The Surface Validation of RDSS Severe Weather Detections and Documentation of Manitoba Farmers' Views and Perceptions of Issues Associated with Severe Weather Hazards

By

Ryan T. Tombs

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
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Natural Resources Institute
University of Manitoba
Winnipeg, Manitoba
R3T 2N2

0-612-53127-9

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FACULTY OF GRADUATE STUDIES
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Abstract

This thesis conducted a limited study of the performance of the RDSS severe detection algorithms for the 1999 summer convective storm season, and successfully documented Manitoba farmer's views and perceptions of severe weather related issues. The successful collection and analysis of available RDSS logged data, radar animations, damage assessments, and questionnaire contents have delivered encouraging performance results for the severe weather detection algorithms. Obtaining detailed ground truth verification data proved critical in determining the RDSS algorithm's true performance. Examining all cases showed that the Hail Probability Algorithm (HPA) over-forecasted the occurrence of severe hail for Vertically Integrated Liquid (VIL) density thresholds. RDSS detected severe wind gusts (>90km/hr) with the highest efficiency. The supercell algorithm also performed well, detecting approximately 62 percent of cells associated with severe weather features.

Farm operators' views and perceptions of severe weather events in southern Manitoba were also successfully documented. Obtained through lengthy interviews, farm operators discussed freely about personal experiences and perceptions they have of severe weather. The majority of farm operators had experienced monetary loss due to severe weather events, and most had negative comments related to these events. The most serious damage resulting from these hazards was delivered by hail and standing water. The majority of farm operators chose increased amounts of rain and snow as future threats to farming in Manitoba. Interestingly, climate change was not perceived as a future threat to agriculture in Manitoba with many farmers citing a longer growing season as the reason. Farmers perceived the frequency of hail and severe rain events as

increasing, but did not perceive the frequency of wind and tornadoes as increasing. Farm operators also showed a preference towards weather data provided by American media outlets and the National Weather Service (NWS) over Canadian weather data and media. The use of Internet weather information by Manitoba farm operators was found to be in its infancy with only one respondent having used it for weather related information.

Acknowledgements

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I would like to give a special thank you to my mother, father and brother for all the support they provided me over the last two years.

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1 Introduction

1.1 Preamble

It is well established that forecasting rare severe weather events is extremely challenging, but equally challenging is the problem of developing meaningful radar verification techniques (Brooks, et. al. 1998), and documenting farm operators' perceptions and views of severe weather (Clyde, 1981). Currently the majority of severe weather observations indexed by the Prairie Storm Prediction Centre (PSPC) come from volunteer weather spotters or casual phone calls from the public. Although valuable, this increases the complexity of the verification problem because there are no spatial or temporal constraints on the information collected. Information and ground truth data on severe weather occurrences are frequently unavailable where radar fails to detect it. The Prairie Storm Prediction Centre (PSPC), located in Winnipeg, Manitoba, Canada is in the process of verifying the efficacy of a Radar Decision Support System (RDSS) developed for the automated recognition of summer severe weather features. Recognizing that random observational reports will not suffice in the improvement of the RDSS prediction algorithms, the PSPC suggested this research project, which involves the systematic surface validation of suspected storm damage and interviews of residents living in the affected area.

This thesis will also study the perceptions held by farm operators in southern Manitoba during the 1999 convective weather season. The majority of meteorological studies exclusively consider the physical aspects of the natural hazard problem (Clyde, 1981). Although much work has been done on the socio-economics of natural hazards

(White, 1974; Farhar, 1977); there is a significant gap in the literature concerning the views and perceptions Manitoba farm operators hold of severe weather. Of particular interest, is the perceptions farm operators hold of hazards such as severe wind, hail, rain, and tornadoes.

1.2 Background

The Radar Decision Support System (RDSS) has been constructed and used in the Prairie Storm Prediction Centre (PSPC) for three years, but measures of the utility of the system have been hampered by the lack of an extensive and reliable database of severe convective weather events. An extensive database could be accumulated through systematic surface validation of severe convective weather events detected by RDSS. Because the software decision-making follows an "expert systems" approach, there is considerable room to improve the accuracy of severe weather detection as additional knowledge is acquired. Additional investments in RDSS can only be justified if the ability of the system to warn of impending hail, destructive winds and tornadoes can be proved. These data would then be used to improve the ability of the RDSS to predict severe convective weather phenomena through the modification of several predictive algorithms.

Crop-losses due to severe weather are known to be heavy. Paul (1980) estimates that crop losses on the Canadian prairies at one-seventh that of the entire United States. With such damage it is no wonder that weather related folklore has developed among the farmers of the Canadian prairies. Yet still, much is unknown about the perceptions Manitoba farmers have of severe weather. Farm operators have unique knowledge and views concerning severe weather that remains untapped. Stories have been passed on from generation to generation concerning weather events and trends. Knowledge of this type could help Environment Canada in the future development of verification procedures, weather warning dissemination techniques, and climate change projects. Accordingly, the research undertaken for this section of the thesis was spearheaded with the idea of better understanding the farmer's point of view, knowledge and fears.

1.3 Problem Statement

Although development of the RDSS was completed in 1998, its severe weather detection algorithms although scientifically based, have been prone to inaccuracy. More specifically, the probability RDSS has of detecting severe weather features is high, but a tendency to over-warn (high rate of false alarms) has left meteorologists apprehensive in its use. Despite many American studies, there is a lack of systematic verification of the severe weather detection algorithms in a Canadian setting.

The dissemination of severe weather warnings is one measure taken by the Canadian Government to protect the public and keep them informed. The general public is surveyed frequently, but there continues to be little known of the perceptions Manitoba farm operators hold of Environment Canada and the weather warning dissemination techniques utilized.

1.4 The Purpose of this Study

The purposes of this study are to test the validity and reliability of RDSS severe weather algorithms, and to document and catalogue the views and perceptions farm operators' hold of severe weather, Environment Canada and current weather warning dissemination techniques.

1.5 Objectives and Scope

Specific objectives include:

1. To collect and analyze available RDSS archived data, radar animations, damage assessments, and questionnaire contents to ascertain the forecast performance of the RDSS severe weather detection algorithms for the summer of 1999;

2. To determine if farm operators perceive hail, strong winds, heavy rains, and tornadoes to be more frequent hazards in the current decade than in previous decades;

3. To examine the 1999 farm operators' perceptions of the economic impact of hail, strong winds, heavy rains, and tornadoes in southern Manitoba;

4. To examine the 1999 farm operators perceptions of and preferences for current weather warning dissemination techniques; and

5. To make recommendations that may lead to the improvement of RDSS severe weather detection algorithms, Environment Canada's RDSS verification procedures, severe weather warning dissemination techniques, and understanding of Manitoba farm operators' perceptions;

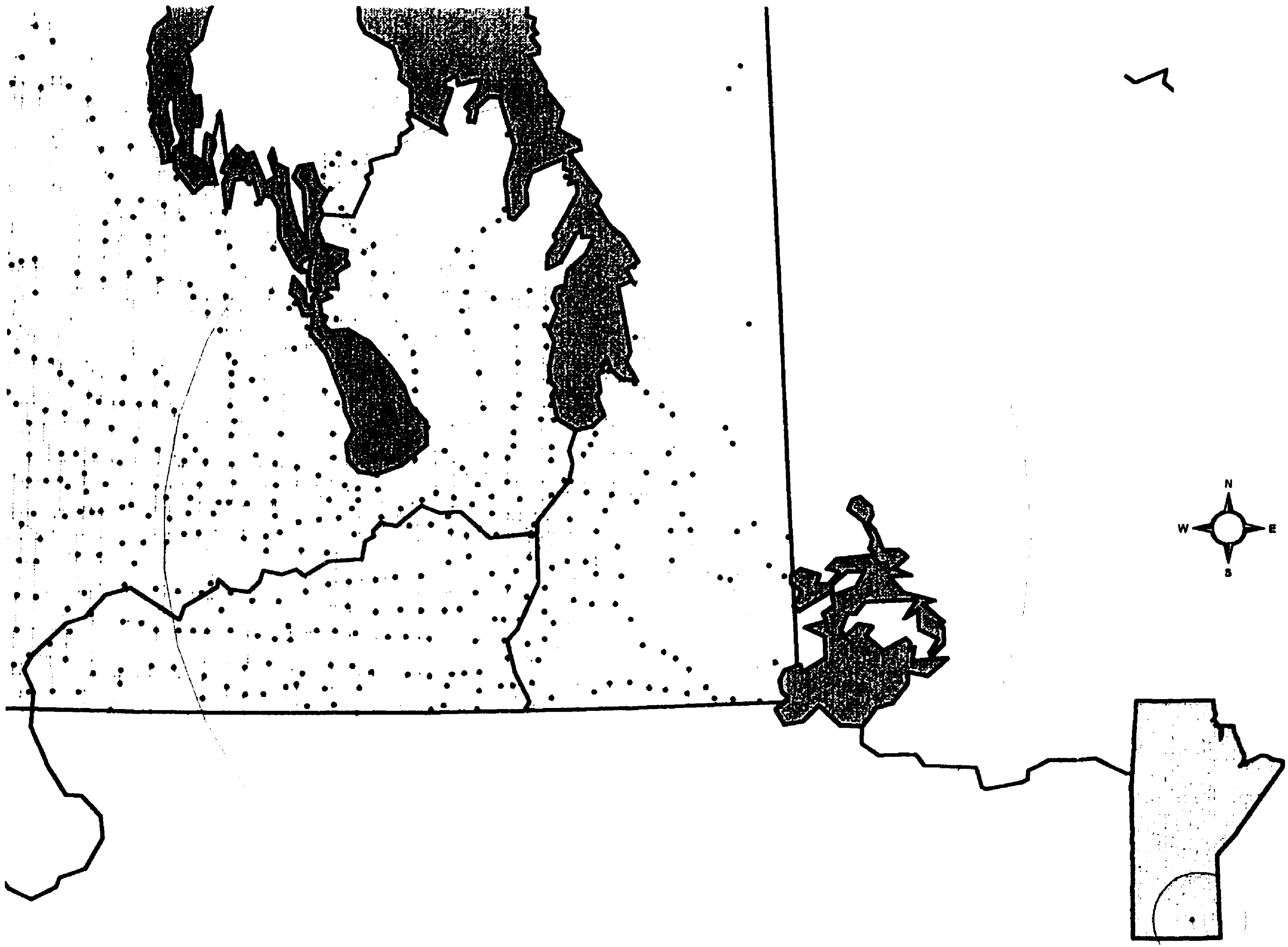

Figure 1: RDSS surface validation study area (all areas within 240 km radius of Vivian radar. Depicted as circle on map).

1.6 Description of the Area

The Vivian radar station is located 40km east of Winnipeg, and has a range which covers much of southern Manitoba (Figure 1). The central location of the study area in the North American continent has imparted it with a continental climate with a long cold winter and short, hot summer. Much of the study area is relatively flat, allowing air masses to cross it predominantly from the west. The most southwest portions of Manitoba are located in the transitional parklands, made up of broadleaf and mixed forests with an associated low population density. The land classification of interest for this study is the grasslands, associated with agricultural activity and higher population densities. The Vivian radar range, encompasses much of this region, with a detection radius of 240 kilometers. The western extent of the radar range includes portions of southwestern Manitoba where there is a large population of farm operators. Northerly and easterly regions infringe upon the Canadian shield, where population densities are much lower due to large water bodies and high concentration of marginal land. Figure 1 shows the Vivian radar range with the road network and towns encompassed by it. Similar maps were consulted in the verification planning stage, to ensure storm cells were in locations with adequate road networks and population density.

2 Severe Weather

2.1 *Introduction*

Manitoba residents may be unaware that we experience natural hazards on a regular basis. On television, we are exposed to images around the world of devastating floods, fires, and earthquakes that cause death and destruction. Although prairie residents do not live on any active fault lines, every summer they experience severe weather that can cause tremendous property damage. Extreme wind, hail, and tornadic events can transform a crop to a worthless mass in minutes, insurance claims on this damage can run into the hundreds of millions of dollars (Figure 2). Because compensations have been made for many decades, hazards are generally accepted without any conscious realization of the adjustments made to compensate (Clyde, 1981).

Weather warnings and crop insurance are some of the compensations that have been made to protect lives and livelihoods of Manitoba residents. Indirectly, through information provided to the Canadian Wheat Board (CWB) and grain companies, farm operators once dependent on instinct can now plan their seeding and harvest with the use of long term forecasts provided by Environment Canada. Until recently (August 12th, 2000) remotely sensed images did not make it to the farmer's gate. They are used by meteorologists in forecasting weather conditions, and indirectly aid the farmer in their agricultural planning. RDSS radar volume scans (Figure 3) are beginning to be used in the issuance of severe weather warnings, while satellite images are used for both severe weather predictions and longer term forecasts.

