiation and Downburst Experiment (CINDE) took place over Colorado from 22 June to 7 August 1987. CINDE focused on *“understanding kinematic and thermodynamic structure of the boundary layer, emphasizing those processes that influence the development of convective storms, including terrain effects, and to investigate the forcing and initiation of intense downdrafts known as microbursts”* (Wilson et al. 1988). Specific objectives were defined with respect to convection initiation, downbursts, and tornadoes. Of primary interest was improved understanding of processes determining which boundaries might result in CI, where, and why. Collaborators from various universities and institutions utilized surface mesonets, fixed and mobile soundings, profilers, radars, and research aircraft to sample the ABL and upper atmosphere. A review of the project is provided by Wilson et al. (1988). Results have been published related to the Denver convergence-vorticity zone (e.g., Schreiber-Abshire and Rodi 1991), the role of ABL convergence zones (e.g., Wilson et al. 1992), and nowcasting (e.g., Wilson and Mueller 1993, Mueller et al. 1993).

CaPE (1991, Florida)
The Convection and Precipitation/Electrification Experiment (CaPE) took place in central Florida from 8 July to 18 August 1991. The focus was the development of techniques for nowcasting CI, downbursts and tornadoes. CaPE included observations from surface mesonet stations, radiosondes, radars, and research aircraft. Results from the experiment have been published, for example, with respect to sea-breeze fronts (Wakimoto and Atkins 1994), horizontal convective rolls (Weckwerth et al. 1996), and the effects of small-scale moisture variability on CI (Weckwerth 2000).

VORTEX (1994, 1995, 1997 Southern U.S. Plains)
The Verification of the Origins of Rotation in Tornadoes EXperiment (VORTEX) took place primarily during spring 1994, 1995 over the southern Great Plains of the U.S. A smaller 'Sub-VORTEX' took place in 1997. The focus of VORTEX on the whole was to use a variety of data collection platforms (surface stationary and mobile mesonets, radar, radiosondes, aircraft, and profilers) to evaluate a set of hypotheses related to tornadogenesis and tornado dynamics (Rasmussen et al. 1994). While focussing specifically on tornadoes, various results from this project are relevant for UNSTABLE. A description of the project is given by Rasmussen et al. (1994), publications derived from the experiment are too numerous to mention here. Plans are underway for VORTEX-2 (http://www.vortex2.org/), though funding difficulties have hampered its implementation. See also:
http://www.research.noaa.gov/spotlite/archive/spot_nssl.html
http://www.nssl.noaa.gov/noaastory/book.html

ELBOW 1997, ELBOW 2001 (1997, 2001, Southwest Ontario)
The Effects of Lake Breezes On Weather (ELBOW) field experiments took place over southwestern Ontario during summer 1997 and 2001. A variety of data collection platforms, including aircraft, were deployed to investigate the role of lake breezes in CI and severe thunderstorm development. Results have been published on the projects and preliminary results (King and Sills 1998, Sills et al. 2002), impacts on tornado climatology in the region (King et al. 2003), and high-resolution numerical modeling during ELBOW 2001 (King et al. 2002). See also:
http://www.yorku.ca/pat/elbow2001/
http://quark.physics.uwo.ca/~whocking/elbow/home.html

STEPS-2000 (2000, East Colorado, West Kansas)
The Severe Thunderstorm Electrification and Precipitation Study (STEPS) took place over Eastern Colorado and West Kansas during 15 May to 10 August, 2000. The main goal of STEPS was to increase understanding of kinematic, precipitation production, and electrification processes associated with severe storms on the High Plains. The project utilized multiple radars, mobile sounding units, mobile mesonet units, armoured aircraft, and specialized lightning detection / observations. Results have been presented at international conferences and more information can be found at:
http://www.mmm.ucar.edu/community/steps.html

MOCISE (2000, 2001, North Texas, Western Oklahoma)
The Mesoscale Observations of CI and Supercell Experiment (MOCISE) took place over portions of the Southern Plains from 1 April to 15 May 2000 and 1 to 30 June 2001. The experiment utilized fixed and mobile mesonets, soundings, and radars to sample thermodynamic and kinematic structures in the ABL associated with the dryline, CI, and the forward-flank downdraft region of supercells. See:
http://stormeyes.org/pietrycha/mocise/mocise.html

IHOP_2002 (2002, Southern U.S. Plains)
The International H_2O Project (IHOP_2002) was a large-scale collaborative field experiment that occurred from 13 May to 25 June 2002 over the southern Great Plains of the U.S. (Kansas, Oklahoma, and North Texas). The primary focus for IHOP was to better understand the four-dimensional evolution of water vapour in the atmosphere to improve forecasts of quantitative

precipitation. IHOP goals were developed around four main research components; Quantitative Precipitation Forecasting, CI, the Atmospheric Boundary Layer, and Instrumentation. Motivation for the project is described in Weckwerth and Parsons (2006) and an excellent summary of the project is given by Weckwerth et al. (2004). The January 2006 issue of Monthly Weather Review (Volume 134, 3-430) was devoted to IHOP_2002 results. See also:
http://www.eol.ucar.edu/dir_off/projects/2002/IHOP.html

BAQS-Met (2007, Southwest Ontario)
The Border Air Quality Study – Meteorological Measurements project is a combined air quality and meteorology field program that took place over extreme southwestern Ontario during the summer of 2007. The meteorological component of the study is related to improving understanding of how lake breezes and other boundaries influence CI and the development of severe thunderstorms in that region. BAQS-Met utilized some of the instrumentation that is planned for use in UNSTABLE (e.g., ATMOS stations, AMMOS mobile station, tethersonde. See section 6 for instrumentation descriptions).

4. Project Goals and Deliverables

The overall goals of UNSTABLE may be summarized as:

- To better understand atmospheric processes leading to thunderstorm development over the Alberta foothills (both prior to and during CI) with an aim to extend results to the rest of Canada
- To improve accuracy and lead time for severe thunderstorm watches and warnings
- To assess the utility of the GEM-LAM model in resolving physical processes over the Alberta foothills and its ability to provide useful numerical guidance for the forecasting of severe convection
- Through observational, case, and numerical modeling studies refine current existing conceptual models describing CI and the development of severe thunderstorms over Alberta and the western prairies

The above goals may be realized through the completion of a number of tasks:

- Deploy an array of data collection platforms during the 2008 convective season to obtain targeted high-resolution measurements of thermodynamic and kinematic ABL and upper tropospheric characteristics
- Characterize the spatial extent, depth and temporal evolution of water vapour in the ABL prior to and during CI
- Identify processes leading to the development of mesoscale convergence, moisture or other boundaries or features that may inhibit (e.g., capping lid) or promote CI (e.g., dryline)
- Identify and characterize locations, strength, spatial extent, duration and evolution of mesoscale boundaries and features associated with CI and severe thunderstorms (drylines, convective rolls, low-level jets, convergence lines, thunderstorm outflow boundaries)
- Document and model sensible and latent heat fluxes between the surface and ABL, especially with respect to evapotranspiration and its contribution to CI
- Identify and characterize the association of mesoscale boundaries and their behaviour with synoptic-scale atmospheric processes and non-meteorological factors such as , terrain, land use / vegetation type, soil moisture, crop phenology
- Examine in detail the output from the real-time GEM-LAM-2.5 model runs, and compare to observations, as well as perform hind-cast modeling studies
- Transfer UNSTABLE results to the meteorological science and forecast communities through traditional and experimental means

Data from UNSTABLE are anticipated, at least initially, to be analysed by researchers, staff, and students at:

- The Hydrometeorology and Arctic Lab, Environment Canada
- The Cloud Physics and Severe Weather Research Section, Environment Canada
- The Nowcasting and Remote Sensing Lab, Environment Canada
- Centre for Earth Observation Science, University of Manitoba
- Department of Earth and Atmospheric Science, University of Alberta
- Laboratory for Severe Weather Meteorology, Environment Canada
- Recherche en Prévision Numérique (Numerical Weather Prediction Research Section), Environment Canada
- The Prairie and Arctic Storm Prediction Centre

Deliverables from UNSTABLE will include the following:

- A unique set of surface and upper-air measurements from various data collection platforms with spatial and temporal resolution surpassing those obtained in past field experiments. These data will be a legacy of the project to be analysed in future studies.
- Peer-reviewed articles in recognized meteorological journals.
- Numerous presentations and posters at international meteorological conferences and workshops. This should include a special session at a future CMOS congress.
- Presentations and reference material targeting operational meteorologists detailing how knowledge gained from UNSTABLE can be applied operationally to improve convective watches and warnings.

A primary goal of UNSTABLE is to improve accuracy and lead time for severe thunderstorm watches and warnings. For this to be achieved, appropriate mechanisms must be in place to ensure knowledge gained from UNSTABLE is transferred to operational forecasters. Collaboration between the National Labs and Storm Prediction Centres within Environment Canada is increasing. Already, lab staff is involved in training workshops and seminars and have implemented Research Support Desks (RSDs) directly in forecast operations within two of Canada’s five Storm Prediction Centres. The PASPC is anticipated to be involved in UNSTABLE during the field campaign and is involved to a lesser extent in the planning of the project. Following a period of data analysis, lab staff will work with the PASPC (and other Storm Prediction Centres) to incorporate results into operational conceptual models and forecast techniques. This will be accomplished through traditional means such as those listed above but also through the RSD where researchers can work with forecasters in real-time to apply UNSTABLE results to convective forecast and warning decisions.

5. Science Questions

For this scientific overview and for planning purposes, UNSTABLE goals from the previous section have been formulated into science questions we will seek to answer through the experiment. For each primary question a number of more specific sub-questions are posed in order to address UNSTABLE objectives in detail. Experimental design and measurements required to answer the questions are then discussed. A number of additional questions are important to consider thought they may be difficult to answer directly through UNSTABLE observations. These questions are included at the end of each of the next three sections.

5.1 ABL Processes

The importance of ABL water vapour and convergence lines, including small-scale variability in their characteristics for CI in general, is clear. The characteristics and significance of these factors for severe thunderstorm development over the Alberta foothills is less certain. The bulk of observational and modeling studies related to CI and severe thunderstorms in Alberta have focused on upper-air, synoptic-scale features. Observational data used in these studies have been of insufficient spatial and temporal resolution to resolve ABL characteristics that are known to be important for CI in other regions. To address this we pose a number of science questions to be discussed in the remainder of this section. Answering these questions will require data from targeted measurements of atmospheric characteristics in the ABL and aloft. These measurements must be of sufficient spatial and temporal resolution to capture the four-dimensional structure of ABL water vapour, convergence lines, and their associated circulations. To facilitate this, a data collection array has been designed within a defined area of the Alberta foothills coincident with the highest frequency of thunderstorm activity and numerous severe weather reports in the region (see section 6 for details).

Science Question 1: What are the contributions of ABL processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?

a. What is the 4-dimensional characterization of ABL water vapour through the diurnal mixing process and prior to / during CI?
b. What role do mesoscale boundaries and circulations (e.g., mountain-plain circulation, dryline or other convergence boundaries, horizontal convective rolls) play in CI, the development of severe thunderstorms, and their evolution?
c. What is the 4-dimensional characterization of the dryline, and how often is it a key factor in the development / evolution of severe thunderstorms?
d. What synoptic / mesoscale processes act to inhibit CI in the region?
e. Are existing conceptual models for CI and severe thunderstorm development / evolution in this region adequate?

Question 1a requires sampling of water vapour both at the surface and through the depth of the ABL through the diurnal cycle. Data collection[7] will occur in two periods during a 24 h day. The nocturnal period (i.e., during the overnight to early morning period ~02Z to 12Z) will utilize fixed instrumentation only while the daytime period (i.e., during the daytime hours including CI or ~12Z to ~02Z) will utilize both fixed and targeted mobile instrumentation. The actual transition time between periods will depend on the timing of CI and degree of ongoing convection during the early evening hours as mobile instrumentation may still be in operation at this time. Data collected during the nocturnal period will be a subset of those collected during the daytime. The instrumentation described for question 1a will also be required for the remaining sub-questions. To avoid repetition, the discussions for subsequent questions are limited to modification of data collection strategies as appropriate.

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[7] See chapter 6 for descriptions of instrumentation introduced in this, and the remaining sections of chapter 5.

Data collection during the nocturnal period will rely largely on automated data collection platforms, in fixed locations with high temporal resolution, including the following:

Surface Mesonet

Transportable surface mesonet stations will be deployed prior to 1 June using both grid and linear orientations to obtain one-minute averaged measurements of atmospheric variables (i.e., pressure, temperature, humidity, wind speed and direction, and precipitation) over the primary and secondary UNSTABLE domains[8]. These stations will augment existing surface weather stations to result in a mesonet of 22-27 stations in the primary domain with ~25 km spacing (an additional 124 partial observation stations, i.e., temperature, humidity, and precipitation only, are already in place within the primary UNSTABLE domain). Within the main mesonet, one or two (depending on station availability) higher density lines of stations with ~10 km spacing will be deployed on axes perpendicular to the regional terrain and known orientation of observed moisture gradients and convergence lines. Where possible, data from these stations will be made available in real time to dedicated nowcasting support staff and PASPC/CMAC-W operational staff. Within the secondary UNSTABLE domain no stations will be deployed but data from the existing 9 full-observation, and 92 partial-observing stations will be used in conjunction with those from the primary UNSTABLE domain. Surface mesonet data will be used to resolve moisture (and other) fields in spatial terms and will provide temporal evolution in surface moisture at fixed locations.