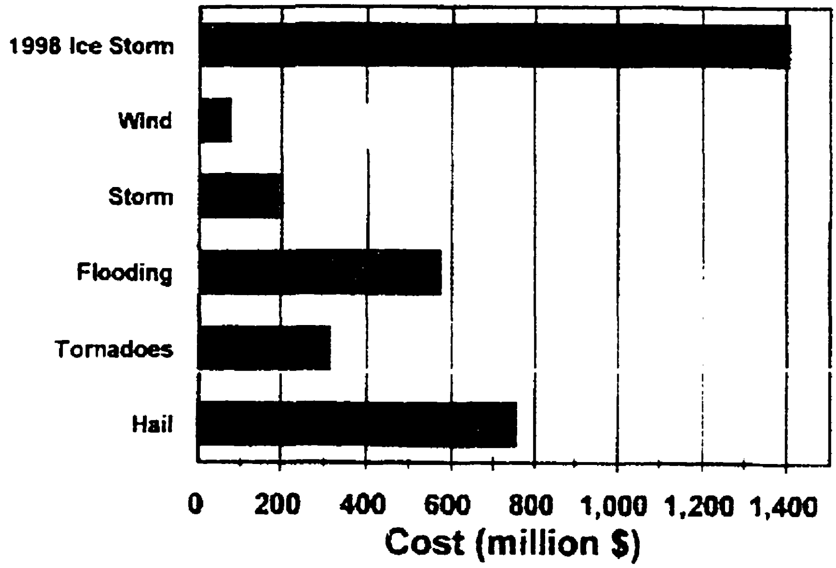

Figure 2: Weather-related insurance costs across Canada (1984-1996). (Source: Etkin and Brun, 1999).

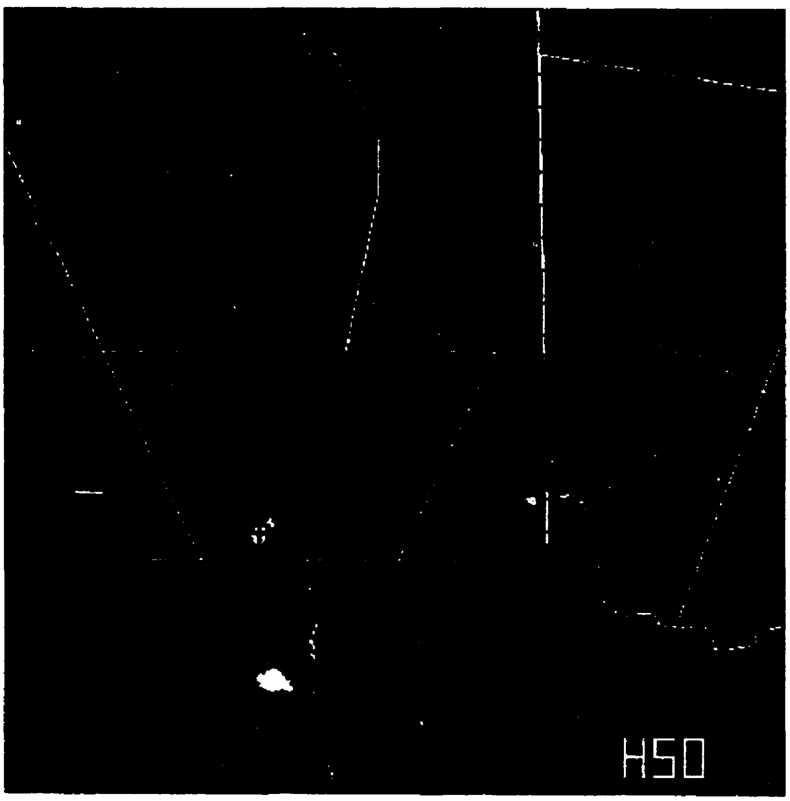

Figure 3: RDSS radar volume scan. (Source: Prairie Storm Prediction Centre)

A ten to forty percent chance of rain in the forecast can either hasten or delay the harvest of a crop. The summer months have a relatively high degree of unpredictability in continental interiors, resulting in farm operators using a mixture of instinct, science and luck in determining their crop maintenance schedules.

This chapter will deal with these issues from several angles. Initially the severe weather hazards, produced in Manitoba by severe thunderstorms will be addressed. The characteristics of these thunderstorms will be examined in terms of their various stages of development, internal structure, radar signatures, and effect on farm operations in southern Manitoba. The impact of severe weather events associated with thunderstorms such as hail and wind will be examined in more detail. Special consideration will be given to previous and current projects involving the improvement of severe weather detection algorithms and weather related decision support systems. To address the social angle of severe weather, previous studies detailing how farm operators perceive severe weather will be reviewed for methodological structure and questionnaire content. Drawing on the experience of previous studies, a methodology was developed which addressed the positive and negative aspects of radar verification and in-person questionnaires.

2.2 Manitoba Severe Thunderstorms

A thunderstorm is a local storm produced by a cumulonimbus cloud, and is always accompanied by lightning and thunder, usually with strong wind, heavy rain, and sometimes with hail (Environment Canada, 1982).

On the Canadian Prairies, thunderstorms are associated with the spring and summer months. During these months, the warmer and moister tropical and polar air masses move meridian to reside in mid-latitudes. July is the peak thunderstorm month, with approximately one third of the total annual thunderstorm days. August and June have the second most thunderstorm days, making up 50%. A small percentage of storms sometimes occur in March and September, but these are rare and seldom occur. Thunderstorms, although intriguing to the curious onlooker, may bring with them the power to destroy land, livestock and lives. They can be categorized according to certain characteristics they exhibit according to various conceptual models, radar images, or visual features (Lemon, 1980). In the following sections, these features will be described in terms of their role in the development of the severe thunderstorm.

2.2.1 Stages of Development

Recognizing the concentrations of precipitation in storms, hydrologists have long used the term "cell" to describe this phenomenon (Knight, et. al., 1982). One definition in particular, formulated by Byers and Braham in 1949, has been the basis on which most subsequent thunderstorm projects have been based. Their classic description of how a thunderstorm develops, identifies through the cumulus, mature, and dissipating stages.

> Under favorable conditions, each of the individual updraft areas... develops into a unit of convective circulation characteristic of a thunderstorm. Many of these units are initially detectable as separate echoes appearing on a radarscope. Also, if interpreted in terms of like stage development, observed conditions... are found to repeat themselves. This leads to the fundamental concept that in the thunderstorm, there are convective units having similar properties and characteristics, which are therefore capable of analysis as a class of convective phenomenon. These units or subdivisions are called thunderstorm cells and are defined as regions of localization of convective activity within the thunderstorm. Just as in the laboratory experiments with fluids, where it is found that the cellular circulation frequently does not extend throughout the medium, portions of the thunderstorm cloud often cannot be identified as separate cells, nor can they be considered as parts of other, well-defined cells... Use of the term cell, as applied to these convective units, is not new; many previous investigations have indicated that there are subdivisions within a thunderstorm. However, there has been some confusion concerning the use of the term, since the identifying features of the units depended upon the nature of the particular investigation....

The Byers and Braham investigation was based on measurements in 1946 and 1947 and dealt mostly with large cumulus-type clouds and relatively small thunderstorms of the so-called air mass type which form primarily as a result of surface heating. Their characteristics are not in all respects similar to those of severe storms but are similar in some of their major features (EC, 1982).

The structure is described by three stages of evolution of the thunderstorm cell: the cumulus stage, the mature stage, and the dissipating stage. They are outlined below (extracted from Byers and Braham, 1949).

Cumulus Stage (Figure 7)

a) Circulation

- Upward motion of cloud air (updraft) occurs everywhere in the cell;
- Upward motions varies in time and space;
- Maximum speed in this stage occurs at higher altitudes late in the period;
- Vertical and horizontal air speed can exceed 15 m/s within the cell,
- The updraft extends from the surface and is accompanied by horizontal convergence at all levels, especially at the surface.
- Entrainment occurs at the cloud boundaries.

b) Temperature

- Cell temperature exceeds the environmental temperature at each level.
- The magnitude of these positive temperature anomalies in the updraft increases with time, reaching a maximum at the end of the cumulus stage.

c) Precipitation

- Greatest concentration of hydrometeors is found at or above the freezing level.
- No precipitation reaches the surface of the earth.

Mature stage (Figure 8)

With the continual updraft during the cumulus stage, more and more vapor condenses, and the water droplets and ice crystals in the cloud become more numerous and larger. When "cloud loading" exceeds the updraft strength, the drops or ice particles begin to fall to earth. The occurrence of precipitation at the surface marks the beginning of the mature stage.

Typical characteristics include the following:

a) Circulation

- Downdrafts have been initiated at mid-levels;
- Updrafts continue (locally speeds may exceed 30 m/s);
- Downdrafts increase in space and time, becoming a maximum in falling precipitation;
- Surface flow associated with the downdraft (known as outflow) has a strong horizontal divergence;
- Surface wind gusts exceed 60 km/hr;
- Cloud grows physically;
- Maximum turbulence occurs in regions of greatest vertical motion.

b) Temperature

- Cloud top reaches temperatures less than -40°C;
- Cold anomalies occur at downdrafts, with maximum in low levels;

- Warm anomalies still occur in updrafts.

c) Precipitation

- Ice crystals are present at the cloud top;
- Low-level precipitation is liquid (solid precipitation is possible); horizontal boundary of the surface precipitation roughly marks the downdraft boundary;
- Hail, when present, occurs in mature stage.

As the rainfall continues during the mature stage of the cell, the downdraft increases in size until, in the lower levels, it extends over the entire storm cell. This characteristic is considered to mark the end of the mature stage, which usually lasts for a period of 15 to 30 minutes. During this stage the cell reaches its greatest height, which is normally about 12 kilometers. An occasional cell may extend above 18 kilometers while another may complete its life cycle without extending over nine kilometers.

Dissipating stage (Figure 9)

As the downdrafts and precipitation increase to dominate the entire cell, the dissipating stage begins.

Typical features include the following:

a) Circulation

- Cell is "collapsing";
- Downdraft spread through the entire cell;
- Downdraft speeds are less than in the mature stage;
- Surface wind divergence rapidly decreases;
- Turbulence intensity diminishes;

b) Temperature

- Cell temperature falls below that of the environment at each level but eventually is equal to the environmental temperature.

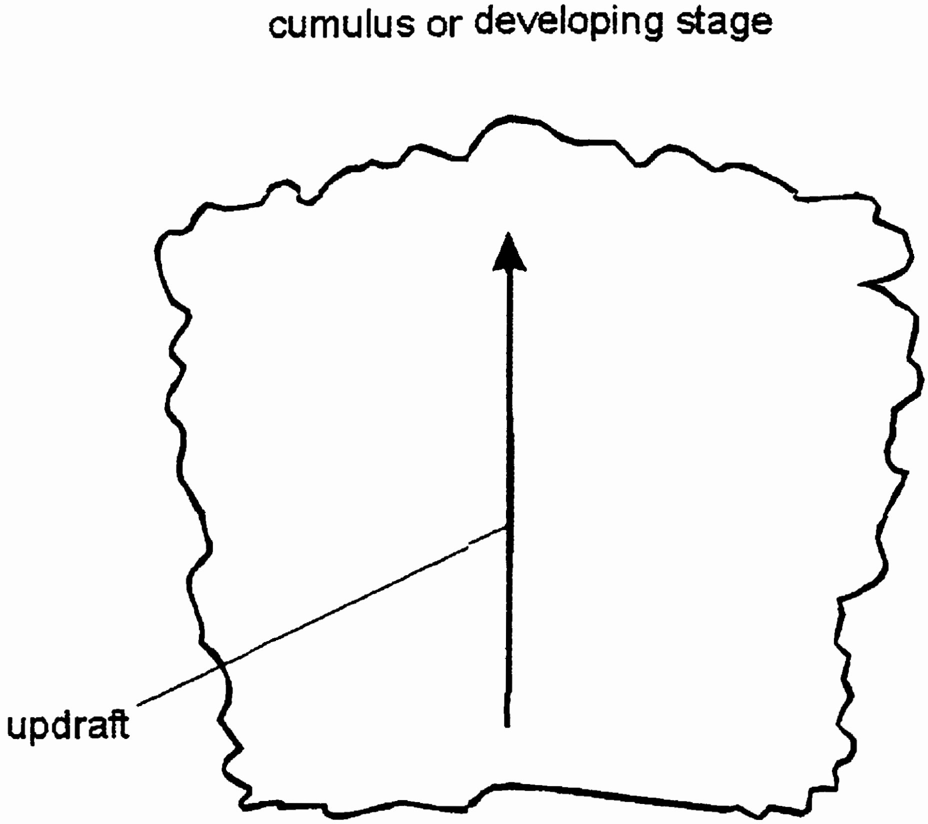

Figure 4: Cumulus Stage. Towering cumulus clouds indicate rising air. Usually little if any rain during this stage. Lasts about 10 minutes. Occasional lightning during this stage. (Source: Central Institute for Meteorology and Geodynamics (ZAMG), 1999)