GPS Integrated Precipitable Water Vapour (IPWV)

A network of 6-10 GPS sensors (operated by the University of Calgary) measuring total column PW vapour will be deployed for the duration of the experiment at fixed locations within the UNSTABLE domains (some sites still to be determined). These instruments will provide near-continuous (30 min. resolution or better) IPWV estimates throughout the diurnal cycle and will augment surface and upper-air measurements to capture the evolution of IPWV with high temporal resolution.

WVR-1100 Radiometers

Two total-column water vapour radiometers are anticipated for deployment at fixed locations throughout the duration of UNSTABLE. These instruments will be deployed in data voids within the GPS PW network. The radiometers will provide near-continuous measurements of total column water vapour and liquid water high temporal resolution over their locations.

Tethersonde

A recently acquired Environment Canada system unit will be used to provide continuous measurements of atmospheric variables (pressure, temperature, humidity, and wind) at several discrete altitudes. The unit can be equipped with up to 3 km of line and up to 6 tethersondes to extend beyond the depth of the nocturnal ABL and possibly the daytime ABL. The tethersonde will be deployed at a fixed location near the eastern edge of the primary UNSTABLE domain. If possible, this location will coincide with the easternmost mesonet station of the northernmost high density line (e.g., at Chedderville or Dovercourt, N of Caroline) for the duration of the UNSTABLE IOP. This will allow the unit to remain within the moist ABL on most days during the IOP. The tethersonde system will be deployed every day during the IOP (weather permitting) from 12Z. The tethersonde system will continue operations throughout the daytime phase of measurements or until thunderstorms or other precipitation are observed within close proximity.

Fixed Radiosondes

Two radiosonde stations will be established at fixed locations during the UNSTABLE IOP (see section 6.3). These will be located at the Olds-Didsbury airport and one other location within the primary UNSTABLE domain (e.g., Cochrane, Calgary, Bearberry NW of Sundre). The majority of soundings will be released during daytime hours but a 12Z sounding will characterize atmospheric moisture at the end of phase 1 and a late day (e.g., 00Z or later) sounding, released

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[8] See chapter 6 for definition of UNSTABLE primary and secondary domains.

on selected days, will characterize atmospheric moisture at the beginning of phase 1. Fixed location soundings will be released every morning during the IOP at 1145Z. On IODs, additional soundings will be released in 2 h intervals valid at 14Z, 16Z, 18Z, and additionally every 2 h until CI occurs in the target area for that day. For a 23-day IOP 46 sondes will be required for the 12Z launches. Estimating 11 IODs and an additional 5 soundings on each IOD requires an additional 110 sondes bringing the total to 156 sondes for the fixed radiosonde stations. These soundings will provide consistent temporal resolution of ABL (and upper-air) evolution of water vapour to be used in conjunction with mobile instrumentation platforms. Soundings released at Stony Plain at 12Z and 00Z will also be included in the final data set.

Radar Data

Fabry (2006) has shown the utility of radar refractivity data to characterize low-level moisture fields and identify small-scale convergence boundaries. It is unclear whether radar data from the Strathmore Environment Canada radar or the Olds-Didsbury radar operated by WMI can be used in this manner for regions of the Alberta foothills. The feasibility of using these radars for water vapour measurements and utility of the data will be explored.

Daytime measurements will include the period of ABL mixing early in the day leading up to, and including, the development of convection. Instrumentation during this phase will include those discussed above but will also employ the use of mobile instrumentation to sample ABL water vapour.

Mobile Radiosondes

It is anticipated that three mobile radiosonde systems will be available for the UNSTABLE IOP. These will be deployed on IODs in areas favourable for the development of convergence boundaries / circulations or otherwise favourable areas for CI. When possible the mobile radiosonde teams will be in place prior to 14Z so that sondes can be released simultaneously with the fixed radiosondes at 2 hour intervals. Locations of the mobile teams will be estimated on the previous evening and refined early on IODs to ensure timely deployment of balloons. Two mobile radiosonde teams will be deployed along with other surface -based mobile platforms and, where possible, will obtain simultaneous soundings on both the moist and dry sides of developing or existing moisture boundaries. In the absence of boundaries, mobile radiosonde units will release soundings from within the pre-storm ABL in conjunction with surface mobile measurements. Estimating 11 IODs and up to 6 soundings per mobile station (i.e., at 14Z, 16Z, 18Z, 20Z, 22Z, time of CI) will require 198 sondes and expendables.

Mobile Atmospheric Research System (MARS)[9]

The MARS system will allow for near continuous profiles of humidity and liquid water up to 10 km (under ideal conditions) from the profiling microwave radiometer and water vapour in the lowest 3 km every 10 minutes from the Atmospheric Emitted Radiance Interferometer (AERI). The MARS will also house a mobile radiosonde system so that soundings can be launched on IODs on the moist side of detected moisture boundaries or within the moist ABL of the pre-storm environment. Deployment of mobile radiosondes in close proximity to the MARS trailer will allow comparison between various methods of obtaining atmospheric soundings.

Automated Mobile Meteorological Observation System (AMMOS)

The AMMOS will be used primarily for detection of surface moisture (and other) gradients. The AMMOS will be deployed together with two mobile sounding units and the MARS to provide continuous surface transects between soundings on either side of detected boundaries during the daytime mixing period and the initiation of convection. A second mobile data collection platform (pressure, temperature, humidity) will be used either along with the AMMOS or in other locations on non-boundary IODs.

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[9] See section 6.1.3 for details on MARS instrumentation.

The AMMOS is designed to obtain rapid samples of environmental variables and will record data every second during IOD transects. Varying the speed of the vehicle during transects will in turn vary spatial resolution of measurements. E.g., traveling at 40 kmh^{-1} the AMMOS can record a measurement every ~ 11 m with sampling at 1 s intervals. Studies in the US (e.g., Pietrycha and Rasmussen 2004) have experimented using multiple mobile mesonet stations on the same boundary with varying transect lengths and traveling velocities. Similar experimentation can take place during UNSTABLE.

Aircraft Observations

Airborne measurements are critical to characterize moisture stratification through the depth of the ABL in spatial terms (filling in data voids between soundings or other profiling instrumentation) as well as horizontal moisture gradients above the surface. The NRC Twin Otter aircraft is well-suited to this role. Measurements required to answer question 1a (and subsequent questions) include pressure, altitude, temperature, dewpoint / mixing ratio, 3-axis winds and gusts, and surface radiation fluxes.

On IODs two flights would be anticipated with the option of a third on individually selected days of interest. The first flight would begin taking measurements in the 15-16Z (0900-1000 LT) time frame and the second ~20Z (1400 LT). If based at the Olds-Didsbury airport each flight should require, on average, a maximum 100 km transit to the location where measurements will be taken. When at the location of interest (over the surface-based mobile instrumentation) the aircraft will fly a combination of ascending / descending spirals, stepped traverses, and 'box' circuits depending on pre-determined flight patterns (e.g., boundary vs. no boundary). Each flight should be limited to near 3 h in duration. Assuming two flights on 11 days during the UNSTABLE IOP and optional third flights on 5 IODs will require 81 h of flight time during the IOP. Including transit time from Ottawa to Olds-Didsbury (~ 2885 km), an estimated total of ~ 112 h of flight time would be required for the Twin Otter amounting to an estimated cost of ~ $204000[10]. Details on flight patterns for boundary and no-boundary days will be presented in the UNSTABLE operations plan under development.

As part of their hail mitigation program, Weather Modification Inc. operates an instrumented King Air aircraft for cloud seeding (see section 6.1.4 for a description). WMI has offered to allow chartering of this aircraft at rates as low as $ 500 per hour on UNSTABLE IODs for pre-storm ABL flights in the primary UNSTABLE domain. These flights would only be available up to the late morning to early afternoon period but could be used to augment the Twin Otter aircraft measurements during stages prior to CI. The data collected would enhance the airborne measurement dataset from the field campaign. Estimating 66 h of project flight time would amount to an estimated cost of $ 33000.

The above instrumentation and measurements are required to fully characterize the evolution of water vapour in the boundary layer through the diurnal period. There may be an option to deploy the mobile instrumentation for a nocturnal campaign depending on expected weather and the number of IODs during the UNSTABLE IOP.

Instrumentation required to answer 1b include those discussed above. The same deployment strategies will be used on IODs where it is anticipated that mesoscale boundaries and / or circulations may develop that could influence the development of thunderstorms. In this case sampling of both the thermodynamic and kinematic characteristics of the ABL is required and will depend heavily on the use of the mobile data collection platforms. Remote sensing information will be combined with in situ instrumentation to correlate the development of mesoscale boundaries and circulations with thunderstorm development as described below.

Fixed Instrumentation

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[10] Using cost guidelines (plus $20 estimated increase in fuel costs per hour) in the 2007 "Call for Projects", Environmental Research Aircraft Facility NRC Convair-580, NRC Twin Otter; FY 06/07 document.

The surface mesonet will be used to develop spatial analyses of pressure, temperature, and moisture parameters as well as sample the surface wind field. Gradients and discontinuities in these fields will be used to identify general locations of convergence (or other) boundaries and will be used by the nowcaster / field coordinator to direct mobile teams to areas where higher resolution measurements can be taken. Fixed GPS PW and WVR radiometer data will be used to characterize column water vapour differences across convergence and moisture boundaries, e.g., the dryline, and may also help in identifying the general region where these boundaries exist. Temporal changes in PW in the vicinity of boundaries / circulations will be used to characterize gross moisture evolution in response to low-level convergence and circulations aloft. The tethersonde and fixed radiosondes will be placed in areas likely to be on the moist side of mesoscale boundaries to record temporal changes in profiles of thermodynamic and kinematic variables in response to the development of boundaries and circulations.

Mobile Instrumentation

The AMMOS, MARS, mobile radiosondes, and aircraft will be deployed during the morning hours to begin sampling preferred areas for boundary / circulation development and CI. Using the strategy outlined in question 1a; mobile radiosondes will be released from either side of observed boundaries with the MARS trailer instrumentation activated on the moist side of the boundary. The AMMOS (and other mobile surface stations if available) will conduct multiple transects across the boundary and aircraft measurements will commence at prescribed times over the location of the mobile instrumentation teams. Data from the mobile instrumentation platforms will be used to characterize the precise location, evolution, and character of mesoscale boundaries and circulations leading up to CI and thunderstorm development. The array of mobile measurement will provide high-resolution measurements on the thermodynamic and kinematic properties of these features at the surface and aloft throughout the ABL. Cameras will be used by the mobile (and fixed) teams to document CI and storm development for comparison with remote sensing data.

Remote Sensing Data

Radar-observed fine lines and observations of Cu on satellite imagery are primary ways to identify low-level boundaries in the absence of detectable precipitation. UNSTABLE will utilize the Carvel and Strathmore Environment Canada C-band Doppler radars (see section 6.1) for nowcasting support and for later studies. Access is anticipated as well to the C-Band radar operated by Weather Modification Inc. (WMI) at Olds, AB, as part of their hail damage mitigation project. The WMI and Strathmore radars are the only radars that will have an opportunity to sample clear-air echoes in the UNSTABLE study area(s) and neither is ideally located to detect fine lines over the majority of the primary UNSTABLE domain. The possibility of portable radar inclusion into the project is under investigation. Other remote sensing data including satellite imagery will be used both in real time for nowcasting and for later studies.

Satellite, radar, and lightning detection data will be used for nowcasting information and to document the development and evolution of thunderstorms. All these data will be archived at full spatial and temporal resolution and combined with data from fixed and mobile instrumentation deployed during UNSTABLE. The PASPC receives reports of severe weather from the public and registered storm spotters, mobile teams in the field during UNSTABLE will also provide reports when possible. These data will be used to gain information on severe weather produced by storms in the UNSTABLE domains.

The dryline is a special case of a mesoscale boundary observed over the Alberta foothills. Observational strategies to answer question 1c will be similar to those already discussed with the focus with respect to the dryline on measuring ABL moisture gradients and changes in the wind field across the dryline. Sampling of both horizontal and vertical components of the wind is necessary to resolve secondary circulations associated with the dryline and other boundaries. Synoptic patterns favourable for dryline development in Alberta have been identified (e.g., Taylor, 2001, 2004, Hill 2006) and will be used to identify potential dryline days at least one day in advance. On dryline days mobile units will be deployed with sampling of the dryline the priority.

Roads to be used by the ground-based mobile teams will be predetermined based on known regions for dryline development and early morning nowcast information.

To determine how often the dryline is a key factor in the development of severe thunderstorms will require the use of both UNSTABLE and historical observational data. A methodology to develop a short-term climatology of dryline-associated severe weather events has been developed by the lead author (e.g., Taylor 2004). This approach involves identification of days with significant severe weather (i.e., three or more reports of severe hail, one or more report of hail ≥ 30mm in diameter, or one or more reports of a tornado) and the use of surface observations and remote sensing data to correlate dryline development with CI and generate ensuing storm tracks.