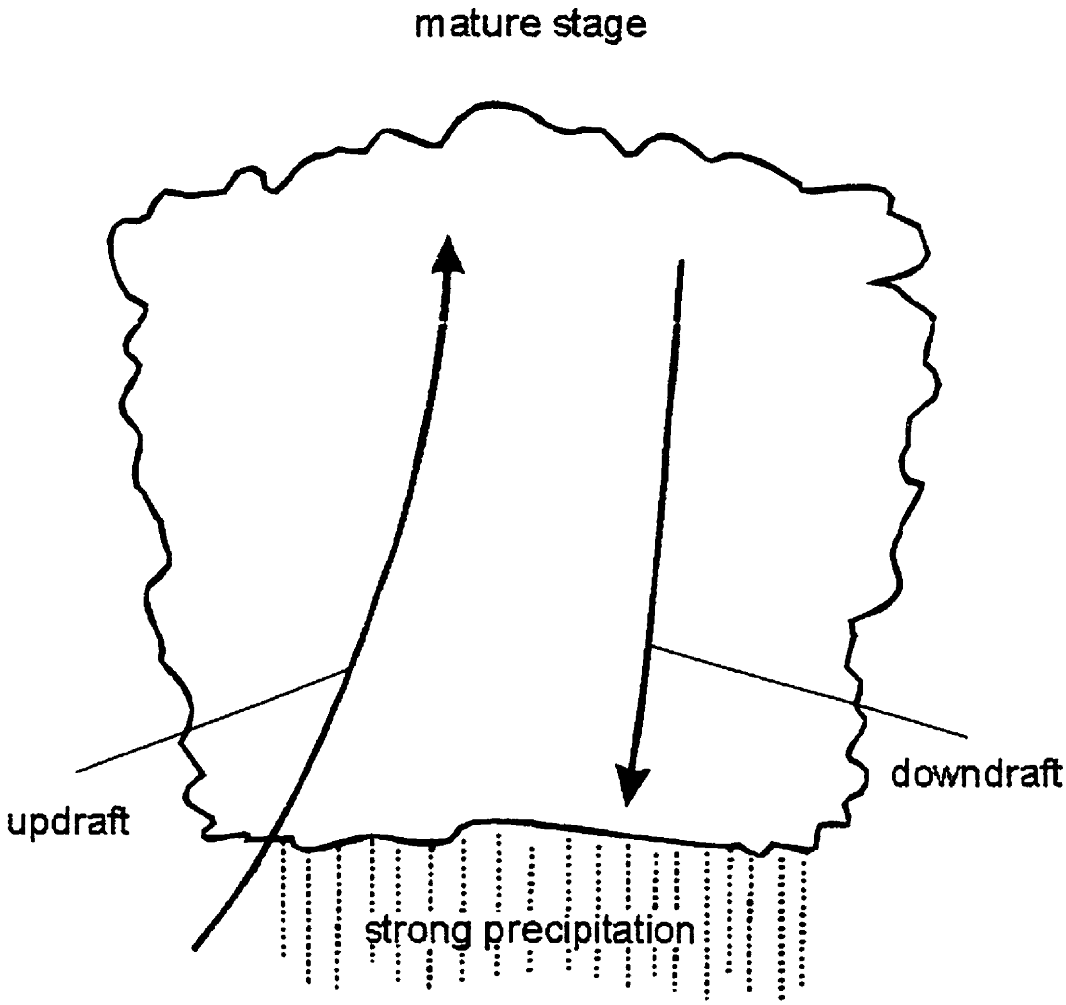

Figure 5: Mature Stage. Most likely time for hail, heavy rain, frequent lightning, strong winds, and tornadoes. Storm occasionally has a black or dark green appearance. Lasts an average of 10 to 20 minutes but may last much longer in some storms. (Source: ZAMG, 1999).

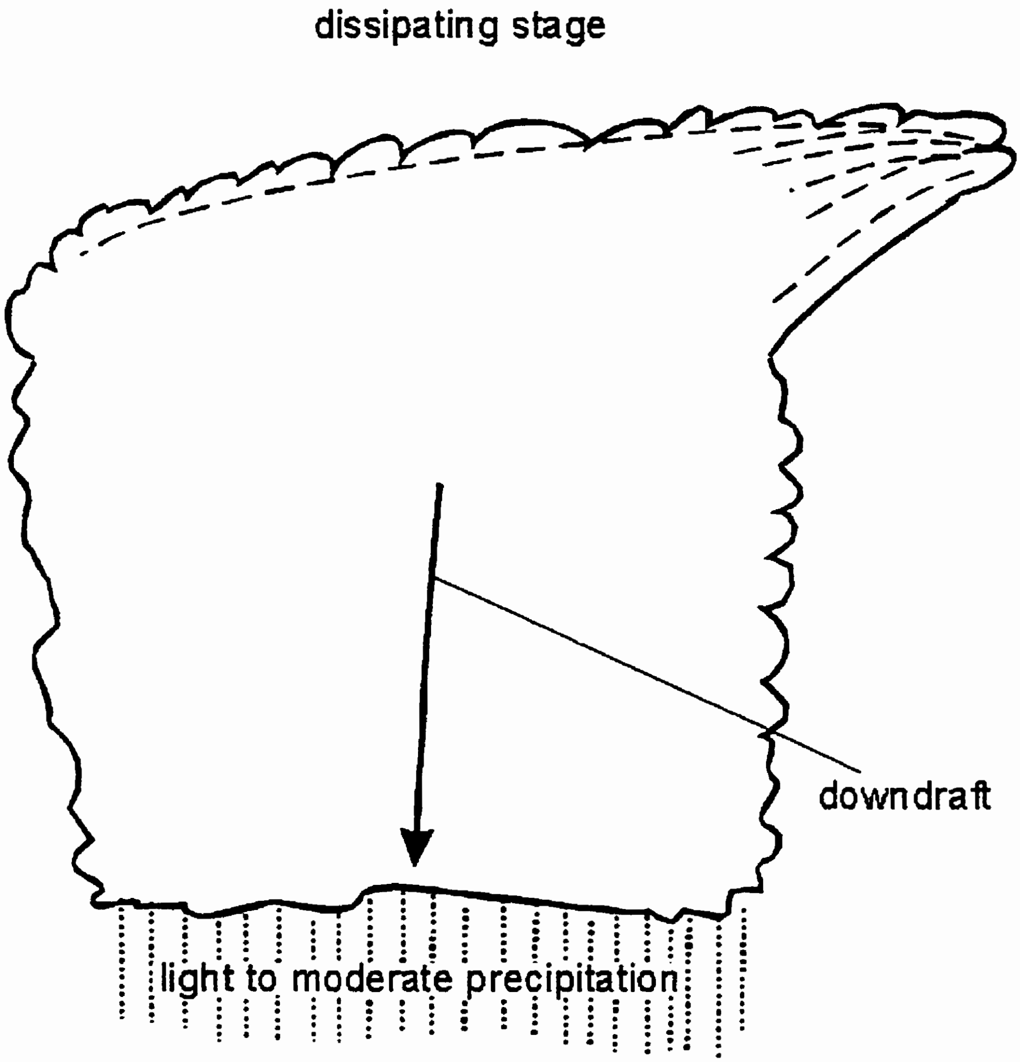

Figure 6: Dissipating stage, rainfall decreases in intensity. Lightning remains a danger. Some thunderstorms will produce a burst of strong winds during this stage. (Source: ZAMG, 1999)

c) Precipitation

- Ice crystals (cirrus) blow off the cell tops;
- Shower activity is generally light and decreases.
- As this stage continues, high, middle, and low-level clouds may persist. New cumulus may be developing in the vicinity, partly fed by the dissipating cell's moisture and forced by the lift above the cool outflow air.

2.2.2 Severe Thunderstorm Structure

Severe Thunderstorm: a meteorological event consisting of a severe weather occurrence (large hail, tornado, etc.) produced by a very large cumulonimbus cloud. The Byers and Braham (1949) study described in the preceding section presented observations of the typical structure of thunderstorms which are generally not severe. Although the description is for the most part accurate, there are significant features that must be included in a description of the severe thunderstorm.

Unlike a typical thunderstorm, during the mature stage the severe cell becomes organized with the environment in such a way that the dissipating stage is postponed (Burgess and Ray, 1986). Interaction between the cloud circulation and the environment perpetuates the mature stage. The updraft is a current(s) of air with marked vertical upward motion. It is an intense ascending current of buoyant air extending continuously from the horizontal warm and moist "inflow" near the surface upward through the depth of the troposphere. This current, at cloud top, forms the overshooting top (Figure 7), which penetrates into the stable stratospheric air. The updraft exhausts at high levels into the upper environmental flow as ice crystal clouds or falls as precipitation.

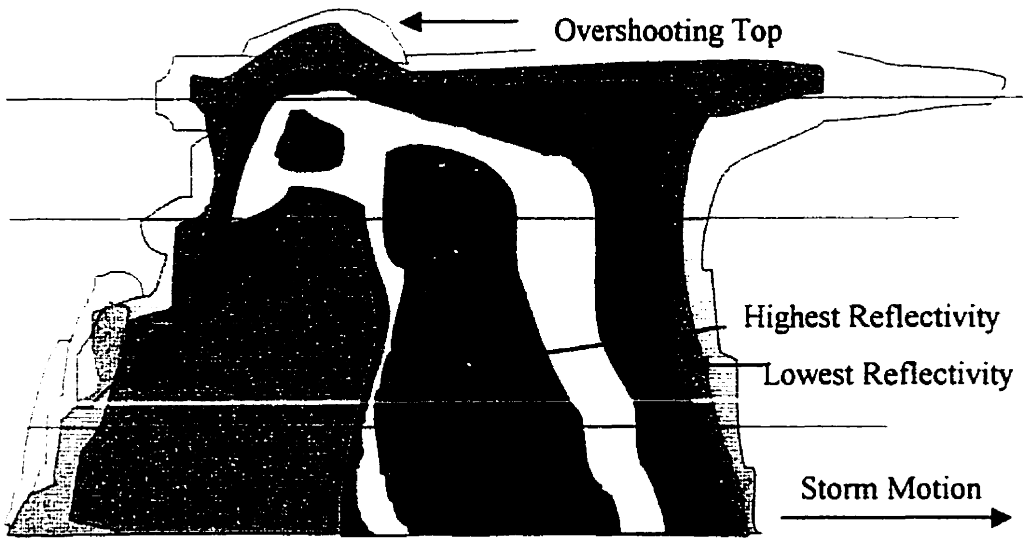

Figure 7: Vertical cross section of severe thunderstorm. (A) Represents the back of the cell, (B) the front. Dark colours indicate a high radar reflectivity, indicative of heavy precipitation.

The updraft is sloped with the low-level inflow at one of the cells foreword or side flanks.