In question 1d factors leading to the delay or inhibition of CI will be considered. Mechanisms for the formation of a capping lid in Alberta have been proposed by Strong (1986, 2001) and Smith and Yau (1993b) though neither may have been adequately verified with observational or modeling studies. It is reasonable to assume that other factors leading to subsidence or warm air over an unstable ABL (e.g., shear in the ABL or near the LCL/LFC, gravity waves, sub-cloud base entrainment, shallow ABL water vapour) may contribute to the delay or inhibition of CI. Deployment of radiosonde systems and the MARS trailer in the moist, pre-storm ABL will complement aircraft measurements to provide detailed data on the thermodynamic structure and evolution of the ABL and any inversions or other factors suppressing convection. These data will also provide details on the horizontal and vertical wind structure near the top of the moist ABL prior to and near the time of CI. It is hoped that these high-resolution observational data will provide information as to the origin and evolution of the capping lid, or other mechanisms for delaying or suppressing CI, that were not observable in previous studies.

Appropriate conceptual models for CI and severe thunderstorm development are a critical component of the forecasting process for meteorologists. Existing conceptual models for severe thunderstorm development in Alberta (e.g., Strong 1986, Smith and Yau 1993b) were developed using synoptic-scale networks and antiquated technology. The comprehensive dataset to be compiled during UNSTABLE provides an opportunity to test the utility of these models and identify processes that they may not include. New information gained during UNSTABLE can be compared to signals evident in the current observation network to infer processes that may not be resolved by those data. High-resolution data collected during the project, and subsequent modeling studies, can be used to modify, or if necessary, propose new conceptual models. These may better reflect current understanding of the physical processes contributing to CI and severe storm development in this highly severe weather prone area.

Additional Questions to Consider

- Can the influence of mesoscale boundaries and circulations be seen in the severe weather climatology of the region?
- How does the varied terrain in the foothills region influence mesoscale boundary and circulation development?
- How are mesoscale boundaries and circulations observed within the UNSTABLE domain(s) influenced by synoptic-scale processes?
- Under what conditions do thunderstorms generated in the central Alberta Foothills intensify and move southeast over the Calgary area?
- Using the UNSTABLE dataset, can factors be identified that determine which storms become severe?
- How can the current observational network be improved to better represent ABL processes that contribute to the initiation and development of severe thunderstorms?

5.2 Land Surface Interactions

Land surface interactions are most pronounced on quiescent days; that is, days when there is minimal large-scale forcing, especially in terms of moisture and thermal advection. Consequently, questions posed in this section will mostly be addressed on days that are deemed to be quiescent. The importance of land surface interactions with the ABL, especially with respect to sensible and latent heat fluxes, for severe storm development were discussed in section 3.3. Clearly, these effects must be considered for UNSTABLE. To address this we pose the following science questions:

Science Question 2: What are the contributions of surface processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?

a. Are there detectable gradients of surface (and ABL) water vapour across the major wet/dry areas over the cropped region (as quantified by root-zone soil moisture)?
b. Are there detectable gradients of water vapour between cropped land and forested areas?
c. Is there a noticeable difference in the location and timing of CI with respect to wet and dry areas over the cropped region?
d. Are mesoscale circulations detectable between areas of contrasting root-zone soil moisture or vegetation type?
e. Under what conditions are mesoscale circulations (land breezes) observed to trigger deep convection?

Answering the above questions will require data from a variety of existing and specially deployed data collection platforms. Another critical component will be the PAM-II agrometeorological model, which has been shown to simulate soil moisture and ET quite well at specific sites in Alberta. Output fields from PAM-II will be used in conjunction with radar-derived daily precipitation maps to identify mesoscale gradients in root-zone soil moisture and ET. For questions (a) and (b) mesoscale gradients of water vapour in the ABL need to be resolved using high-resolution fixed and mobile measurements of state variables. This will be accomplished via the fixed UNSTABLE mesonet, fixed and mobile soundings, and observations from MARS, AMMOS and research aircraft. The influence of wind shear on CI was introduced in section 3.2. Dynamic impacts of ambient flow on weak mesoscale circulations are thought to be important. For (c) through (e), a combination of satellite, radar and lightning strike data will be employed to identify the location of convection initiation each day. Frequent mesoanalyses in conjunction with field observations (especially using the MARS, AMMOS, and aircraft across the wet/dry areas) will help identify mesoscale circulations. It can then be determined whether or not the CI zones are located in the vicinity of mesoscale circulations, and/or gradients in root-zone soil moisture. If so, common characteristics of the mesoscale features (e.g., strength of soil moisture gradient) that lead to CI can be identified and quantified.

See section 6 for further details on experimental design.

Additional Questions to Consider

- Are differences in cloud base heights evident over regions of contrasting root-zone soil moisture or land use?
- Can the surface contributions of ET to total ABL moisture be quantified using surface-based (and airborne) observation platforms?
- Are soil moisture discontinuities from the GEM-LAM consistent with observations? Do these virtual gradients affect where the model triggers deep convection?
- How does the orientation of synoptic (background) flows modify gradients in surface water vapour and associated circulations on a day-to-day basis?

- What are the latent and sensible heat fluxes over the region, especially across any wet/dry areas that may exist? How do they influence temperature and water vapour stratification?

5.3 Numerical Weather Prediction

Computational resources are now permitting weather centres to run high-resolution (meso-*α*-scale) NWP models over specific regions. Since the summer of 2005, the Canadian Meteorological Centre has been running the GEM-LAM model in a real-time experimental mode over two experimental domains in Canada with horizontal grid-spacing of approximately 2.5 km. With increasing interest on high-resolution grids in Canada, one of the next logical steps is to examine the potential for a high-resolution configuration of the GEM-LAM to provide useful numerical guidance for the prediction of CI and severe convection in western Canada and elsewhere.

The NWP component of UNSTABLE will consist of two main parts, both with the ultimate goal of maximizing the usefulness of high-resolution model grids to contribute to the forecasting of deep convection. The first part is to assess the ability of the existing GEM-LAM model configuration to provide useful forecast information pertaining to Alberta thunderstorms. The assessment stage will involve examining how the current configuration of the model handles the evolution of the boundary layer evolution and surface fields as well as the subsequent development of convective storms. Comparison of the model fields will be made to observations taken during the IOP. The second part will examine possible ways of improving the model for forecasting severe convection.

The following main science question and associated sub-questions are hereby proposed:

Science Question 3: To what extent can high-resolution numerical weather prediction models contribute to forecasting the initiation and development of severe convective storms that originate in the Alberta foothills?

a. What defines a “success” for a high-resolution simulation in terms providing useful numerical guidance from the current GEM-LAM configuration?
b. Can the atmospheric state be classified a priori as “predictable” or “non-predictable” in terms of recommended use of the GEM-LAM run to guide the forecast?
c. How realistic are the simulated storm structures and microphysical fields?
d. How realistic is the evolution of the boundary layer and surface processes in the foothills region for the high-resolution model simulations?
e. What would be the effect of performing a subsequent nest to a higher-resolution grid, driven from the 2.5-km GEM-LAM run?
f. Can an ensemble of high-resolution runs improve the prediction of convection?

For question 3a, the assessment must also evaluate the overall skill of the model to predict the type of convection that will occur. This does not simply imply that skill scores will be computed to measure whether or not specific storms have been predicted. It must be recognized that with the current limitations in the operational observations which are used to produce gridded analyses, as well as uncertainties and limitations in the way that physical processes are treated, NWP models cannot be expected to explicitly predict *specific* thunderstorms. Rather, for a given mesoscale environment that is well represented in the initial conditions, the model should be evaluated in terms of its ability to predict the overall *nature* of the observed convection. Furthermore, the evaluation − and use − of a single deterministic NWP forecast must be done with caution, particularly when examining small-scale phenomena such as thunderstorms. The development of meso-*α*-scale features is very sensitive to small perturbations in the atmosphere, both in reality and in the model. Thus, defining what constitutes a “success” for the high-resolution runs, and examining approaches to quantifying the skill of the model to simulate the general nature of the observed convection, will be important in assessing the current configuration of the GEM-LAM.

The numerical solution given by any limited-area model is strongly influenced by the initial conditions and boundary conditions supplied by the driving model. The forecast from the 2.5-km GEM-LAM is thus greatly influenced by the solution of the 15-km GEM-REG. The implication is that while the GEM-LAM is capable of generating high-resolution features not present in the GEM-REG – which is the essential reason for running the GEM-LAM – it cannot correct for forecast errors in the large-scale flow from the GEM-REG model run. Poor numerical forecasts from the GEM-REG are often worsened by the GEM-LAM. There exists a danger, therefore, in using the GEM-LAM to provide numerical guidance in situations when the GEM-LAM forecast should not even be considered. This could potentially lead to poor forecasts in such cases and to obscure the potential utility of the GEM-LAM as a useful forecast tool in situations when it should be considered. For question 3b, the challenge is to clearly identify beforehand whether or not the GEM-LAM numerical forecast should be used; that is, to classify *a priori* the driving model solution – that of the GEM-REG – as reliable or unreliable. If the state of the atmosphere can be objectively classified *a priori* as “non-predictable”, then it may be possible to determine a useful criterion to alert forecasters as to whether or not the solution of the GEM-LAM should be considered for numerical guidance on a given day.

With a horizontal grid-spacing of 2.5 km, the model approaches the convective scale, where the flow within individual storms is resolved. It therefore becomes relevant to evaluate the simulated storm structures and microphysical fields as well as the associated surface precipitation. Understanding the model’s strengths and weaknesses in simulating storm fields can provide useful information for improving the model. Since in-cloud measurements will not be taken during this experiment, radar observations will be the primary data source for evaluating storm structures. In addressing question 3c the realism of the simulated microphysical fields within storms, such as particle types, mass contents, sizes, etc., will be evaluated qualitatively based on understandings of storms from previous studies and conceptual models. Simulated surface precipitation quantities will be evaluated against the dense network of rain gauges. Observations of hail sizes at the ground, such as those made from the insurance companies, will be used to evaluate simulated hail sizes from the model. It should be possible with these comparisons to identify strengths and deficiencies in the model’s cloud microphysics parameterization.

To answer question 3d, measurements taken during the IOP of temperature, moisture, and fluxes at the surface and in the boundary layer will be compared directly to the model in order to evaluate how the model simulates the pre-storm environments. This will provide a means to evaluate the skill of the land surface and planetary boundary layer parameterization schemes in the foothills and to identify possible deficiencies in the schemes. Related to this will be an examination of the model's ability to simulate mesoscale circulations (e.g., the mountain-plain circulation) and related boundaries (e.g., the dryline).

Although the current GEM-LAM’s horizontal grid-spacing of 2.5 km approaches the convective scale, this may not be sufficiently small to adequately resolve the flow features of individual thunderstorms. While this may not affect the prediction of CI, the simulation of storm structures and the prediction of the convective modes may be greatly improved through the use of higher-resolution grids since the strong vertical motion in convective updrafts can be more accurately simulated. To investigate the effect of running at higher-resolution (question 3e), a sub-domain covering the project area – with a grid-spacing of 1-km – will be run daily, nested from the output of the 2.5-km run. Comparison of model storms between the 2.5-km and 1-km runs will be made to investigate the potential added value to forecasting severe convective weather by running higher-resolution grids. Model fields from the 1-km runs will be compared to measurements taken during the IOP, but the 1-km runs will be conducted throughout the entire summer of 2008.

It is well established that the use of any single deterministic model forecast, regardless of its sophistication, is inherently limited due to the chaotic nature of the atmosphere. Weather forecasting of large-scale features is generally improved through the use of numerical guidance from an ensemble forecasting system. For small-scale features such as thunderstorms, it remains unclear whether or not there can be a benefit to forecasting from an ensemble of high-resolution model runs. While a true ensemble forecast system is complicated to set up, as it requires a method of appropriately perturbing the initial conditions, and computationally expensive to run, it is fairly straightforward to set up a “poor man’s ensemble” consisting of a small number of members with different physics parameterizations. Using this approach to address question 3f, hind-cast experiments will be conducted with the 2.5-km GEM-LAM, by re-running the model using different combinations of schemes.

For the examination of the NWP aspects the UNSTABLE project, much of the model data will come from forecast fields from the western (Pacific-Yukon Region) grid of the quasi-operational GEM-LAM-2.5 model, operated by the Canadian Meteorological Centre. Since the 2007 summer season, the eastern boundary of the western grid has been extended eastward, to approximately the Alberta-Saskatchewan boarder, similar to what was done during the summer of 2006. It is anticipated that the current microphysics scheme will soon be replaced by a version of the Milbrandt-Yau cloud scheme, which includes a more detailed representation of cloud microphysical processes and hydrometeor types than in the current model, before the summer of 2008. All other configurations of the model will remain the same as in the current GEM-LAM-2.5. Tentatively, it is anticipated that a similar configuration of the GEM-LAM-2.5 and daily model output will be available during the summer of 2008. None of the special observations taken during the IOP will be incorporated into the real-time model forecasts.