2.2.3 Thunderstorm Types

Each updraft cell has associated with it a region of precipitation that can easily be identified on radar (Weismann and Burgess, 1986). Research has shown that cells oftentimes elicit repeatedly identifiable patterns on radar. On the basis of these patterns, conceptual models have been developed which group convective cells into three distinct categories. The breakdown into single cell (Byers and Braham, 1949), multicell, (Marwitz, 1972b; Newton and Frakhauser, 1975), and supercell (Browning, 1964; Lemon and Doswell, 1979), covers the major storm types within the spectrum.

a) <u>Single cell storms</u>: The single cell is the simplest convective storm (Weisman and Klemp, 1986). While not normally associated with severe weather, the single cell storms do produce hail at times and possibly locally heavy rainfall. They are typically about five to ten kilometers in horizontal extent, short lived (less than one hour) and change rapidly with time. (Chisholm and Renick, 1972). They consist of single updrafts, which rise rapidly through the troposphere and produces large amounts of liquid and ice. Associated winds are usually light, with little vertical shear.

b) Multi-cell storm: Of the three types, multi-cell storms occur the most frequently. Typical multi-cell storms consist of a sequence of evolving cells, each going through a life cycle similar to that of a single cell storms. It can be thought of as a cluster of short-lived single cells (Weisman and Klemp, 1986). Figures 8 and 9 show the sequence of cell development in a multi-cellular storm. Because of their ability to renew themselves frequently through new cell growth, multi-cell storms may last a long time (Weisman and Klemp, 1986). Cells typically form every five to ten minutes and last for 30-60 minutes. As many as 30 or even more cells may develop during a typical storm's lifetime (Chisholm and Renick, 1972), which if moving slowly, may present the potential for flooding. Multi-cell storms are frequently 30-50km in horizontal extent and frequently extend several kilometers into the stratosphere. The close proximity of updrafts within the multicell cluster storm results in updraft competition for the warm, moist low-level air. Thus, updrafts never attain extremely strong vertical velocities.

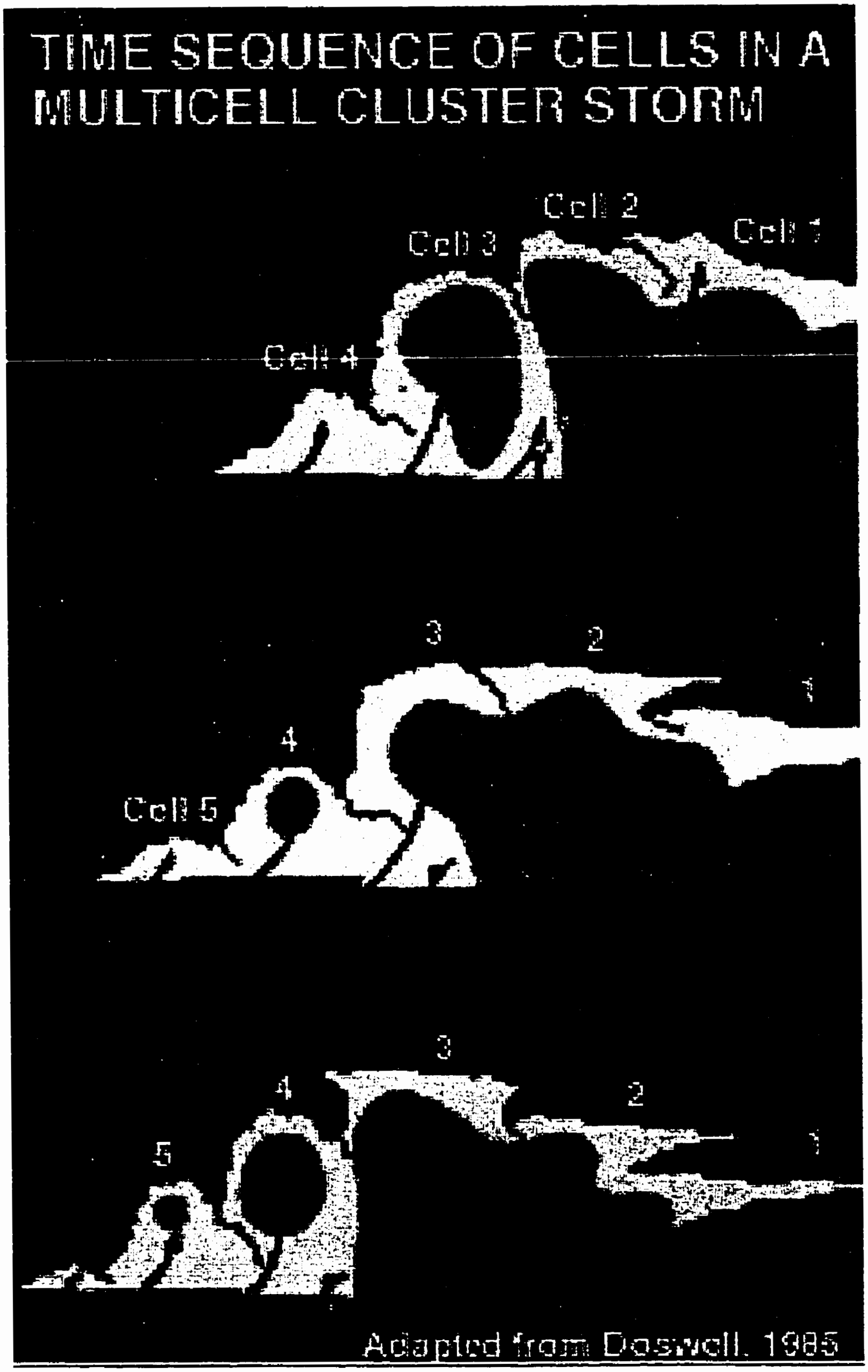

Figure 8: Time elapsed development of multi-cellular storms. (Source: University of Illinois WW2010 Project, 1997)

Figure 9: Picture of multi-cellular storms. Alan Moller NOAA / NWSFO

c) Supercell Storms (Figure 11): The "supercell" term was first used by Browning (1962) to describe a particular form of mature stage of the multi-cell storm. The supercell is far larger, more persistent, and gives more severe weather than the normal mature cell. It may produce high winds, large hail, and long-lived tornadoes over a wide path (Weisman and Klemp, 1986). Browning (1968) stated that environmental flow, continuously veering with height through the storm-bearing layer, is most conductive to producing the supercell thunderstorm. The "intense" updraft storm is almost invariably associated with the supercell, a storm capable of producing the most devastating weather, including violent tornadoes. Brown (1992) characterized the supercell by its broad, intense rotating updraft entering its southeast flank, rising vertically and then turning counter-clockwise in the anvil outflow region.

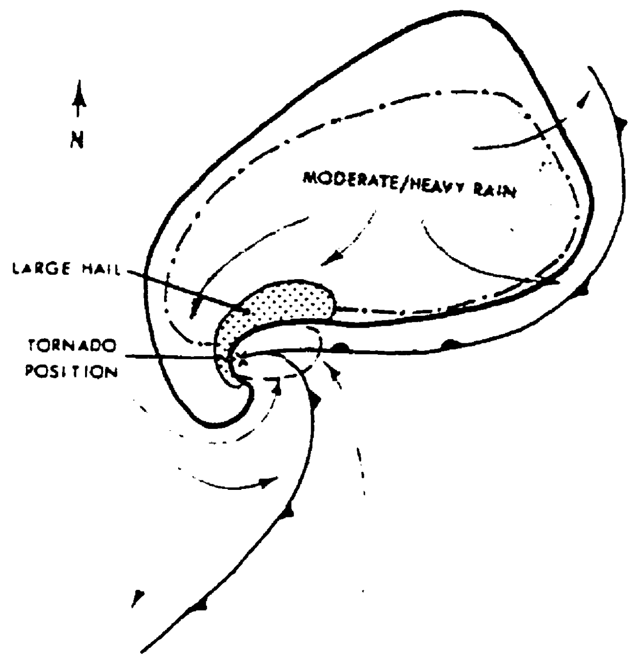

Figure 10: Horizontal cross-section of tornadic supercell thunderstorm. Note the hook-like appendage on southwest corner of cell. (Source: Ladochy, 1982)

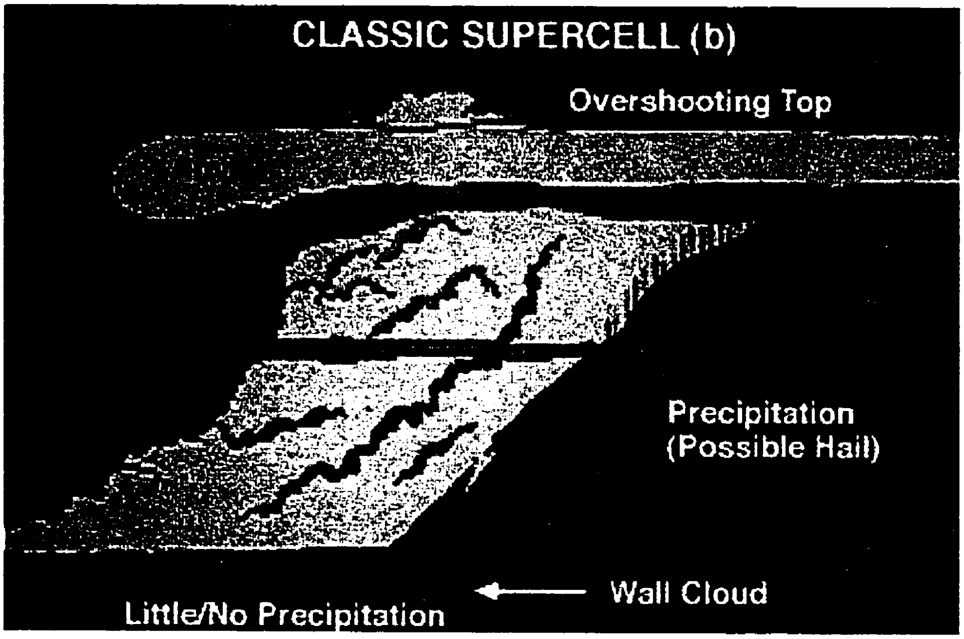

Figure 11: Classic Supercell. (Source: University of Illinois WW2010 Project, 1997) **(Source: University of Illinois WW2010 Project, 1997)**

A tornadic supercell will usually reach maturity within 90 minutes, with a hook-like appendage appearing on the southwest flank of the storm (Figure 10), and a large area of middle-level reflectivity overhanging the low-level echo (Weisman and Klemp, 1986). A region free of radar echo is a distinct feature of the supercell thunderstorm that can be seen on the southeast flank of the storm at the four and seven kilometer levels (Moller, Doswell, & Przbylinski, 1990). Known as a Bounded Weak Echo Region (BWER), it often appears at the middle levels above the edge of low-level reflectivity gradient. It is a radar feature that identifies where the strongest updraft is located in a supercell thunderstorm. The weak echo region is bounded when, in a horizontal section, the weak echo region is completely surrounded or bounded by higher reflectivity values. (Weisman et al., 1983).

The most severe supercells persist for several hours. According to Mogano (1980), this tells us that the thunderstorm must have the appropriate internal wind currents to counterbalance the strong external winds that would otherwise penetrate the thunderstorm and tear it apart.

Even though it is a rare storm type, the supercell is the most dangerous because of the extreme weather generated. Eagleman (1990) explained that the supercell's updraft elements usually merge into the main rotating updraft and then explode vertically, rather than develop into separate and competing thunderstorm cells. In effect, the flanking updrafts "feed" the supercell updraft, rather than compete with it. In summary, supercells are frequently dangerous, but useful warnings are possible once the storm has been properly identified.

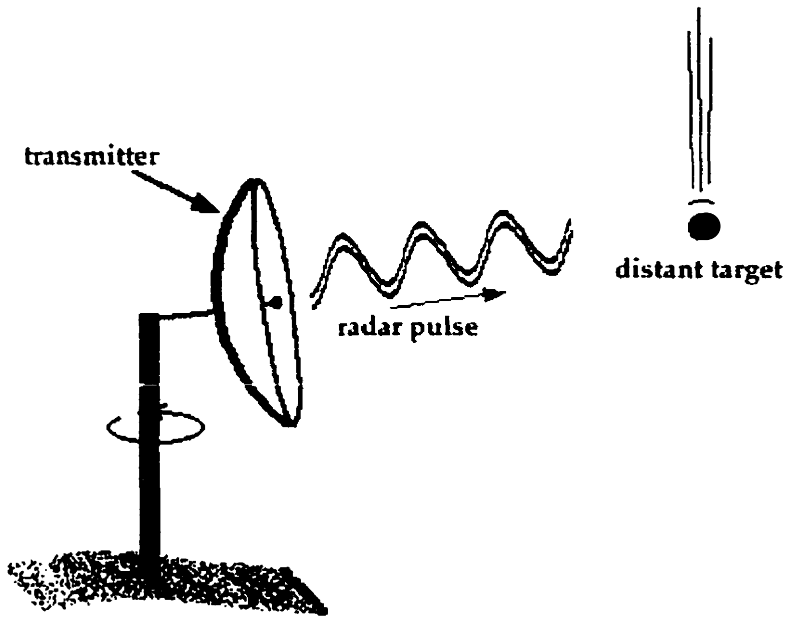

Figure 12: The radar creates an electromagnetic energy pulse that is focused by an antenna and transmitted through the atmosphere. (Source: University of Illinois WW2010 Project, 1997).

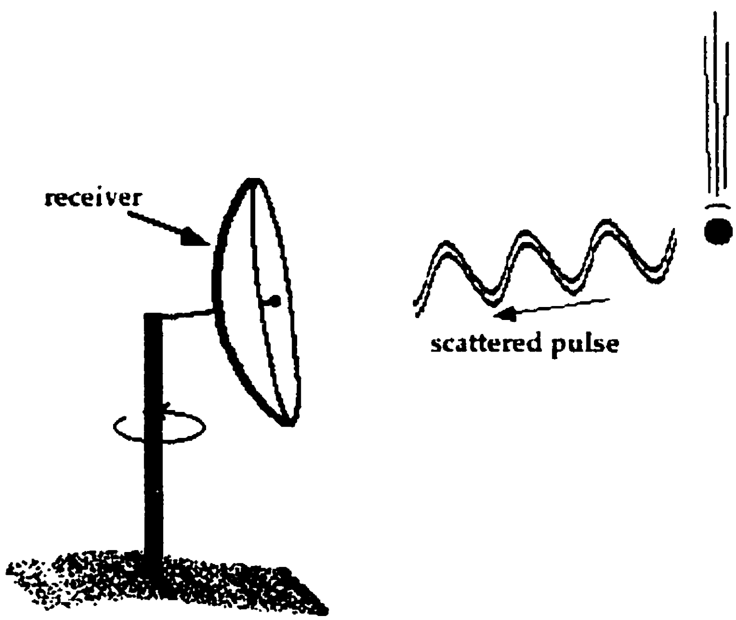

Figure 13: The receiving antenna (which is normally also the transmitting antenna) gathers this back-scattered radiation and feeds it to a device called a receiver. (Source: University of Illinois WW2010 Project, 1997)

2.2.4 Detecting Storms with Radar

Radar was developed during WWII to identify and track warships and aircraft. A radar consists of a transmitter to produce power at a known frequency, and an antenna to focus the transmitted waves to a beam about one to two degrees wide. When a particle intercepts a radio wave, some of the energy is absorbed and some is scattered. The amount of energy scattered depends on the dielectric properties of the particle. Figure 12 and 13 give a basic visual explanation of how radar works.

The magnitude of the reflectivity is related to the number and size of the drops encountered by the electromagnetic pulse. For this reason, high reflectivity generally implies heavy precipitation while low reflectivity implies lighter precipitation. The radar signature of a storm is characterized by a large precipitation area on radar (Cotton, 1990).

Les Lemon (1980) provided a study of warning identification techniques and warning criteria for conventional radar. These techniques are accepted as warning methods used by Environment Canada and the National Weather Service. The Lemon criteria (reflectivity) are used in current RDSS algorithms.

The first four criteria are indicative of updraft strength. The height of the 50-dBZ echo generally applies to warning for hail, but the above ground level height is flexible. During the warmer months this height can be 35,000 ft AGL or higher (especially in more tropical environments) before the updraft is considered strong enough for 21mm hail formation. This is likely due to the high freezing level during summer. Criteria two, three, and four also apply to updraft strength. Middle level echo overhang in a thunderstorm is an indication that the updraft is strong enough to suspend precipitation particles aloft (NWS, 1997). VIP is an acronym for Video Integrator and Processor. This processor was used on the WSR-57 and WSR-74C radars to indicate rainfall rates. It is still used occasionally on WSR-88D radar products. This processor contours radar reflectivity (in dBZ) into six VIP levels. Below are the Lemon criteria as they appear in Les Lemon's 1980 paper.

Table 1: VIP levels of equivalent reflectivity used in the Lemon technique for identifying severe thunderstorms. (Lemon, 1980)

Note: VIP levels of equivalent reflectivity. Values in parentheses indicate threshold for next higher level (i.e., 45.7 dBZ would be VIP 3, 46.0 dBZ would be VIP 4.

VIP Level	DBZ
1	0-(30)
2	30-(41)
3	41-(46)
4	46-(50)
5	50-(57)
6	57 or more

The Lemon criteria for identifying a severe thunderstorm:

1. VIP (Table 1) 5 echo at 8km (27,000 ft Above Ground Level (AGL)) or higher. In the absence of one, all the following must be satisfied:
2. Peak mid-level 16,000 to 39,000 ft AGL) reflectivities must be >= VIP 4.
3. Mid-level echo overhang must extend at least six km beyond the outer edge of (or beyond the strongest reflectivity gradient of) the lower level (<= 5,000 ft AGL) echo.

4. The highest echo top must be located on the storm flank possessing the overhang and be above the low-level reflectivity gradient between the echo core and echo edge or lie above the overhang itself.

Radar indication of a tornado requires the above two, three, and four criteria be satisfied and either or both:

1. A low-level pendant (oriented generally at right angles to storm motion) exists but may be embedded within lower reflectivities. (The pendant must lie beneath or bound the overhang echo on the west.)
2. A BWER is detected.

2.2.5 Effect of Thunderstorms on Farm Operators

Thunderstorms and agricultural activity coexist, with the former occasionally causing damage to the latter's property. Kessler (1983) described in detail the "social impacts" thunderstorms have on agricultural activity.

Severe storms can greatly damage agricultural production, especially if they include hail. Hail losses amount to about one percent of the overall agricultural production of the United States (Rydant, 1979). Between 1984 and 1996, storm damage caused near 200 million dollars in damage in Canada (Etkin and Brun, 1999). The burden of many individual losses is distributed among insurance companies and governmental-sponsored insurance programs (Ladochy, 1985). If a storm occurs later in the summer, rain and heavy winds flatten many crops, especially those near maturity. This results in poor and/or difficult harvest. Ripe grain can be shattered from the head by wind, rain and hail (Kessler, 1983). From a social standpoint the significant features of severe storms are high wind velocity, lightning, intense precipitation, and hail (Cotton, 1990; Eagleman, 1990). All these are variable features that appear in many combinations.

Every severe storm carries benefits and costs for people. Benefits may embrace increases in plant growth, nitrogen fixation, reduced risk of implications for grass and forest fires, scouring of stream channels, and accumulation of surface water. Costs may include loss of property and lives from lightning-caused fires, strong winds, and flash floods; crop and property damage from hail; and the investment made to cope with extreme events, including warnings, insurance systems, control measures, and readjustments in land use and structures (Kessler, 1983).

According to Kessler (1983) every society in a climate that spawns severe summer storms has to make some adaptations to those unpredictable events. Some of the adjustments outlined by Kessler include building design, cropping pattern, and commercial practices. Social adjustments to thunderstorms are made in the form of research projects like this one, forecasting systems (RDSS), insurance programs (LaDochy, 1985), disaster relief actions, building codes, and information programs. Although adjustments are commonly made to mitigate the effects of severe weather damage, the psychological effects can sometimes go unnoticed. White (1974) listed several reasons why the perceptions and estimation of severe weather people make can become distorted from the actual event characteristics . They include;

1. The magnitude and frequency of the hazard (extreme event, ordinary thunderstorm);
2. Time and frequency of personal experience, with intermediate frequency generating greatest variation in hazard interpretation and expectation;

3. Importance of the hazard to income or locational interest. Ex: Killed livestock to a farmer may have more importance than petunias to a city dweller for monetary reasons.
4. Personality factors such as risk-taking propensity and views of nature.

2.3 Hail

In North America, the areas of the greatest hail frequency and intensity occur on the Great Plains and in the lee of the Rocky Mountains. These occur both in Canada and in the United States. The crops most susceptible to hail damage are fruits, vegetables, and grains (Visvader and Burton, 1974, p. 226).

The severe weather hazard of hail has been always been a nuisance to farm operators across the North American prairies (Taylor, 1972). Some designate hail as "the white plague", since it is more destructive than tornadoes in causing great monetary loss in crops and property damage (Flora, 1956). This section briefly reviews the climatology of the Manitoba hail season, and the scientific and social adjustments we have made to mitigate the threat of hail to our property and lives. More specifically, it will examine the changes that farm operators have made to protect their crops and property, as well as the important scientific leaps made in radar hail detection.

With the prairies in mind, it becomes evident that greatest threat by far, is to cereal grains. LeDochy (1985) describes hail is "a thunderstorm phenomenon that causes great losses in Manitoba's agricultural product". According to Raymond Clyde (1981), grains are susceptible to hail particularly during the early stages of growth and at harvest time. Severe hail (Figure 15) can pound a crop into a worthless mass in a few minutes.

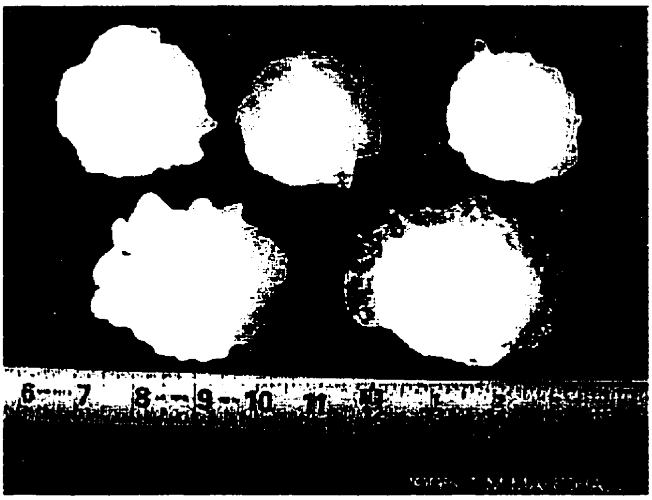

Figure 14: Example of large hail. 2-4 inches in diameter. (Source: Tim Marshall http://storm-track.com/hail.htm)

One of the unfortunate aspects of severe hail is that despite the great leaps in detection and warning, the damage caused by hail can not avoided.

There have been several internationally recognized hail studies conducted in Canada. The Alberta Hail Studies project, conducted in 1956, studied the behavior and structure of hailstorms as observed by radar. Atmospheric Environment Service (AES) meteorologists at Regina conducted an unfinished survey of Saskatchewan farm operators in the 1960's. Another project was the Saskatchewan Hail Research Project (SHARP) that was in operation from 1973 to 1977. The SHARP project collected nearly five thousand hail reports from farm operators in southern Saskatchewan. According to Clyde (1981), these reports contained more detail on the hail characteristics and frequencies than can be obtained from AES observing stations. Nevertheless, Clyde contends that there has been little research on the views and perceptions farm operators have of severe hail. In recognition of the lack of qualitative knowledge in severe weather meteorology, Raymond Clyde (1981) conducted a study, which studied the perceptions Saskatchewan farm operators held of hail, drought and floods.

Manitoba Hail Climatology

Within Manitoba, hail frequencies have been estimated to be highest in the RDSS study area. The hail maxima are located in the southern portion of Manitoba (Figure 1), decreasing towards the north, with one centered around Winnipeg, and the other around Rivers (LaDochy, 1985). A more recent climatology compiled by Etkin and Brun (1999) revealed that Manitoba hail frequencies are generally under two days annually, with relative maxima just southwest of Winnipeg, near Somerset and southwest of Rossburn on the southwest portion of Riding Mountain. The average number of hail days shows an irregular fluctuation through time.

Hailstorms have been found to be associated with isolated supercell storms, multicell thunderstorms, and squall lines (Flora, 1956). The appearance of a thunderstorm that develops hail is unlike an ordinary thunderstorm. The optical character of sunlight striking a hailstorm causes a dark blue-green color. The explanation for this turquoise colour is unknown, but it is likely due to water loading. Due to temperature differences in the atmosphere, the climatology of hailstorms in Canada are different than those required in the Southern US. In Canada, a thunderstorm that reaches a height of eight to 10 kilometers has a 50% chance of producing hail, whereas in Texas a storm reaching a height of 17 km has the same probability (Cotton, 1990). A severe thunderstorm produces rain, hail, and tornadoes in specific areas within the thunderstorm. Hail normally falls in the central part of a thunderstorm with the major rain area in the leading part of the thunderstorm. The major hail area in the central part of the storm (Figure 10) is related to the thermal updraft and the flow of air within the thunderstorm" (Eagleman, 1990). When crops come under the central part of a storm, substantial damage can be done, depending on the susceptibility of the crop.

Hewitt and Burton (1971) state that agricultural hail damage is characterized by:

1. Bruising, flattening, stripping of crop plants;
2. Dents, punctures, fractures in construction material;
3. Maiming and the occasional death of small animals.