Though several aspects dealing with science question 3 will require use of the observations taken during the summer of 2008, the examination of several of the above sub-questions can begin any time. A considerable amount research can be done on the first three sub-questions, pertaining to examining the utility of the current model as a forecast tool, using observations that are currently available. Radar observations and real-time model output, both of are available for the summer of 2007, will be the major data source for those questions. Evaluation of the model’s ability to simulate the boundary layer and surface processes will be done during/after the summer of 2008, when the special observations for the project will be made. Preliminary tests on the final two sub-questions can be done using cases from the summer 2007, though several aspects of evaluating sensitivity tests will benefit from the special observations.

6. Experimental Design

6.1 Instrumentation and Data Collection

The UNSTABLE observational dataset will result from various data collection platforms providing both in-situ and remote sensing measurements of atmospheric variables important for CI and other areas of interest. In this section the data collection platforms utilized for UNSTABLE are described including selected instrumentation specifications where appropriate. All data from sources discussed here will be archived for later use. To test and refine the use of the observation platforms and associated measurement strategies a pilot project has been designed for summer 2008 and is briefly described in Appendix 4.

6.1.1 Existing Instrumentation and Observations

Environment Canada and Province of Alberta Surface Observation Stations

A number of automatic and manned observations stations will be used as part of the UNSTABLE dataset. These stations provide hourly measurements of standard atmospheric variables (station pressure, 1.5 m temperature, dewpoint, 10 m wind speed and direction, tipping bucket rainfall accumulation). In cases where these stations comprise part of the UNSTABLE mesonet their sampling frequency will be increased to as near as once per minute as possible. These stations are denoted as ‘existing’ and ‘AGDM’ stations in Figure 23 and marked as large green circles (some ‘existing’ stations are AGDM stations whose data are currently available to forecasters in real time). A subset of the AGDM stations measure soil temperature and moisture at depths of 0.05, 0.20, 0.50, 1.00 m. These stations exist mostly over agricultural areas of the province to the east of the UNSTABLE study domain (two stations within secondary domain). Despite this, they will be useful for post UNSTABLE studies investigating soil moisture and evapotranspiration associated with moist air advection and CI. Stations with soil measurements are indicated in Figure 28.

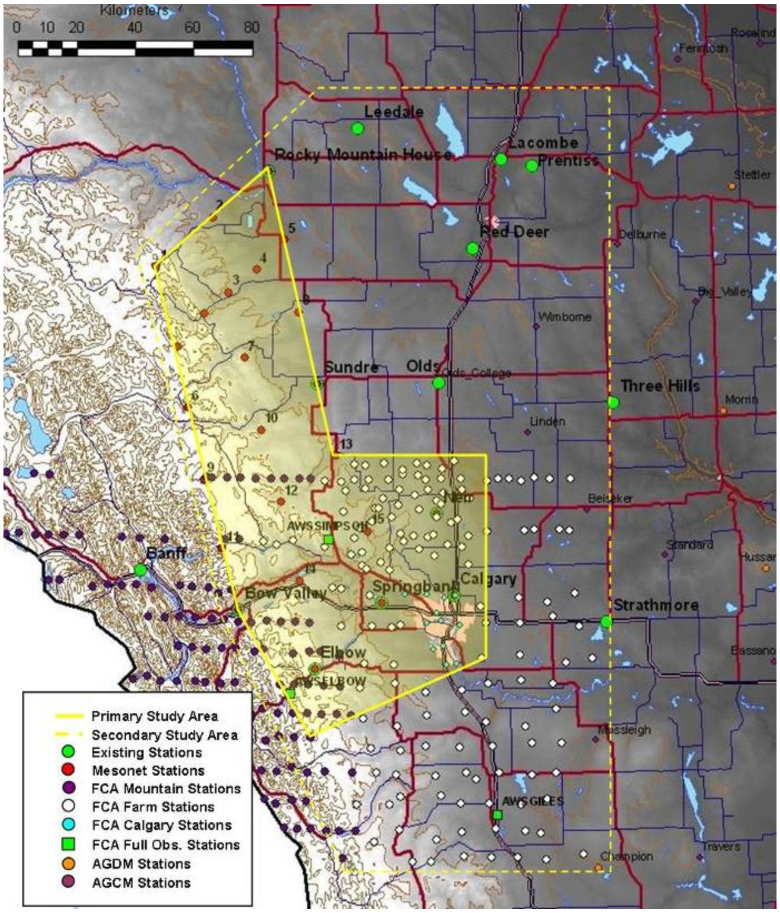

Figure 23: Preliminary primary and secondary study domains as described in the text (section 6.2). The locations of existing stations, the Foothills Climate Array (FCA), and ideal mesonet stations (red circles) are shown. Actual mesonet station locations are to be determined.

FOPEX Surface Observation Stations

Three remaining stations from the Foothills Orographic Precipitation EXperiment (FOPEX – Smith 2005) will comprise part of the UNSTABLE mesonet. Measurements from these stations will be one-minute averages of 1m temperature and relative-humidity, station pressure, 2 m wind speed and direction, and tipping bucket rainfall accumulation. FOPEX stations are indicated in Figures 23 and 28 as small red circles as for the other mesonet stations.

University of Calgary Foothills Climate Array (FCA)

The University of Calgary operates some 285 surface stations over the southern Alberta foothills region. The stations are classified as either ‘farm’ or ‘mountain’ depending on their location. The farm stations record 1.5 m temperature / humidity and 2.0 m tipping bucket precipitation while the mountain stations record 2.0 m temperature / humidity and 2.5 m tipping bucket precipitation (to account for deeper snow cover over the higher terrain). There are also currently 3 full observation stations (including 10 m wind speed and direction) within the FCA network. The locations of the FCA stations are denoted in Figures 23 and 28.

Alberta Agriculture AGCM Stations

Alberta Agriculture operates a class of stations in agricultural areas known as AGCM stations. These stations are indicated in Figures 23 and 28 and record 2.0 m temperature, humidity, wind speed (no direction) and accumulated precipitation.

Environment Canada (and other) Satellite Imagery

UNSTABLE will utilize standard satellite imagery available to operational forecasters at the PASPC. These will include 15 minute temporal resolution imagery of visible, infrared (11 μm) and water vapour (7 μm) imagery. These images will be archived for later studies. Other imagery sources available on the internet may be incorporated.

Environment Canada Radar

Two Environment Canada Radars are in relatively close proximity to the UNSTABLE study area. These are Carvel (53.56 ˚N, 114.14 ˚W) and Strathmore (51.21 ˚N, 113.40 ˚W). Both radars are C-Band (~5 cm wavelength) and offer Doppler capability within a range of 120 km. Some details of the radars are included in Table 4 below.

Table 4: Some specifications of Environment Canada radars to be used during UNSTABLE.

	Carvel	Strathmore
Ground Elevation	748 m	968 m
Wavelength	5.32 cm	5.32 cm
Dish Size	3.6 m	6.1 m
Beam Width	1.10˚	0.63˚
Frequency	5625 MHz	5628 MHz

Weather Modification Incorporated Radar

A C-Band (5.4 cm) radar is operated by Weather Modification Inc. at the Olds-Didsbury Airport (51.71˚N, 114.11 ˚W). This radar has a beamwidth of 1.65˚ and is pending upgrades to Doppler capability and the ability to detect echoes with a minimum detectable signal of 0 dBZ at 100 km (Krauss 2007, personal communication).

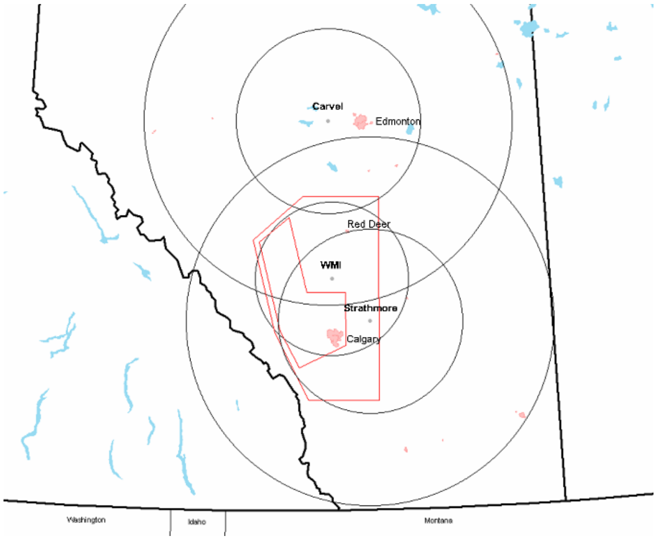

Figure 24: Radar coverage for UNSTABLE showing 120 km (Doppler range) and 240 km (detectable range) range rings for Carvel and Strathmore radars and 100 km (range for detection of 0 dBZ) range ring for the WMI radar. The primary (inner) and secondary (outer) UNSTABLE domains are outlined in red. The primary domain lies almost entirely within 100 km of the WMI radar and partially within the 120 km domain of the Strathmore radar. Carvel utility for UNSTABLE will be limited.

Canadian Lightning Detection Network (CLDN)

Environment Canada meteorologists utilize real-time lightning data via the Canadian Lightning Detection Network. The CLDN (Part of the North American Lightning Detection Network – NALDN) includes 83 sites using either Time of Arrival (TOA) or Magnetic Direction Finder (MDF) sensors providing accurate location and timing of cloud-to-ground (CG) lightning within the network domain (cloud-to-cloud lightning detection efficiency is much lower than for CG lightning).

The UNSTABLE project area lies within the highest resolution area of the network providing 90% detection efficiency and location within 500 m (see Figure 25).

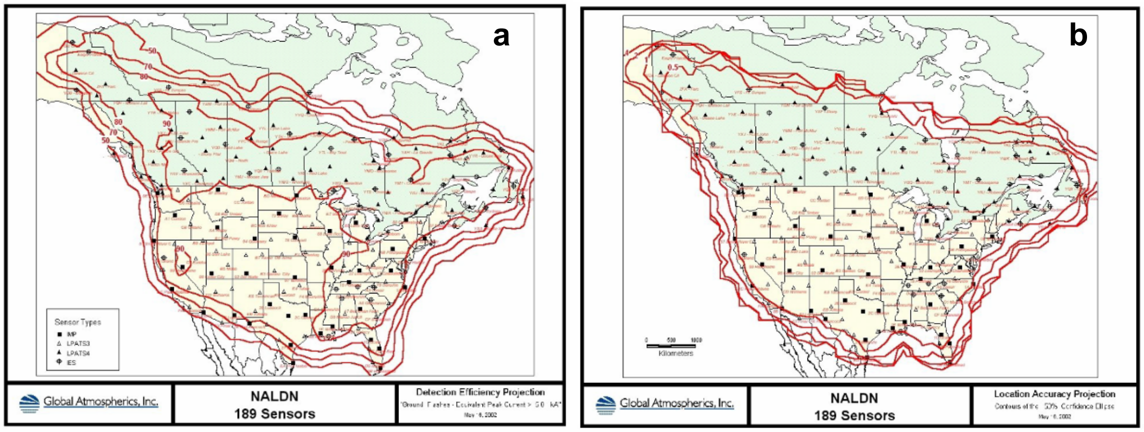

Figure 25: NALDN detection efficiency for cloud-to-ground flashes (a) and location accuracy (b).

Though lightning studies are not currently identified as a primary focus for UNSTABLE the data are useful for storm initiation and storm track information and will be archived along with the other data sets for future study.

Environment Canada Soundings

There are no existing sounding locations within the UNSTABLE project area. The nearest sounding to the project area is at Stony Plain, AB (53.55 ˚N, 114.10 ˚W) a distance of ~225 km to the center of the UNSTABLE mesonet. While some information regarding environmental characteristics may be available from these soundings, their representativeness of ABL and pre-storm environments over the Alberta Foothills is in question (see for example, Golden et al. 1986, Brooks et al. 1994, and Thompson et al. 2003 regarding sounding representativeness). For upstream, upper-level conditions (i.e., west of the Rocky Mountain Divide) the sounding at Kelowna (49.97 ˚N, 119.38 ˚W) is useful, especially with respect to winds passing over the mountains into the UNSTABLE project area. These and other sounding locations surrounding the UNSTABLE project area will be analysed and included in the data archive.

6.1.2 Supplemental Mesonet Stations

The primary source of supplemental surface observations for UNSTABLE will be from a mesonet of 15-20 automatic weather stations with approximately 25 km spacing. These stations are being supplied from various sources, primarily the Meteorological Research Division of Environment Canada (10 ATMOS[11] stations) and York University (3-5 ATMOS stations) with additional stations of varying types being provided from either within Environment Canada or from Universities (see Appendix A2 for a list of all the stations and associated measurements). Deployment of these stations will occur in the spring / early summer of 2008 prior to 1 June. Proposed locations for the mesonet stations are shown in Figures 23 and 28.