The amount of damage depends primarily on:

1. The number, spacing, size, impact velocity, and the impingement direction of the stones;
2. Whether strong winds accompany the hail;
3. Duration and real extent of fall;
4. The hardness of the stones and the susceptibility of objects to the hail damage;

The strongest effect of hail is in agriculture. Across much of Canada, the annual harvest of small grains lies under an omnipresent threat of loss to hail by lodging of stalks and shattering of seed. In an attempt to adjust to the threat of hail farmers sometimes decide to plant hail-resistant crops and scatter the location of cultivated fields to reduce the danger of losing large portions of the harvest to one storm (Kessler, 1983). When available, many farmers invest in crop hail insurance.

Detecting Hail with Radar

Since the advent of radar and its use in meteorology, many efforts have been made to predict which cells will cause severe and damaging hail. While past methods have focused on the structure of the storm cell radar signature (Lemon, 1980), recently developed methods and techniques have focused on parameters such as temperature, echo tops, temperatures aloft, Vertically Integrated Liquid (VIL) and VIL density (Troutman and Rose, 1998; Roeseler and Wood, 1998; Taggart, 1998). These techniques will be discussed in the following section.

Lemon Technique

Along with determining storm cell severity, the "Lemon technique" is also used in the forecasting of severe hail. Lemon's (1980) technique for determining if a cell was capable of producing severe hail involved the use of multiple criteria related to the structure of the storm cell. Two of these criteria were characterized by high reflectivities;

1. Reflectivities of 50dBz or greater at 27,000 feet or higher above ground level (AGL).
2. Peak mid-level (16,000 to 39,000 feet AGL) reflectivities must be greater than the VIP 4 (40-50dBz) pre-88D radar level.

Although the criteria put fourth by Lemon in the early eighties continues to be used today, the reliability of using reflectivities and Weak Echo Region (WER) to predict severe hail has been found to be low. "While high reflectivities aloft and high WERs are almost always associated with severe hail, the optimum height of the 50dbz core and the extent of the WER (updraft strength) are not always consistent" (Lewis III, 1998). With these weaknesses identified, scientists have continued to develop and improve other methods of identifying cells with the capacity to deliver severe hail.

With no apparently reliable method of detecting or predicting hail, new methods are continuously being developed and tested. The testing of algorithms using Vertically Integrated Liquid (VIL) density as a "severe hail indicator" has been the subject of many research papers in the 1990's, and continues to be in the twenty-first century. Currently there is no apparently reliable method of detecting or predicting hail. Described in the following section is the method utilized by RDSS to detect severe hail, VIL density.

VIL and VIL Density

Vertically Integrated Liquid (VIL) is a measure of water content inside a column of air directly above any given point (RDSS technical manual). It is used to:

1. indicate presence and approximate size of hail (used in conjunction with spotter reports);
2. locate the most significant thunderstorms or areas of possible heavy rainfall.

Douglas Green and Robert Clark developed the method RDSS uses to calculate VIL.

$$\textbf{VIL} = 0.00344\sum 10^{(rz/10)(4/7)}$$

Where r_Z are the reflectivity values taken at one-kilometer intervals in the vertical direction and VIL is expressed in kg/m^2 (RDSS Technical Manual). Amburn and Wolf (1996) described VIL density as VIL divided by the Echo Top. The quotient is multiplied by 1000 to yield units of g/m^3. VIL density is used by RDSS to compute the hail probability.

VIL density = (VIL/Echo Top)*1000

The vertically integrated liquid water product has long been used by forecasters for estimating severe thunderstorm potential and hail threat. But the utility of VIL varies day to day depending on airmass characteristics. At times tall thunderstorms with large VIL do not produce large hail, while on other days short thunderstorms with small VIL may produce large hail (Amburn, S.A., and P.L. Wolf, 1996). Studies of VIL density have shown a relationship between VIL density and severe hail probability and hail size (Amburn and Wolf, 1997; Troutman and Rose, 2000). Figure 15 and 16 illustrates the relationship between VIL density and severe hail size. In the Ambun and Wolf (1996) study, the results identified a VIL density of 3.5 g/m^3 as correctly identifying over 90% of the severe cases in Oklahoma. The results of the Troutman and Rose (2000) study

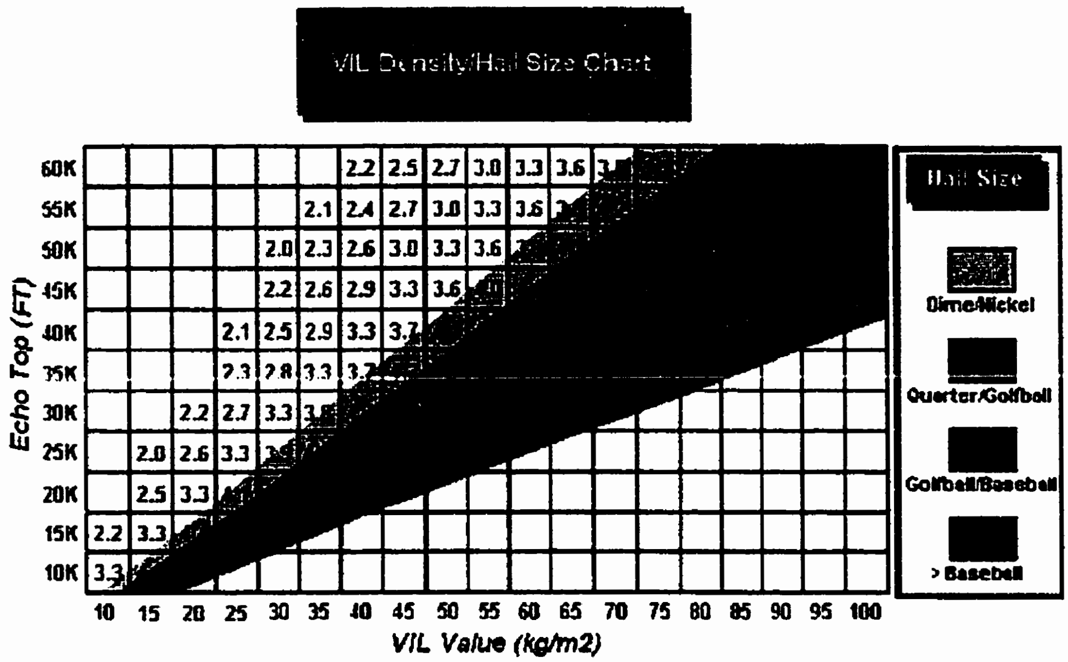

Figure 15: VIL Density Chart (modified for NWSFO LIT) shows that hail sizes become larger when VIL is increased and echo tops remain constant (from Amburn and Wolf, 1996). (Source: http://www.srh.noaa.gov/ftproot/lzk/html/hailfig9.htm).

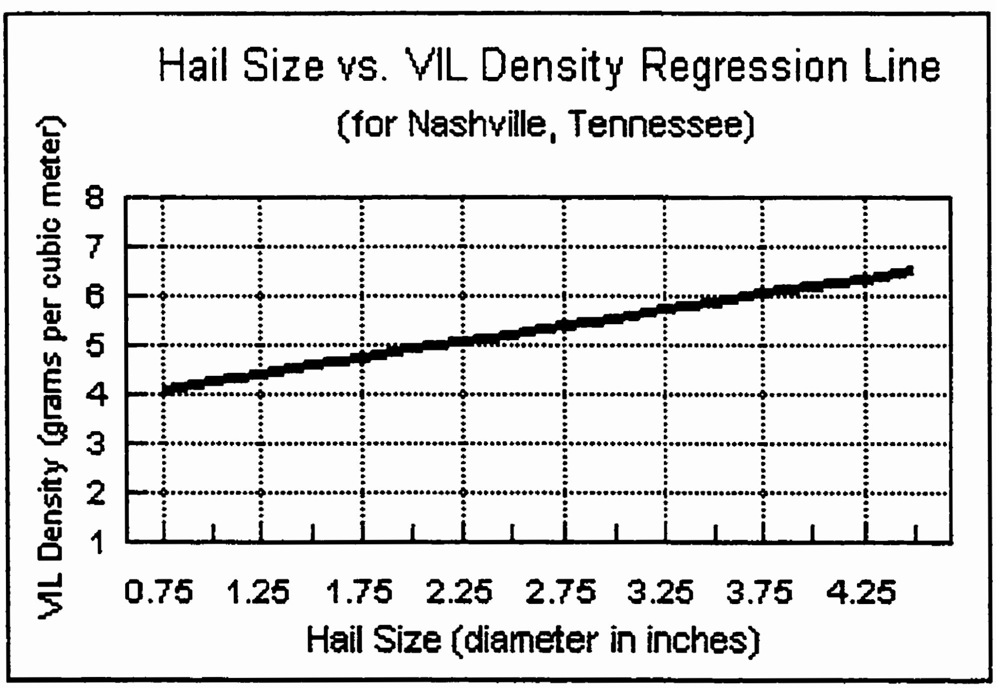

Figure 16: VIL Density vs. hail size regression line used as "quick reference" in determining large hail potential. (Source: Troutman & Rose. 2000)

identified a VIL density of 3.5 g/m^3 identifying 79% of all severe hail cases. The Roesler and Wolf (1997) study correctly identified 72%, and a study conducted by Taggart (1997) matched the Anburn et al study with a detection of 90% of all cells containing severe hail (Table 2). These studies were all conducted in different part of the US resulting in different performances of the VIL density as a severe hail predictor. Roesler et al (1997) suggested in their study that a VIL density of 3.75 g/m^3 to 4.25 g/m^3 may decrease the FAR while remaining an efficient severe hail predictor. Figure 15 and 16 are VIL density charts that illustrate the relationship between VIL densities and hail size.

As can be seen, VIL and VIL density have been found to be of great importance in several different hail studies (Baumgardt and King, LSE local hail study).

Table 2: Comparison of results for studies employing a 3.5 g/m^3 VIL density. The algorithm consists of a straightforward comparison of VIL density values against threshold values (RDSS Technical Manual).

Study	VIL density	Percent Detected
Roesler and Wood (1997)	3.5 g/m^3	72%
Troutman and Rose (2000)	3.5 g/m^3	79%
Amburn and Wolf (1996)	3.5 g/m^3	90%
Taggart (1997)	3.5 g/m^3	90%

Due to the problems associated with using VIL and VIL density to predict severe hail, other methods have been developed to capture the atmospheric effect on VIL values (the thickness of the atmosphere changes moving poleward). The vertically integrated liquid (VIL) guideline for large hail is usually referred to as the "VIL of the Day," (Figure 17) which is a locally determined VIL based on environmental conditions of the day.

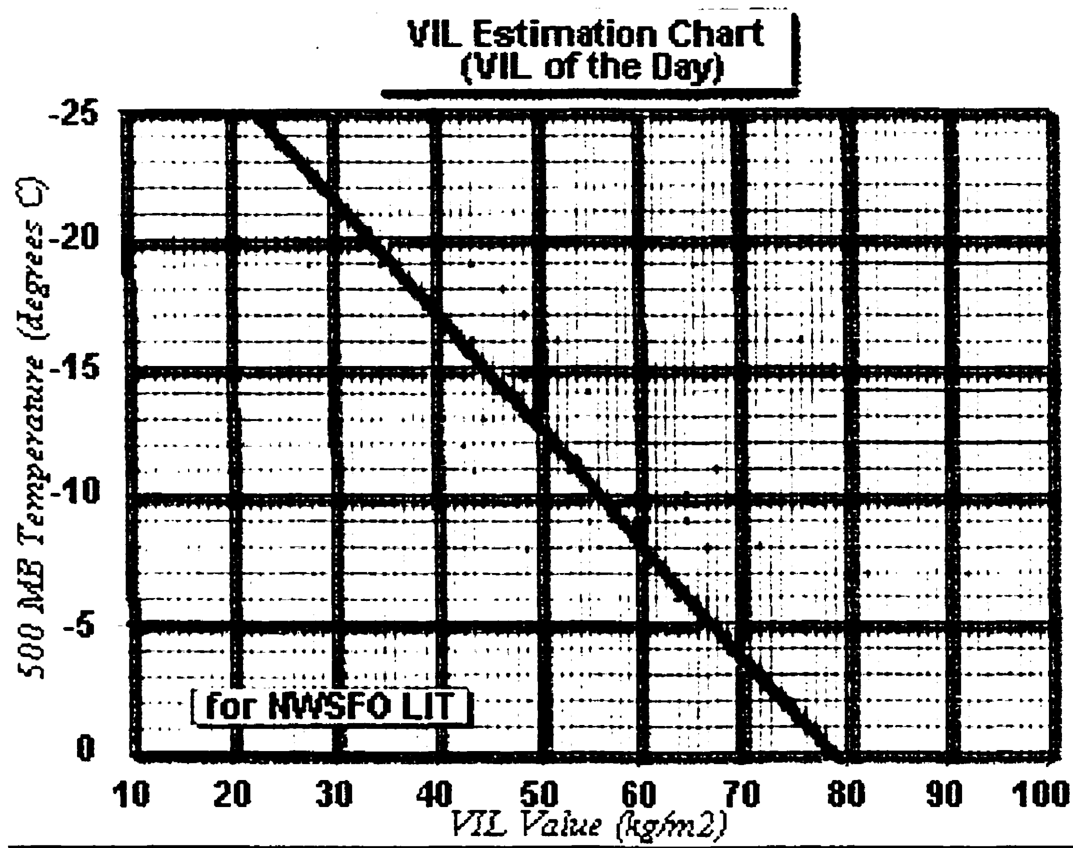

Figure 17: VIL of the Day Chart (Wilken, 1994) shows that the hail threat increases with colder temperatures at 500 mb and/or increasing VILs. Diagonal line is the threshold for large hail. (Source: http://www.srh.noaa.gov/ftproot/lzk/html/hailfig7.htm)

Paxton and Shepherd (1993) provided the following formula for VIL of the Day:

VIL of the Day = 750 / [(T500+T400) / 2]

where T500 = absolute value of 500 mb temp(C), and T400 = absolute value of 400 mb temp(C) VILs of this value or higher would suggest hail 3/4-in in diameter or larger.