The Environment Canada ATMOS mesonet stations are solar powered, have communications capability via cell phone modem, and will record measurements as one-minute averages of the following:

- 10 m Wind Speed and Direction (RM Young 05103-10 wind monitor)
- 1.5 m Temperature and Humidity (HMP 45C T/H sensor + shield)
- Precipitation (liquid) (TE 525 tipping bucket rain gauge)
- Difference in Temperature between 0.5 m and 9.5 m (thermocouple + shields)
- Station Pressure (Vaisala PTB210 pressure sensor + SPH10 static pressure head)

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[11] Automated Transportable Meteorological Observation System

- Incoming Solar Radiation (SP-Lite radiation sensor (1 component - downwelling solar))

Preliminary sites have been selected for portions of the proposed mesonet locations in Figures 23 and 28.

6.1.3 Supplemental Surface-Based Upper-air and Profiling Observations

A number of observation platforms for obtaining upper-air and profile data will be deployed for UNSTABLE, they are listed below.

Radiosondes

It is anticipated that two stationary and three more mobile radiosonde systems will be deployed during the UNSTABLE field campaign (see Appendix A2 for more details). All sondes used in the field experiment will be Vaisala RS92 GPS sondes providing the latest in radiosonde technology and accuracy. Stationary radiosondes will be located at the Olds-Didsbury airport and within the primary UNSTABLE study area so that they are upstream (with respect to ABL flow) of storm initiation areas. Mobile radiosondes will be deployed on a targeted basis depending on positions of observed boundaries or otherwise areas with potential for CI.

Tethersonde

Environment Canada recently purchased a DigiCORA tethersonde system from Vaisala. At present the tethersonde will utilize 2 km of cable and three sondes. The tethersonde will allow either repeated profiles of the atmosphere through ascent / descent of the balloon or high temporal measurements at discrete levels when deployed for a period of time. This will allow detailed thermodynamic and wind measurements in the lowest ~2 km (or less) of the ABL never before recorded near the Alberta Foothills. The system was tested in southern Ontario during the summer of 2007 during the Border Air Quality Meteorological Experiment (BAQS-Met). The tethersonde will be located along the eastern boundary of the primary UNSTABLE study area.

University of Manitoba Mobile Atmospheric Research System (MARS)

The Centre for Earth Observation Science (CEOS) at the University of Manitoba operates a mobile trailer consisting of multiple data collection platforms providing vertical profiles of ABL characteristics. The MARS will be deployed within the UNSTABLE study area throughout the IOP with its location determined in conjunction with observed convergence lines or areas with potential for CI. When in the vicinity of convergence boundaries, the MARS will be closely located with other mobile instrumentation (e.g., mobile mesonet(s)). Instrumentation consists of:

*Atmospheric Emitted Radiance Interferometer (AERI MR100)****:*** The AERI system provides profiles of temperature and water vapour in the lowest 3km of the atmosphere. Vertical resolution is <100 m to 1 km AGL and near 200 m at 3 km AGL. Profiles can be obtained at 10-minute intervals.
http://cimss.ssec.wisc.edu/aeri/

*Doppler Sodar (Ramtech PA1-NT)****:*** The PA1-NT Doppler Sodar provides continuous profiles of thermal structure, wind speed and direction, vertical motion, mixing depth, and turbulence from 20 m to 1300 m (maximum 2000 m).
http://www.remtechinc.com/sodidx.htm

*Profiling Microwave Radiometer (Radiometrics TP/WVP-3000)****:*** The Radiometrics TP/WVP-3000 microwave radiometer provides profiles of temperature, humidity, and liquid water up to 10 km AGL. Profiles can be obtained at 20-second intervals. The unit also measure surface temperature, humidity, and pressure.
http://www.radiometrics.com/3000.pdf

IR Pyrometer (Heitronics KT 19 II): Used to measure convective cloud base temperatures to determine cloud base heights when compared with sounding data.

Airmar PB-100: Designed for marine applications, the Airmar instrument system supplies information on temperature, humidity, pressure, and wind speed and direction while stationary or in motion.
http://www.airmartechnology.com/uploads/brochures/weatherstation.pdf

Atmospheric Microwave Radiometers (Radiometrics WVR-1100)
The University of Manitoba and University of Calgary operate microwave radiometers providing total column integrated water vapour and liquid water at intervals of up to 30 seconds. Both of these radiometers will be deployed at fixed locations within the mesonet domain during the intensive observation period.

Profiling Microwave Radiometer (Radiometrics WVP-1500)
An additional Microwave Profiling Radiometer is anticipated to be available from the University of Calgary. The Radiometrics WVP-1500 provides profiles of water vapour to 10 km AGL and total column integrated liquid water at intervals of 10 seconds. This radiometer will likely be operated at the University of Calgary.
http://www.etl.noaa.gov/technology/radiometers/pdfs/1500.pdf

GPS-Derived Integrated Precipitable Water Vapour (IPWV)
The University of Calgary, Department of Geomatics Engineering operates a network of Global Positioning System (GPS) sensors as a remote sensing tool for IPWV. This network has been used to obtain IPWV estimates associated with thunderstorms over the Alberta foothills (Skone and Hoyle 2005). A number of GPS sensors will be made available to UNSTABLE and be operated within the UNSTABLE study domain providing near-continuous measurements of IPWV during the experiment. Final locations of the GPS sensors are still being determined.

6.1.4 Airborne Observations

As described in section 3.2, the effects of water vapour and convergence boundaries on CI are not limited to the surface. Mobile radiosonde and tethersonde measurements will provide some point profiles of meteorological variables and mobile mesonet stations will allow detailed surface-based transects of observed boundaries. To fully resolve the four-dimensional structure of the ABL and convergence boundaries within it however, airborne measurements are required.

A request will be submitted to the National Research Council for use of the Twin Otter aircraft research facility during UNSTABLE. The aircraft will allow high resolution measurements of atmospheric state, and other, variables (e.g., temperature, humidity, pressure, 3-axis winds and gusts, air and cloud chemistry, radiative measurements and video) at varying altitudes within and above the ABL. Stepped traverses and planar or ‘box’ circuits will resolve the detailed thermodynamic and kinematic structure of the atmosphere in the vicinity of convergence boundaries as related to CI and storm evolution. Phenomena to be measured in UNSTABLE that are important for CI include:

- Above-ground moisture and other gradients associated with drylines and other convergence boundaries or circulations
- Vertical motions adjacent to and within observed convergence boundaries, both within and above the ABL, necessary to determine mass convergence depth
- Mesoscale circulations associated with convergence boundaries or other processes (e.g., differential heating, horizontal gradients in soil moisture)
- Vertical wind shear across and above the top of the ABL, especially near capping lids
- Water vapour mixing depth, stratification and horizontal distribution related to areas associated with CI
- Surface sensible and latent heat fluxes

Measurements of the above are necessary to resolve and understand the processes associated with CI over the Alberta Foothills and for comparison with similar measurements of CI processes in other regions.

As indicated in section 5.1, Weather Modification Inc. has offered the use of their instrumented King Air aircraft for use during UNSTABLE (including the pilot project outlined in Appendix 4). This aircraft will be equipped with the Aircraft Integrated Meteorological Measurement System (AIMMS) instrumentation package designed by Aventech Research Inc. The AIMMS provides measurements of temperature, relative humidity, 3-axis wind, and turbulence at accuracies suitable for research purposes and was utilized in the ELBOW 2001 experiment (Sills et al. 2002). These data during the pre-CI period will enhance the value of the aircraft program during UNSTABLE.
http://www.aventech.com/index.php?content=application&site=atmospheric

6.1.5 Targeted Mobile Observations

Locations of drylines or other convergence boundaries, mesoscale circulations, and other processes leading up to CI within the UNSTABLE study domain will vary during the field campaign. Many of these features may be too narrow for their position to be accurately resolved by stationary surface mesonets (e.g., Mueller et al. 1993). For these reasons, we will follow the approach advocated by Weckwerth and Parsons (2006) and utilize targeted mobile surface and upper-air measurements. These platforms can be deployed with short lead time in the vicinity of observed boundaries or regions where CI is expected. Targeted mobile measurements will include the following.

- NRC Twin Otter and other aircraft measurements
- Two to three mobile radiosonde units
- AMMOS[12] mobile mesonet station (see below)
- CEOS, University of Manitoba Mobile Atmospheric Research System (MARS) including profiles of temperature, humidity, and liquid water to 10 km and wind up to 1.3 km
- Multiple meteorologists in the field providing human and photographic observations

Automated Mobile Meteorological Observation System (AMMOS)

Environment Canada's Cloud Physics and Severe Weather Research Section (CPSWRS) will provide a mobile mesonet unit for the UNSTABLE IOP. The AMMOS measures temperature, humidity, pressure, wind speed and direction and can log measurements every second. Alternative data collection / logging strategies are being investigated to obtain the highest resolution data possible. The AMMOS was tested over the Alberta Foothills during the summer of 2006 and measurements compared with 3 ATMOS mesonet stations also tested during the 2006 convective season. Results were favourable with the AMMOS proving to be physically robust and showing good agreement between mobile and fixed measurements when the AMMOS was collocated with the ATMOS stations. A second mobile data collection platform will be operated in conjunction with the AMMOS by Dr. Geoff Strong, adjunct professor at the University of Alberta.

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[12] Automated Mobile Meteorological Observation System

Figure 26: The Environment Canada Automated Mobile Meteorological Observation System (AMMOS), photo by Dave Sills.

Two or more radiosonde units, the aircraft, the AMMOS and the MARS can be deployed in the vicinity of a convergence boundary prior to CI. This will allow simultaneous soundings of the pre-storm environment on either side of the boundary, resolution of gradients and discontinuities in thermal, moisture and wind fields at the surface and aloft across the boundary, and near-continuous profiles of the thermodynamic and kinematic structure upstream (at low-levels) of the boundary. Coupled with stationary radiosonde, tethersonde, profiling and surface mesonet data we hope to characterize the evolution of the ABL prior to and during CI at multiple locations within the UNSTABLE study area.

6.1.6 Model Output from GEM-LAM-2.5

The GEM-LAM-2.5 will be run every day in real time during the summer of 2008. As for 2007, the western (Pacific-Yukon Region) grid will extended eastward to include all of central and southern Alberta (Figure 27). Gridded model output will be archived for each run. Fields will include the standard meteorological fields as well as surface fluxes, accumulated surface precipitation including total amounts and phases (i.e., rain, snow, graupel, or hail), instantaneous precipitation rates, and 3D fields of synthetic radar reflectivity, hydrometeor mass contents and number concentrations (for six different particle types). The frequency of the archived model output will depend on the available resources, but it will always be possible to reproduce data that has not been archived.

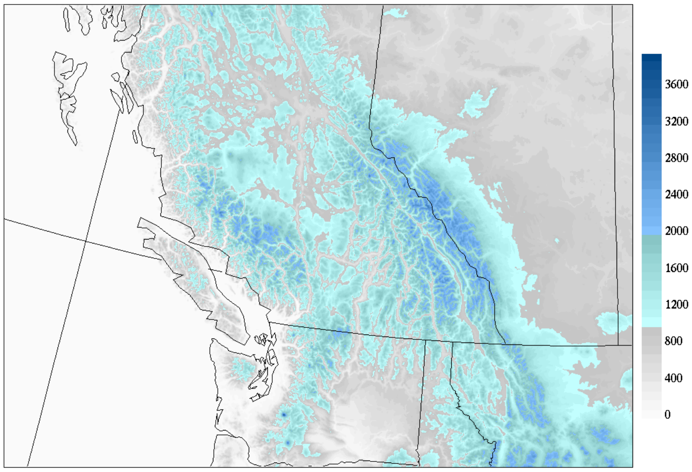

Figure 27: Proposed western domain of the GEM-LAM-2.5 for the real-time runs during the summers of 2007-08. Shading represents model elevation (m).

6.1.7 PASPC Forecasting and Nowcasting Support

To successfully obtain desired measurements during the UNSTABLE IOP will depend on the identification of a target area early in the day. Sills (2006, personal communication) identified nowcasting support as a critical factor for the success of UNSTABLE following his experiences with the ELBOW project (e.g., King and Sills 1998, Sills et al. 2002). To facilitate this, the lead author is working with the PASPC to formulate a plan for forecasting / nowcasting support to UNSTABLE from convective weather experts within the forecast office. This will likely be achieved through PASPC staffing of a Research Support Desk (RSD) during the 2008 convective season. Forecasters will provide briefings and take part in morning discussions on strategic deployment of field participants and instrumentation. On intensive observation days the forecaster will be in communication with the field coordinator to help direct those in the field to be collocated with features of interest. The details on the logistics in this regard will appear in the UNSTABLE operations plan.

6.2 UNSTABLE Study Area and Instrumentation Deployment

This section outlines the UNSTABLE study domain and deployment strategies for instrumentation during the field campaign.

6.2.1 UNSTABLE Domain

The UNSTABLE domain has been defined following the meteorological and socio-economic motivations described in section 2, the primary thunderstorm initiation region in Alberta as described in section 3, and relative to existing surface-based instrumentation (see Figures 23 and 28). The primary UNSTABLE domain is the region encompassing portions of the existing (Foothills Climate Array) and proposed locations for the special UNSTABLE mesonet. A secondary domain has been defined extending the UNSTABLE study area to the south and east encompassing further existing surface stations and one of the stationary radiosonde locations (Olds-Didsbury Airport, 51.71˚ N, 114.11˚ W). An additional reason for the secondary domain is to account for tracking of severe storms that either may initiate in the primary domain and track east, southeast, or be initiated outside of the primary domain on synoptic or mesoscale boundaries. While these events may occur outside of the high-resolution mesonet, deployment of mobile instrumentation platforms will still allow targeted measurements useful for the experiment.

6.2.2 Targeted Measurement Deployment Strategies

Data collection during UNSTABLE will consist of both fixed surface and upper-air measurements and targeted mobile measurements. Locations of fixed instrumentation will be determined relative to mesonet stations and in areas with potential for sampling boundaries and the pre-storm ABL environment.

Deployment of mobile instrumentation will be determined on a day-to-day basis during the IOP. Target areas will be defined through discussions with participating PIs, PASPC forecasters supporting the project, the field coordinator, and members of the mobile instrumentation teams. A decision will be made on whether or not to conduct operations on a given day based on opportunities to address the science questions and measurement strategies outlined in the UNSTABLE operations plan..

The following general deployment strategies will be employed for Intensive Observation Days (IODs), further details will appear in the UNSTABLE Operations Plan (under development).

1. **Fixed Radiosondes, Tethersonde, Profilers:** On an IOD efforts will be made to launch soundings at two- hourly intervals from 1200 or 1400 UTC through to storm initiation.
2. **Identify likely areas for significant thunderstorms:** If a thunderstorm threat area is identified within the UNSTABLE study area(s) this will become the general target area for the mobile teams.

3. **Identify most probable initiation mechanism:** The most probable initiation mechanism and location will be identified and mobile units (including aircraft) deployed to sample the boundary / circulation. Attempts will be made to obtain simultaneous soundings on either side of the boundary, AMMOS surface transects through the boundary, MARS sampling of the pre-storm / CI environment near the boundary (upstream with respect to ABL flow), and aircraft transects through and in the vicinity of the boundary.
4. **Identify Potential surface or ABL moisture gradients**: On days with potential for strong gradients in surface or ABL moisture (e.g., from agrometeorological model forecasts, previous day / overnight precipitation, mesonet observations) mobile surface and upper-air instrumentation can be deployed in an attempt to sample and mesoscale circulations that might develop.

Morning radiosondes from fixed locations will be used to help assess convective potential for the day. Generally, on non-IODs no further radiosondes will be launched though selected mobile or other instrumentation may still be deployed or activated on occasion. This might include AMMOS transects into the foothills, tethersonde deployment and / or radiometer measurements should interesting atmospheric phenomena be expected to occur.

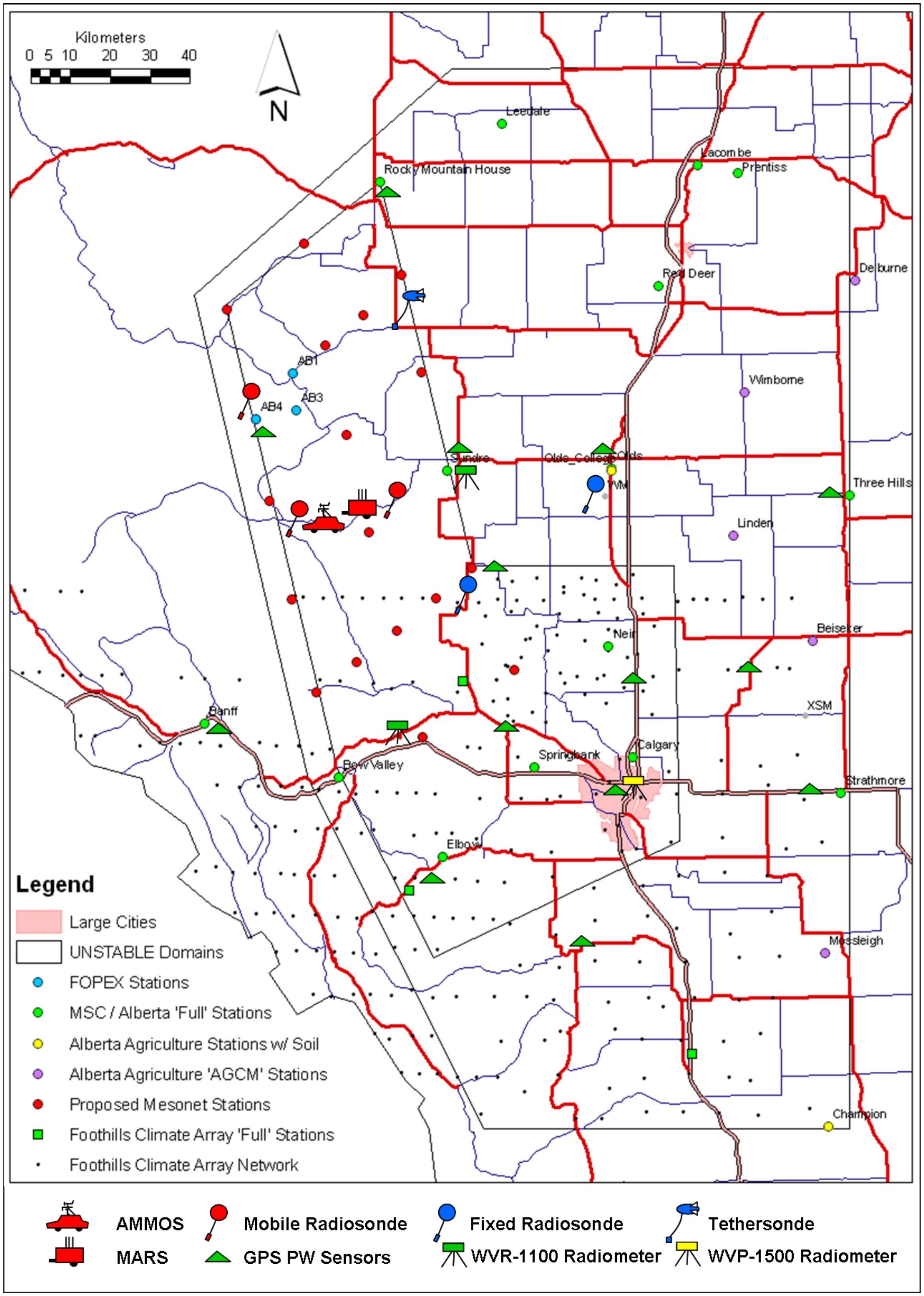

Figure 28: Map showing proposed instrumentation locations within the UNSTABLE domain(s). Fixed surface mesonet and other stations are as indicated as are other instrumentation to be deployed. Final locations of fixed profiling / other platforms are to be determined and will appear in the UNSTABLE operations plan.

6.3 Timeframe for Field Campaign and Intensive Observation Period

The UNSTABLE study period is planned for 1 June to 31 August. During this period all fixed mesonet stations will be in place and recording data. Other fixed instrumentation (e.g., radiometers) may be in place and recording data or undergoing calibration and testing prior to 1 July. Intermittent tests of mobile and other instrumentation (e.g., AMMOS, tethersonde, MARS, radiosondes) may also occur to ensure technical and other issues are resolved prior to the intensive observation period.

The IOP is tentatively planned to occur between 9 to 31 July, inclusive (23 days). During this time all efforts will be made to sample the ABL and upper atmosphere with all available instrumentation according to the science questions. The specific dates and/or duration or of the IOP may be limited or modified due to

- aircraft availability
- availability of expendables for radiosonde launches
- duration of availability of individuals for the field campaign
- funding shortfalls

7. Data Management

The majority of the fixed surface mesonet stations to be deployed during UNSTABLE are equipped with cell phone telemetry or other communications to facilitate real-time transfer of data. During UNSTABLE data will be collected, where possible, in near real time using LoggerNet software (for the ATMOS stations) and other means. Where possible, these data will be made available to PASPC (and CMAC-W) operations in support of their summer warning program. During the IOP these data will be used by the nowcasting support meteorologist to aid in IOD decisions and positioning of mobile instrumentation teams in the field.

Efforts will be made to ensure that all data collected during UNSTABLE will be archived and collected for quality control (QC) and later access. Collation of the data from various sources may be delayed as compared to the traditional data available to EC (e.g., synoptic surface and upper-air observations, satellite, radar, and lightning data) as QC may be performed first at universities or other institutions. After a period of analysis by UNSTABLE PIs and collaborators the data will be made available to external users.

8. Summary

The Alberta Foothills is a frequent severe thunderstorm genesis zone with storms developing there typically moving eastward to affect the Edmonton to Calgary corridor, one of the most densely populated and fastest growing regions in Canada. The Understanding Severe Thunderstorms and Alberta Boundary Layers Experiment (UNSTABLE) seeks to better understand ABL processes associated with severe thunderstorm development in this region. The experiment is motivated by the socio-economic impacts of severe weather in Alberta, challenges currently facing operational meteorologists to accurately forecast severe weather, and Environment Canada's mandate as related to its results-based organizational structure. The ultimate goal of UNSTABLE is to improve the lead time and accuracy of severe thunderstorm watches and warnings in an effort to mitigate the costly, and sometimes deadly, impacts of summer severe weather on Canadians.

Previous severe thunderstorm studies in Alberta have focused mainly on synoptic-scale and upper-air processes. Most of these studies were conducted some 20 years ago. Recent research in the U.S. and elsewhere in Canada has highlighted the importance of ABL processes related to water vapour, convergence boundaries, land-surface interactions, and mesoscale circulations for the development of severe thunderstorms. In the last few years greater attention been given to near-surface mesoscale processes in relation to the development of Alberta thunderstorms. UNSTABLE is an opportunity to obtain measurements with higher resolution than ever before to improve our understanding of the processes associated with severe weather in this region. The experiment is unique with its northern study area, proximity to the Rocky Mountains, and investigation of the dryline with genesis mechanisms that may be different than those associated with the dryline on the Great Plains of the U.S.

UNSTABLE is being designed to address three main science questions:

1. What are the contributions of ABL processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?
2. What are the contributions of surface processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?
3. To what extent can high-resolution numerical weather prediction models contribute to forecasting the initiation and development of severe convective storms that originate in the Alberta foothills?

ABL water vapour and convergence processes, including interactions with the land surface, are an area of active research in the meteorological community and there are still many unknowns associated with CI. With advances in high-resolution NWP, meteorological processes can be simulated, in a timely manner, at spatial and temporal scales never before available. For each question above a number of secondary questions and tasks have been defined so that, through UNSTABLE, we can improve our understanding of these processes and their importance for development, and forecasting, of severe thunderstorms.

A pilot field experiment in 2008 has been designed to test and refine appropriate instrumentation and measurement strategies to be used during UNSTABLE. During the summer of 2011 the full-scale UNSTABLE experiment will take place with contributions from a team of scientists from Environment Canada, Canadian Universities, and the private sector. Various special data collection platforms will be used to sample the ABL and upper troposphere in association with CI. During an intensive observation period, the array of instrumentation used will include a mesonet of fixed and mobile surface stations, upper-air stations, profiling and column water radiometers, and a tethersonde. Additional data collection will include multiple radar and GPS integrated precipitable water vapour estimates. A critical component of the data collection is above-ground measurements in the ABL and above via research aircraft. A submission will be made for use of the NRC Twin Otter aircraft to sample thermodynamic and kinematic variables associated with mesoscale convergence boundaries and circulations important for CI. These measurements are necessary to characterize the four-dimensional development and evolution of these features and processes responsible for CI within the UNSTABLE study area.

In addition to journal publications and presentations at conferences and workshops, Environment Canada researchers will work to transfer the results from UNSTABLE directly to MSC operational meteorologists. This will be accomplished through internal presentations, workshops, development of visualization and other tools and via the Research Support Desk where National Lab staff work directly with forecasters in real-time during high-impact weather events.

UNSTABLE is being led by scientists within and external to Environment Canada. It is a truly collaborative project with participation from multiple divisions of Environment Canada, Provincial agencies, four Canadian Universities, and the private sector. Success of the project is dependent on instrumentation and other contributions from the participants who will also work collaboratively on analysing and publishing results. Most importantly, UNSTABLE is a large-scale and tangible effort to help understand, and through improved warnings, mitigate the effects of severe thunderstorms thus safeguarding the lives and property of Canadians.

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Appendices

A1 Participants and Research Interests

Principle Investigators

Neil Taylor, Science Question 1 Co-Lead, Project Manager
Hydrometeorology and Arctic Lab, Environment Canada
Research Interests: CI with respect to ABL water vapour distribution / evolution, the dryline, and other convergence boundaries on the Canadian Prairies. Operationally-oriented techniques for forecasting high-impact weather.

David Sills, Science Question 1 Co-Lead
Cloud Physics and Severe Weather Research Section and
Nowcasting and Remote Sensing Lab, Environment Canada
Research Interests: CI and severe thunderstorm evolution with respect to the dryline and other convergence boundaries on the Canadian Prairies.

John Hanesiak, Science Question 2 Lead
Centre for Earth Observation Science (CEOS), University of Manitoba
Research Interests: CI with respect to ABL thermodynamic structure / evolution, associations with wet/dry surface boundaries and background flow modification of the boundaries / mesoscale circulations.