According to Lewis (1996), if VIL density and VIL of the day techniques are used in concert, more accurate hail size predictions could be made. While VIL is easy to use, it has a weakness. The moisture used in the VIL calculation is entrained into a thunderstorm by updrafts that vary in strength as the seasons change. With moisture most plentiful in the warm months (stronger updrafts), VILs would ordinarily be highest in the summer.

Several studies have successfully linked VIL to hail size and probability of hail, other studies have not been as conclusive. Billet, DeLisi, and Smith (1997) attempted to predict hail size and the probability of large hail from a set of independent variables that included the VIL, the 850-hPa (The hectoPasca (hPa) is equivalent to the previously used millibar). The research revealed little success in predicting hail stone size but showed some skill in determining the probability of severe hail.

Although tremendous improvements have been made in methods used to forecast severe hail events, there has yet to be extensive testing of all the predictive models. From the studies reviewed, it is evident that the use of VIL density has some promise, but in general VIL/VIL density are regarded as having marginal utility.

Forecasting severe hail is a tricky field of business which has yet to develop any reliable predictive models.

2.4 Wind

Convective downbursts are considered to be a hazard worldwide, wreaking havoc on farm operators, pilots and recreationists alike. All thunderstorms have outflow winds, most are weak, but some are strong enough to inflict damage on ground level (Smith, Elmore, Scharenberg, 1998). This section will focus on the nature of severe convective winds, as well as the scientific and technical advances that have been made in the detection of severe winds.

A downburst is defined as a rapid downdraft of wind from a single cell thunderstorm that produces a sudden outflow of horizontal winds at the surface (Fujita 1981). They can be interpreted visually using radar data and conceptual models.

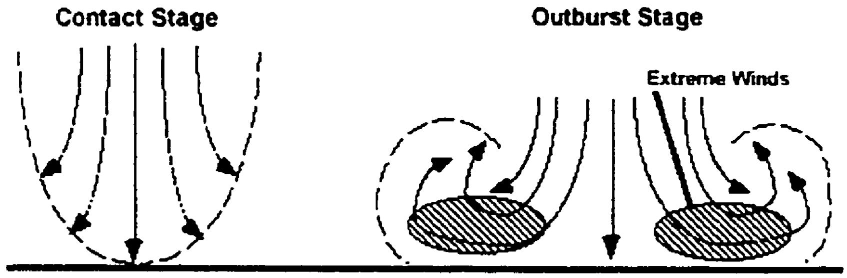

Figure 18: Visual depiction of a downburst. (Source: University of Illinois WW2010 Project, 1997)

A low-level divergence of winds will occur as the downburst contacts the ground (Fujita 1981). According to Byers and Braham (1949), as the storm cell grows and a downdraft develops, the surface winds take on an entirely different character, becoming strong and gusty as they flow outward from the downdraft region (Figure 18).

Convective windstorms are driven by downdrafts, the physics of which are relatively simple and correspondingly well understood. The downdraft is a main descending current of negatively buoyant air originating at high to mid-levels of the cloud which incorporates drier environmental air at mid-levels and then descends adjacent to the updraft to the surface (Fujita, 1981). The strongest downdrafts are usually encountered within the main precipitation fallout zones. The vertical velocity of these downdrafts varies, but tends to be roughly half as strong as the updrafts. Some localized regions of more intense downdrafts can occur. The cold descending air diverges in all directions at the surface. At its leading edge, this cold outflow forms the "gust front" or "meso-cold front". Damaging downdrafts are now often referred to as downbursts, and occur over a range of scales. Downbursts are made up of a range of intensities, and even relatively mild convective windstorms can be a danger in some societal settings. High-based cumulonimbi may produce light but measurable rain at the surface and raise clouds of blowing dust, as in where a rain shower has spawned a "gustnado" (gust front tornado) (Doswell, 1997). Although the effects of downbursts are commonly known, they remain difficult for operational forecasters to predict and detect (Smith, Elmore and Scharfenerg, 1998).

<u>Wind Gust Analysis</u>

In an effort to understand and predict damaging winds, many studies have been conducted. Studies conducted by Roberts and Wilson (1989) and Elits (1997) identified several radar signatures that precede the occurrence of severe wind events.

They include:

- Descending reflectivity cores (Figure 19): The most significant radar precursors are convergence near or above cloud base and a descending reflectivity core (Eilts et al. 1996). Although descending reflectivity cores are relatively small in size, they tend to be reliable microburst predictors and forecasters need to monitor cell tendencies very closely. About 86 % of surface damage events reported in Ontario to the severe weather log were coincident with the descent of a maximum reflectivity core (Joe, 1997).

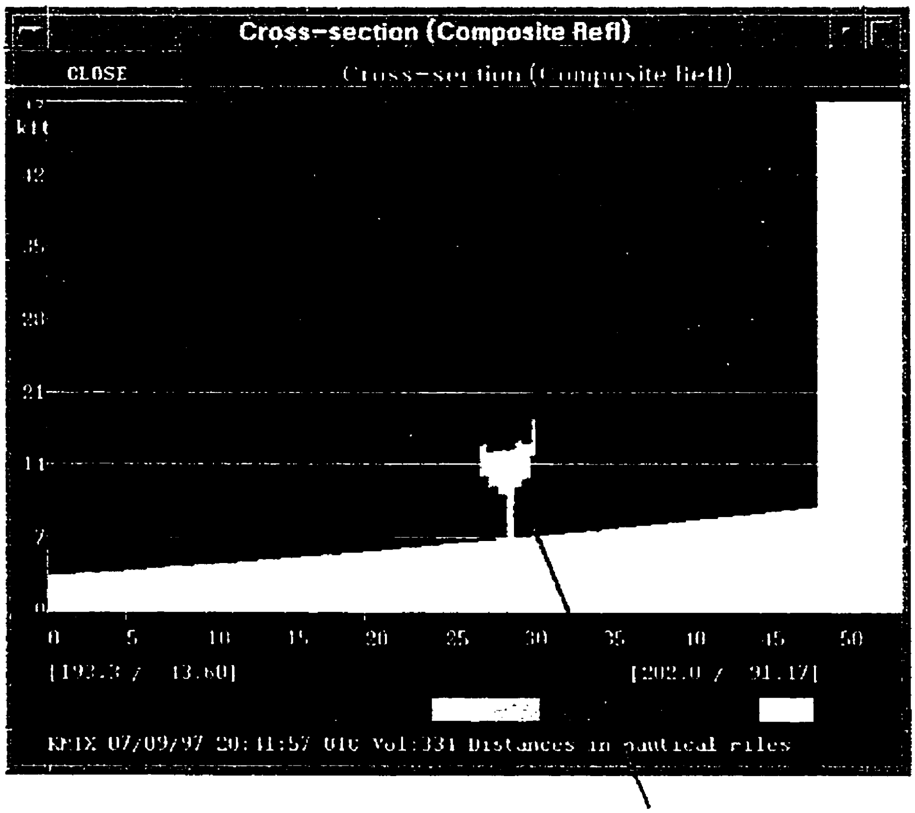

Figure 19: WSR-88D radar image. A downdraft rapidly descending as indicated by narrow 34-dBZ-echo "shaft" extending downward. Horizontal axis units are dBZ and vertical units are kft (ft*1000). (Source: Stewart, 1999).

- Inflow Notch: A radar signature characterized by an indentation in the reflectivity pattern on the inflow side of the storm.
- Increasing radial convergence within the cloud: Radial convergence in Doppler velocity most reliably marked the gust front, which amassed insects, dust, and hydrometeors in its leading circulation.
- Rotation

Using these signatures, the Damaging Downburst Prediction and Detection Algorithm (DDPDA) was designed. The algorithm attempts to locate downburst precursors, events that can be detected in the middle and upper levels of a storm prior to the onset of strong surface winds. Early versions have focused on predicting damaging wind events from short-lived thunderstorms. To test the DDPDA algorithm, Smith et al (1998) conducted a study, which evaluated thirty high reflectivity downburst events and 197 non-severe cells from eight different days. Table 3 displays the performance statistics for the DDPDA. The researchers felt that the algorithm performed relatively well considering the small sample size.

Table 3: Performance statistics for the DDPDA (Source: Smith et al, 1998).

Hits	Misses	False Alarms	Correct Null Events
20	10	21	175

Probability of Detection	False Alarm Ratio	Critical Success Index	Heidke's Skill Statistic	Average Lead Time (minutes)
67%	51%	39%	0.566	8.5

RDSS employs a similar algorithm for the detection of damaging convective winds. The Wind Gust Potential (WGP) algorithm uses a measure of the maximum downdraft that can occur in a pulse type thunderstorm as a result of cloud penetrative downdrafts.

The method RDSS uses to calculate Wind Gust Potential was developed by Stacy R. Stewart (RDSS technical manual) and uses the following equation to calculate a value that can be associated with a column of air.

$$WGP = 3.6\sqrt{20.628571 \bullet VIL - 3.125 \bullet ET^2}$$

Where
WGP = Wind Gust Potential
VIL = Vertically Integrated Liquid
ET = Echo Top

RDSS provides an automatic severity rating for storms based on characteristics that can be associated with wind gusts. A rating between zero (low severity) and three (high severity) is assigned depending on the structure and characteristics of the cell (Appendix C). As a cell exhibits radar characteristics indicative of an impending downburst, the cell is assigned a severity level depending on the strength and number of characteristics exhibited.

In general, convective winds on their own, inflict some damage to property (Etkin and Brun, 1999), but with the relatively high frequency of hail with severe wind, further testing and study of severe wind detection algorithms is warranted.