Jason Milbrandt, Science Question 3 Lead
Recherche en Prévision Numérique (Numerical Weather Prediction Research Section), Environment Canada
Research Interests: High-resolution atmospheric modeling and numerical weather prediction, and the representation of moist processes.

Craig Smith, Upper-Air Program Lead
Climate Research Division, Environment Canada
Research Interests: The influence of topography on precipitation in the Alberta foothills. Atmospheric moisture dynamics, including boundary layer evolution, and their impact on precipitation and CI.

Pat McCarthy
Prairie and Arctic Storm Prediction Centre, Environment Canada
Research Interests: Science gaps impacting operational forecasting of high-impact weather, evapotranspiration and its impact on the boundary layer, the application of weather radar and lightning detection for storm-scale analysis, the psychology of weather prediction, and the psychology of human response to weather forecasts and warnings.

Geoff Strong
University of Alberta (Adjunct)
Research Interests: Alberta thunderstorms: large-scale and boundary layer initiation and maintenance mechanisms, and their role in the prairie water balance climate.

Collaborators and Participants

Dr. Terry Krauss, *Weather Modification Inc.*
Julian Brimelow, *Centre for Earth Observation Science (CEOS), University of Manitoba*
Dr. Susan Skone, *Dept. of Geomatics Engineering, University of Calgary*
Dr. Gerhard Reuter, *Dept. of Earth and Atmospheric Sciences, University of Alberta*

Dr. Shawn Marshall, *Department of Geography, University of Calgary*
Dr. Peter Taylor, *Dept. of Earth and Space Science and Engineering, York University*
Hydrometeorology and Arctic Lab, *Environment Canada*
Prairie and Arctic Storm Prediction Centre (PASPC), *Environment Canada*
Alberta Environment
Alberta Agriculture and Food
Jeff Sowiak, *Technical Services, Environment Canada*
Centre for Atmospheric Research Experiments (CARE), *Environment Canada*

A2 Table of UNSTABLE Instrumentation

Table 5: List of special instrumentation to be deployed / utilized during the UNSTABLE field campaign (excludes existing surface stations operated by Environment Canada, NAV Canada, Alberta Agriculture). We will pursue the inclusion of eddy covariance towers to measure surface fluxes though none are confirmed at this time.

Parameter(s)	Mobility	Instrument	Owner	Comments
Surface Measurements				
T, T_d, Wind, P, PCPN, RAD, ΔT (9.5 m-0.5 m)	Stationary	10 ATMOS	EC - CPSWRS	
T, T_d, Wind, P, PCPN, RAD, ΔT (9.5 m-0.5 m)	Stationary	3-5 ATMOS	York U	
T, T_d, Wind, P, PCPN	Stationary	Wx Station	EC – Tech Svcs	
1m T, T_d, P, PCPN 2m wind	Stationary	3 FOPEX Station	EC - CRD	No pressure at one FOPEX station
T, T_d, PCPN	Stationary	208 FCA	U of C	FCA stations within UNSTABLE domains
T, T_d, Wind, P, PCPN	Stationary	3 FCA	U of C	
T, T_d, Wind, P, PCPN	Mobile	Wx Station (MARS)	U of M - CEOS	
T, T_d, Wind, P	Mobile	AMMOS	EC - CPSWRS	
T, T_d, Wind, P	Mobile	Weather Sensor	U of M - CEOS	
Upper Air Profiles				
T, T_d, Wind, P	Stationary	Radiosonde	WMI	
T, T_d, Wind, P	Stationary	Radiosonde	EC – Tech Svcs	
T, T_d, Wind, P	Mobile	2 Radiosonde	EC - CRD	
T, T_d, Wind, P	Mobile	Radiosonde	U of M - CEOS	
3km T, RH	Mobile	AERI (MARS)	U of M - CEOS	
1.3km T, Wind, VV, Mixing Depth, Turb.	Mobile	SODAR (MARS)	U of M - CEOS	
Cloud-base height	Mobile	Pyrometer (MARS)	U of M - CEOS	
10 km T, RH, liquid H_2O, integrated water	Mobile	Profiling Microwave Radiometer (MARS)	U of M - CEOS	
10 km RH, liquid H_2O, integrated water	Stationary	Profiling Microwave Radiometer	U of C	
1.5 km T, T_d, Wind, P	Stationary / Mobile(?)	Tethersonde	EC - MRD	
Wind, T_v	Stationary	UHF Wind / RASS	EC - CPSWRS	
Total Column Water				
PW	Stationary	5-8 GPS PW	U of C	
Water Vapour, Liquid H_2O	Stationary	Water Vapour Radiometer	U of C	
Water Vapour, Liquid H_2O	Stationary	Water Vapour Radiometer	U of M - CEOS	
Airborne				
T, T_d, P, Wind, VV		Twin Otter	NRC	
T, T_d, P, Wind, VV		Aventech AIMMS	WMI	

AERI – Atmospheric Emitted Radiance Interferometer
AIMMS – Aircraft Integrated Meteorological Measurement System
AMMOS – Automatic Mobile Meteorological Observation System
ATMOS – Automatic Transportable Meteorological Observation System
CPSWRS – Cloud Physics and Severe Weather Research Section, EC
CRD – Climate Research Division
ΔT – Change in temperature (between heights indicated)
EC – Environment Canada
FCA – Foothills Climate Array
FOPEX – Foothills Orographic Precipitation Experiment
GPS – Global Positioning System
MARS – Mobile Atmospheric Research System
NRC – National Research Council
P – Pressure
PW – Precipitable Water
RAD – Radiation (downwelling solar)
RADAR – Radio Detection and Ranging
RASS – Radio Acoustic Sounding System
RH – Relative Humidity
SODAR – Sonic Detection and Ranging
T – Temperature
T_d – Dew point temperature
T_v – Virtual Temperature
U of C – University of Calgary
U of M – University of Manitoba
UHF – Ultra-High Frequency
VV – Vertical Velocity
WMI – Weather Modification Incorporated

A3 Budgeting Requirements

Scope of the UNSTABLE project depends on funding received and in-kind or other support from UNSTABLE collaborators (e.g., instrumentation, services, students for fieldwork). The inclusion of research aircraft, for example, is contingent on sufficient funding from within Environment Canada or elsewhere. All costs specific to the development of the project thus far have been incurred by Environment Canada (excepting travel of collaborators for meetings and workshops) via the Hydrometeorology and Arctic Lab (HAL), Climate Research Division (CRD), Air Quality Research Section or the Cloud Physics and Severe Weather Research Section (CPSWRS) of the Meteorological Research Division (MRD). UNSTABLE contributions from Environment Canada have exceeded $50000 for such expenses as radiosondes, travel, radiometer coefficients, computer software, maps and other miscellaneous supplies, and testing of the ATMOS and AMMOS stations. From the HAL perspective, UNSTABLE is the single biggest project it will be involved with in the next two years and the intention is to allocate as much funding as is possible to ensure the success of the project. Similarly from CPSWRS / MRD financial contributions will continue as funding is available.

A summary of required funding estimates is included in see Table 6. These are for the full-scale, 23-day UNSTABLE field campaign as described in this document (estimating 11 IODs). Cost estimates for a smaller-scale pilot UNSTABLE campaign in 2008 have also been compiled (not shown).

Table 6: Projected expenses associated with the UNSTABLE field campaign and preliminary estimates of cost. Values are rounded to the nearest $ 500. Overtime estimates include Saturday and Sunday operations. Estimates include some expenses that are expected to be covered by UNSTABLE participants external to Environment Canada (e.g., MARS).

Expense	Cost ($)
Research Aircraft	
NRC Twin Otter (112 h flight time at ~ $1825 / h)	204000
WMI King Air (66 h flight time at ~ $ 500 / h)	33000
Upper-Air Program (Radiosonde)	
Consumables (sondes, helium, balloons, parachutes)	38500
Vehicle fuel for 2 x mobile teams	2000
Shipping Equipment	1000
Upper-Air Program (Tethersonde)	
Shipping	500
Consumables	1000
Infrastructure (shed, balloon enclosure, etc.)	1000
Fixed Mesonet Stations (ATMOS)	
Shipping	5000
Deployment / Removal	1000
Temporary Fencing	5000
Communications	6000
Mobile Mesonet (AMMOS)	
Shipping	500
Fuel for Vehicle (Prius)	500
Fuel 2nd Surface Mobile Station (Strong)	1000
Mobile Atmospheric Research System (MARS)	
Vehicle Fuel	1000
Vehicle Rental	2000
GPS Integrated Precipitable Water Vapour	
Student Data Processing	4000
Field Personnel (IOP)	
Students (HAL)	30000
Accommodations (393 person-days)	39000
Per Diems (393 person-days)	31000
Training (OHS, Tethersonde, First Aid)	2500
Field Personnel Overtime	71000
Field Communications (Cell Phone)	2000
Field Personnel (Deploy/Remove stations)	
Accommodations (12 person-days)	1000
Per-Diems (18 person-days)	1500
Overtime	2000
Field Personnel (station inspections)	
Accommodations (16 person-days)	1500
Per-Diems (24 person-days)	2000
Total	490500

A4 UNSTABLE 2008: A Pilot Project

Prior to conducting the full-scale UNSTABLE project it is desirable to test the instrumentation and measurement strategies to be used during the field campaign. Some preliminary testing of instrumentation occurred in Alberta in 2006 (ATMOS and AMMOS – see http://www.umanitoba.ca/faculties/environment/envirogeog/weather/unstable/docs/Update.pdf) and the ATMOS, AMMOS, and tethersonde were used during the BAQS-Met experiment in 2007. Measurement strategies outlined in this document (including mesonet design) remain largely untested over the Alberta foothills. To address this, a pilot experiment (UNSTABLE 2008) has been designed that incorporates most of the components of the UNSTABLE project described in this document. Modifications have been made to the quantity of instrumentation deployed and the duration of the intensive observation period. The experimental design of the pilot project is outlined below with details appearing in the UNSTABLE 2008 Operations Plan.

Some of the components of UNSTABLE that will be tested in 2008 include:

- Mesonet station placement and spacing (including defined UNSTABLE domains)
- Instrumentation performance and the ability of the AMMOS and other mobile teams to resolve the dryline and other boundaries / circulations
- Nowcasting support from PASPC-Edmonton
- Field mission measurement strategies including pre-defined aircraft flight plans (altitudes, flight patterns) and mobile team routes
- Field Coordination from Olds-Didsbury and communication technology (e.g., real-time GPS location and other data transmission)

The UNSTABLE investigators are confident that in addition to an opportunity to test concepts for UNSTABLE, the pilot project will itself result in observational data suitable for publication and to begin the knowledge transfer process of UNSTABLE results to forecast operations.

Objectives

The objectives of UNSTABLE 2008 are in line with those of the full-scale experiment (i.e., answering the science questions) but are focused mainly to ensure success of the latter in 2011. Objectives include:

- To test and refine instrumentation and measurement strategies / methodologies over the Alberta foothills to sample the ABL in support of addressing the UNSTABLE science questions
- To test logistical issues such as field coordination, forecast / nowcast support, and field communications prior to the larger-scale experiment
- To apply pilot results to the UNSTABLE scientific overview document and operations plan and revise accordingly
- To obtain, QC, and analyse a unique dataset over the Alberta foothills characterizing the ABL in support of UNSTABLE science questions
- To publish and present results regionally, nationally, and internationally and begin directed transfer of knowledge to the operational forecasting community on important processes related to CI

Experimental Design

UNSTABLE 2008 will utilize the same domains and existing observation networks already described. To supplement the existing surface stations, 5 ATMOS stations will be deployed at locations indicated in Figure 29. The result of these placements is two mesoscale lines of stations. The northern line (called the high-density line) will have station spacing of ~ 10 – 15 km and is identical to the high-resolution line indicated in Figure 28. The southern line (called the medium-density line) will have station spacing of 15 – 25 km and will be integrated with FCA stations. The orientation of both these lines is nearly perpendicular to the sloping terrain to resolve moisture and other gradients (e.g., the dryline) as described elsewhere in this document. The placement, orientation, and spatial resolution of these lines will be a test of the UNSTABLE primary domain, mesonet design, station spacing, and integration of ATMOS data with other data collection platforms. Land-use agreements for the sites indicated in Figure 29 have been obtained with formal documentation underway.

The mesonet station lines in 2008 will act as anchor points for intensive observations with surface routes for mobile teams and aircraft flight plans designed to exploit these higher-resolution lines of stations. Measurements from the mesonet stations (and all existing stations in the primary domain where possible) will record 1 min averages of meteorological parameters to maximize temporal resolution of developing or evolving surface moisture (and other) gradients and boundaries.

Other targeted instrumentation platforms to be used during the pilot project are indicated in Table 7. Much of the instrumentation remains the same as is planned for the full-scale experiment. Exceptions are that only two mobile radiosonde systems will be used (one being the U of M MARS), only the WMI King Air aircraft will be used for airborne measurements, and the profiling radiometer normally part of the MARS will not be available in 2008. With respect to aircraft, though the WMI King Air will only be available for morning (and possibly early afternoon) flights, use of the WMI plane provides a cost-effective way to test flight pattern strategies for sampling the 4D characteristics of the pre-storm ABL.

In general, measurement strategies remain similar to those outlined in section 5 and 6 with the mobile teams dispatched together to sample mesoscale boundaries or other features of interest. IOD missions are described in the UNSTABLE 2008 Operations Plan and are designed to exploit the measurements of the two mesonet station lines in Figure 29. Field coordination for the pilot experiment will take place from WMI operations at the Olds-Didsbury airport with forecast support from the PASPC.

Field Schedule

The study period for UNSTABLE 2008 will be reduced as compared to the full-scale experiment. In 2008 deployment of the 5 ATMOS stations will occur in early June and will be functional by 15 June. A 15-day IOP is planned for the period 9-23 July during which time instrument teams will be in place as described in sections 5 and 6 of this document. Mobile teams will be dispatched following IOD criteria defined in the UNSTABLE 2008 Operations Plan. Eight IODs are planned for the pilot project each requiring 14 people in the field each day. Four aircraft missions are planned amounting to 12 hours of flight time using the WMI King Air. Following conclusion of the IOP the ATMOS stations will remain in operation for another two weeks to capture the remaining portion of the peak severe weather season in Alberta. The stations will be removed following 15 August. Data analysis and QC will commence in early Fall 2008.

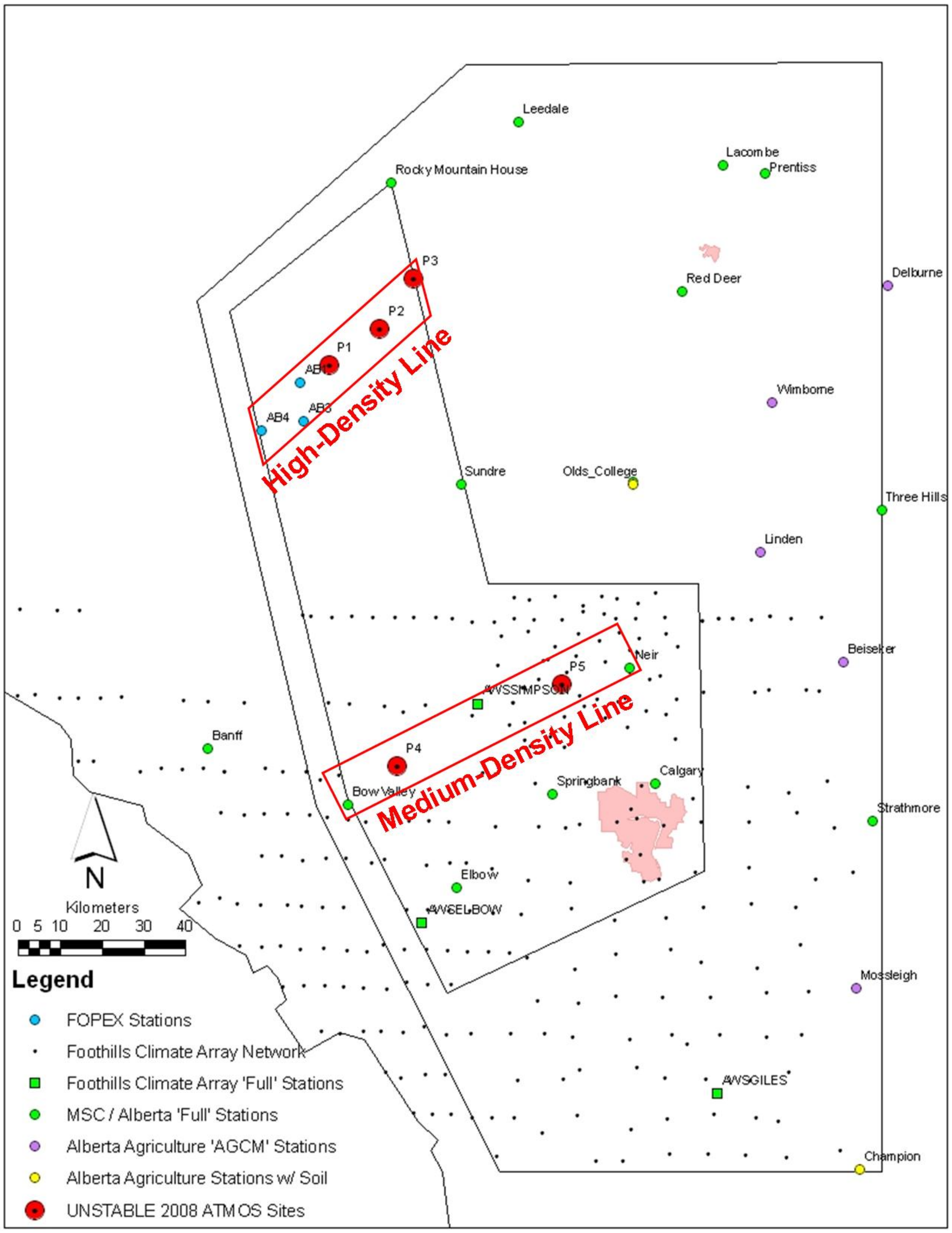

Figure 29: Proposed placement of ATMOS stations for the UNSTABLE 2008 pilot experiment. ATMOS stations are indicated as large red circles and labelled P1 through P5. Existing surface stations are as indicated in the legend and described in section 6 of this document.

Table 7: List of instrumentation to be used in the UNSTABLE 2008 pilot experiment.

Parameter(s)	Mobility	Instrument	Owner	Comments
Surface Measurements				
T, T_d, Wind, P, PCPN, RAD, ΔT (9.5 m-0.5 m)	Stationary	5 ATMOS	EC - CPSWRS	
1m T, T_d, P, PCPN 2m wind	Stationary	3 FOPEX Station	EC - CRD	No pressure at one FOPEX station
T, T_d, PCPN	Stationary	208 FCA	U of C	FCA stations within UNSTABLE domains
T, T_d, Wind, P, PCPN	Stationary	3 FCA	U of C	
T, T_d, Wind, P, PCPN	Mobile	Wx Station (MARS)	U of M - CEOS	
T, T_d, Wind, P	Mobile	AMMOS	EC - CPSWRS	
T, T_d, Wind, P	Mobile	Weather Sensor	U of M - CEOS	
Upper Air Profiles				
T, T_d, Wind, P	Stationary	Radiosonde	WMI	
T, T_d, Wind, P	Stationary	Radiosonde	EC – Tech Svcs	
T, T_d, Wind, P	Mobile	2 Radiosonde	EC - CRD	
3km T, RH	Mobile	AERI (MARS)	U of M - CEOS	
1.3km T, Wind, VV, Mixing Depth, Turb.	Mobile	SODAR (MARS)	U of M - CEOS	
Cloud-base height	Mobile	Pyrometer (MARS)	U of M - CEOS	
10 km RH, liquid H_2O, integrated water	Stationary	Profiling Microwave Radiometer	U of C	
1.5 km T, T_d, Wind, P	Stationary / Mobile(?)	Tethersonde	EC - MRD	
Total Column Water				
PW	Stationary	5-8 GPS PW	U of C	
Water Vapour, Liquid H_2O	Stationary	Water Vapour Radiometer	U of C	
Water Vapour, Liquid H_2O	Mobile	Water Vapour Radiometer	U of M – CEOS (MARS)	
Airborne				
T, T_d, P, Wind, VV		Aventech AIMMS	WMI	

Budget Requirements

Reduction in the IOP duration, number of people in the field, use of only WMI aircraft and limited aircraft missions will require a budget only a fraction of that for the full-scale UNSTABLE experiment. Projected expenses for UNSTABLE 2008 are shown in Table 8 including some costs that will be covered by participants external to Environment Canada. Removing these costs from consideration results in an expected Environment Canada expense of $ 110500.

Summary

A pilot UNSTABLE project is proposed for the summer of 2008 to ensure success of the full-scale experiment in addressing the science questions posed in this document. UNSTABLE 2008 will allow testing and refinement of instrumentation and measurement strategies to be used during the full-scale field campaign to answer the UNSTABLE science questions. The pilot study period will be two months in duration with a 15-day IOP during which time all fixed and mobile instrumentation teams will be in the field. While smaller in scale and duration, the UNSTABLE 2008 IOP will serve as an opportunity to obtain a high-resolution dataset of observations characterizing ABL structure and evolution associated with CI in Alberta. These data are anticipated to be of suitable quality for publication.

Significant investments, both in time and finances, have been made to realize the long term vision of the UNSTABLE project. A strong commitment has been made both within Environment Canada and in the academic community to move forward with field operations in 2008. The pilot experiment is a scientifically sound path forward both to ensure success of the full-scale UNSTABLE project and to take advantage of university and other commitments to provide in-kind support to the initiative.

Table 8: Projected expenses for the UNSTABLE 2008 pilot project. Figures include some costs that are anticipated to be covered by project participants external to Environment Canada (e.g., MARS).

Expense	Cost ($)
Research Aircraft	
WMI King Air (12 h flight time at ~ $ 500 / h)	6000
Upper-Air Program (Radiosonde)	
Consumables (sondes, helium, balloons, parachutes)	10000
Vehicle fuel for mobile team	1000
Shipping Equipment	500
Upper-Air Program (Tethersonde)	
Shipping	500
Consumables	1000
Infrastructure (shed, balloon enclosure, etc.)	1000
Fixed Mesonet Stations (ATMOS)	
Shipping	3000
Deployment / Removal	1000
Temporary Fencing	1000
Communications	2000
Mobile Mesonet (AMMOS)	
Shipping	500
Fuel for Vehicle (Prius)	500
Fuel 2nd Surface Mobile Station (Strong)	500
Mobile Atmospheric Research System (MARS)	
Vehicle Fuel	1000
Vehicle Rental	2000
GPS Integrated Precipitable Water Vapour	
Student Data Processing	4000
Field Personnel (IOP)	
Students (HAL)	10000
Accommodations (234 person-days)	23500
Per Diems (234 person-days)	18000
Training (OHS, Tethersonde, First Aid)	2500
Field Personnel Overtime	44000
Field Communications (Cell Phone)	1500
Field Personnel (Deploy/Remove stations)	
Accommodations (4 person-days)	500
Per-Diems (6 person-days)	500
Overtime	500
Field Personnel (station inspections)	
Accommodations (4 person-days)	500
Per-Diems (8 person-days)	500
Total	137500

A5 Timeline and Milestones

The UNSTABLE project has been a long-term vision since its original proposal in 1999 from what was at that time the Prairie Storm Prediction Centre in Prairie and Northern region. The project was championed by Environment Canada's national science branch but at that time neither regional nor national science groups were in a position to carry out a field campaign. In 2002 the first formal UNSTABLE meeting was held in Winnipeg. At this meeting a number of science, data, and science infrastructure gaps were identified to be overcome. Since that time formation of the Hydrometeorology and Arctic Lab, capital purchases of science infrastructure, and national support of university research have increased the capability of Environment Canada science groups to continue the development of the project. The second formal UNSTABLE meeting was held at the 40th CMOS Congress. Table 9 highlights the progress and milestones since that time as planning for UNSTABLE moves forward.

Table 9: Timeline and milestones for UNSTABLE.

Date	Event / Milestone	Comments
30 May 2006	***UNSTABLE Meeting at 40th CMOS Congress***	First 'formal' UNSTABLE meeting since April 2002 and first meeting with current project leads
Summer 2006	Test deployment of ATMOS stations in Alberta Foothills	Stations performed well. Good test for mesonet siting
July 2006	Test of AMMOS in Alberta Foothills	
27-29 September 2006	Preliminary mesonet site selections	
1 March 2007	***UNSTABLE web site online***	Thanks to Dave Carlsen (PASPC-Wpg) for development and John Hanesiak for hosting the site.
March 2007	Hanesiak and Milbrandt become science leads for science questions 2 and 3.	
6 April 2007	***Draft science plan circulated to UNSTABLE participants***	
18-19 April 2007	***First UNSTABLE Science Workshop***	Results from workshop used to refine science plan
28 May – 1 June 2007	41st CMOS Congress	UNSTABLE overview and results of AMMOS tests
18 June – 13 July 2007	BAQS-Met Field Project SW Ont.	ATMOS / AMMOS stations and tethersonde used in field experiment
26-28 September 2007	Mesonet site selection	
31 October 2007	Finalize Science Plan	
1 November	Develop UNSTABLE Operations Plan	
29 February 2008	Operations Plan finalized Land use agreements finalized	
1-15 June 2008	Deploy pilot ATMOS stations	
15 June – 15 August	***UNSTABLE2008 Study Period***	*Begin pilot study period*
9-23 July	***UNSTABLE 2008 IOP***	*Pilot intensive observations*
1-15 August 2008	Remove ATMOS stations	
1 September 2008	Begin data QC / analysis	
Late Fall 2008	UNSTABLE article for CMOS / BAMS	
2009	Analysis and formal publications of results	
Spring 2009	Special session at 43rd CMOS Congress	
2010	Refinement of science overview and operations plan	
Fall 2010	Presentations at 25th SELS	
Spring 2011	Deployment of mesonet stations	
1 June 2011	UNSTABLE study period begins	Beginning of 3-month study period
9-31 July 2011	UNSTABLE IOP	
1-15 September 2011	Remove mesonet stations	
Fall 2011	Data QC and analysis	