2.5 Surface Validation in Meteorology

"Ground truth" plays an important role, before, during, and after a meteorological event. Until recently, severe thunderstorm (STS) forecast verification involved time-consuming manual processing and offered little reward for forecasters because there is no established procedure for timely, regular diagnostic feedback. In a study conducted by Hoium (1997), an evaluation of the warning process was conducted. This study examined the

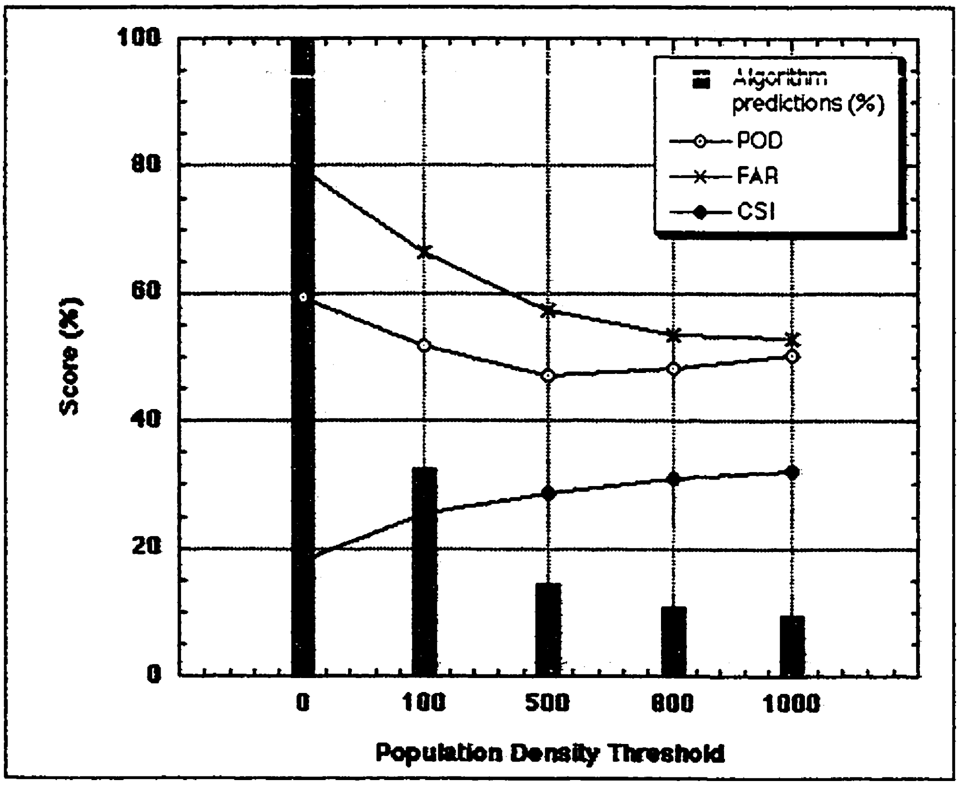

Figure 20: Line plots are False Alarm Ratio, Probability of Detection and Critical Success Index. Blue bars represent percent of convective activity which occurred over given population density regions (relative to entire radar domain). (Source: Wyatt & Witt. 1997)

decision process by documenting the types of information leading to warning decisions. Even though the radar used in the study was extremely sophisticated, Hoium (1997) found that ground truth was the most vital part of the verification system. Without reliable ground truth data, the timely issuance and dissemination of watches and warnings would be impeded. It has been proven that improved forecasts, advances in warning technology, and improved ground truth verification techniques, have contributed to a considerable decline in severe weather related deaths. Although ground verification techniques have proved very useful in meteorology, they also have their associated shortcomings. Some of these deficiencies can be attributed to the spatial and temporal heterogeneity of the human and physical landscape (Wyatt and Witt, 1996). It can be expected that a hail event occurring in an agricultural area in the spring may not elicit the same reaction as an event in the fall, due to the difference in focused weather awareness between these dates. As an example, Maximum Expected Hail Size (MEHS) was compared for two regions where spotter activity was "low" and "high". The resulting analysis made it quite obvious that MEHS output performed much better in the spotter region characterized as "high" in activity (Baumgardt, 1998).

Other studies also found that a major weakness in Severe Thunderstorm (STS) verification is the lack of (quality) verifying data, especially in sparsely populated areas. Even where STS are observed, reports of tornadoes and estimates of hail-size and wind-gust intensity are often subjective and prone to inaccuracy (Alfrod, 1998). Hoium (1997) encountered similar issues in verification projects. In this study, a higher probability of detection (POD) was experienced in areas with higher population densities. As well, significantly more warnings were issued for more highly populated regions, where presumably, verification is more likely (Hoium, 1997). In addition, a study conducted by Wyatt and Witt (1997), revealed that the FAR decreases and CSI increases as population densities increase (Figure 20).

2.6 Meteorological Decision Support Systems

Weather warning systems have been developed in an effort to increase the lead-time meteorologists have in issuing a weather warning. The mathematical algorithms used to analyze radar and satellite images are being continuously upgraded (Baumgardt & King, 1998). Decision support systems are the most recent development in the battle to warn citizens of impending severe weather (Sharp, 1997). Intelligent radar data processing modules have been designed to help the user analyze information and make quicker decisions (Keck and Legal, 1996). In meteorology, decision support is needed to determine if a weather warning is warranted or not. A computer can now interpret information in seconds, which previously could take up to fifteen minutes for a meteorologist to collect and digest. These systems can also monitor and track many storms simultaneously.

Theirauf (1988) defines decision support systems as tools which allow the decision-maker to combine personal judgment with computer output in a user-machine interface to produce meaningful information for support in the decision-making process.

Such systems are capable of solving all types of problems (structured, semi-structured, and unstructured) and use query capabilities to obtain information by request. As deemed appropriate, they use quantitative models as well as database elements for problem solving. From an enlarged perspective, decision support systems are an integral part of the decision-makers' approach to problem solving (Mittra, 1986). Fundamentally, the RDSS is a system that has been designed to support the decisions of severe weather meteorologists and some operating personnel. Previous to the advent of Decision Support Systems, personnel in many different fields were required to conduct lengthy manual data processing. Systems such as RDSS and WDSS assist organization personnel to reach effective decisions that contain elements of subjectivity and objectivity. The capability of combining subjectivity (individual judgment) with objectivity (the computer's output) permits a more thorough exploration of the problem (Theirauf, 1988).

Environment Canada's Radar Decision Support System (RDSS)

The Radar Decision Support System (RDSS) program is one of the most critical projects underway at Environment Canada (McCarthy, 1997). In 1996 the first verification project was undertaken, SMART'96. SMART'96 had two primary objectives:

1. Ground-truth the RDSS by collecting real-time and post-event storm data.
2. Enhance the region's severe weather program by providing pre-storm data, and real-time weather and storm data back to the local weather centers (McCarthy, 1997).

To fulfill these two objectives, the Prairie Northern Region's (PNR) Techniques, Technology and Training Division (TT & T) collected severe weather data focusing mainly in southern Manitoba. The project had mixed success, although information that was gathered in the pre-storm phase proved to be valuable, the limited number of severe weather events did not allow for the adequate verification of the RDSS.

SMART'97 (the follow-up to SMART'96) was EC's second RDSS verification project. Similarly to SMART'96, the 1997 project's main objectives were to ground-truth the latest version of RDSS by collecting accurate and detailed storm data (often referred to as Gold Standard Data or GSD). GSD are needed to determine accurately the storm's behavior, evolution and RDSS performance (McCarthy, 1997).

The real-time investigators followed significant thunderstorms and recorded their observations. Observations were both visual (storm structure, storm evolution, tornado sightings, etc.), and measured (hail size, wind speeds, temperatures, location and extent of damage tracks, etc.) (McCarthy, 1997). From these previous studies, it becomes evident that a significant number of events are needed to adequately verify the utility of the radar system. The summers of 96 and 97 did not supply an adequate amount of storm cells for study.

National Weather Service's (NWS) Warning Decision Support System (WDSS)

In modernizing the National Weather Service (NWS), the United States has also developed a similar tool to the RDSS. The American Weather Decision Support System (WDSS) is similar to the Canadian RDSS in that it tries to puts the right information in the hands of the meteorologist to make timely decisions (Theirauf, 1988). More specifically, the WDSS is a system that incorporates data from available weather sensors and model outputs, interprets these data (through a variety of severe-weather detection algorithms), and displays the information (both sensor and algorithm output) using unique interactive display concepts (Naistat & Stumph, 1996). In a study spearheaded by the National Severe Storm Laboratory, enhanced algorithms were developed and used to help detect severe weather occurrences (Eilts, M., Johnson, J., Mitchell, E., Sanger, S., Stumpf, G., Witt, A., Thomas, K., Hondl, K., Rhue, D., & Jain, M. 1996). Unlike the RDSS, WDSS has the ability to integrate datastreams such as surface observations, satellite imagery and ground strike locations from the National Lightning Detection Center (Sharp, 1997).

Another American WDSS research project also involved algorithm evaluation. Similar to this proposed research study, "the algorithms were evaluated qualitatively via feedback questionnaires from NWS personnel. Also, National Severe Storm Laboratory (NSSL) staff assisted the NWS staff in collecting real-time verification data and conducting post-storm damage surveys to enhance the quality and quantity of ground truth" (Stumpf & Foster, 1996). Similar tests have been conducted elsewhere (Naistat & Stumph, 1996; Johnson et al. 1997). The NSSL also conducted a proof-of-concept test of their severe weather WDSS. It tested the enhanced Doppler radar-based algorithms in the southern plains in a springtime environment during actual National Weather Service (NWS) operations (Stumpf and Foster, 1996). Other studies on the operational assessment of the WDSS have also been undertaken. Sharp (1997) had all operators of the WDSS fill in forms outlining improvements that could be made to the display and the user friendliness.

In 1995 the National Severe Storms Laboratory published the algorithms and capabilities of WDSS (Stumph, 1995). These include;

- An enhanced mesocyclone detection algorithm (MDA), which includes a 3D integrated strength index (MSI), Neural Network derived probability functions (i.e., the probability of severe weather or tornadoes in the next 20 minutes associated with each circulation), and a tracking function.
- An enhanced tornado detection algorithm (TDA) and a tornado tracking function.

- An enhanced Hail Detection Algorithm (HDA) with the probability products and near-storm environmental temperature data input.
- An enhanced storm cell identification and tracking (SCIT) algorithm.
- A lightning Association Algorithm (LAA) which associates lightning ground-strike and polarity data with storm cell.
- DDPDA

(Stumph, 1995).

Conclusions

This chapter has examined severe weather from several angles. The characteristics of thunderstorms were examined in terms of their various stages of development, internal structure, radar signatures, and effect on farm operations in southern Manitoba. Particular focus was placed on previous and current projects involving the improvement of severe weather detection algorithms and weather related decision support systems. The social angle of severe weather, detailing how farm operators perceive severe weather was reviewed for methodological structure and questionnaire content. Drawing upon the achievements of previous studies, a methodology was developed which capitalizes on the methodological advantages and acknowledges the disadvantages inherent in meteorological studies.

3 Methodology

The purpose of this chapter is to discuss methods used to gather data for the verification of Environment Canada's RDSS. The methodological scope can be separated into three distinct operations. The first area will focus on the use of Environment Canada's digital information, such as event log databases and on-screen-visual radar data. The second area will concentrate on surface validation methodologies such as damage assessments. The final area will outline the elements of the interview questionnaire in terms of its composition and delivery. In addition, a review of related literature, from books, articles, and web sites will also be conducted.

Prior to outlining the methodologies used in this study, certain qualifications must be made. It must be recognized that severe weather verification has an inherent level of subjectivity with regard to the reporting of these events. Event reports are susceptible to variations in population densities and the collection process itself. It is recognized that hail sizes in the data set may be the largest reported but, not necessarily the largest the storm produced. Baumgardt (1998) discovered in a study that there is a tendency for spotters to report golf-ball sized hail (1.75 inches) once the diameter exceeds one inch. The estimation of wind speeds is also very subjective, especially where instrumentation is not available as a supplement.

3.1 Radar Volume Scan Archive Analysis

The very first step involved in the verification of the RDSS, is the analysis of the matched cell archive. The RDSS has a Radar Data Information Manager (RDIM) which is capable of maintaining a data storage for raw radar volume scans and data products. The data archive of interest in this study is the "cell_ends.log" archive. This archive is a "matched cell archive", which documents the time sequence and severity level information for each tracked cell. Matched cells are stored according to the maximum severity value (wind, cell, hail) that was assigned at any point during the lifecycle of the storm cell. The matched cell archive provides the time the cell started, the time the cell deceased, the maximum supercell severity rating assigned, the maximum wind gust severity rating assigned, the highest probability of large hail assigned, and the location where the cell started in xy and geographic co-ordinates (Figure 21).

A storm cell need not be severe to be tracked by RDSS, but it must demonstrate that it has potential to become a severe storm. Because a storm is tracked despite its severity level, hundreds of cells may be archived in a short period of time with the bulk of the cells being non-severe. Environment Canada is interested primarily in storm cells achieving a minimum severity rating of two and those demonstrating a minimum hail potential of 50. Therefore, cells not demonstrating EC's minimum requirements must be filtered from the storm cells of interest. This was achieved by importing the "cell_ends.log" file into a spreadsheet application and sorting the data according to date, time, severity level, and hail potential (RDSS technical Manual). Following this procedure allows for a better visual representation of the severity and temporal

Microsoft Excel - Cell_Ends Log

Arial 9 97%

F1 CST TIME/DATE START

5/3/99 15:45	5/3/99 16:55	1:10	SC0	WG3	HP90	49	39	3"	97	34'	47"	0	1
5/3/99 15:55	5/3/99 16:20	0:25	SC0	WG2	HP50	49	39	39"	97	26'	47"	0	1
5/3/99 16:05	5/3/99 18:30	2:25	SC2	WG3	HP90	47	54'	40"	94	51'	10"	1	1
5/3/99 16:20	5/3/99 18:10	1:50	SC0	WG0	HP90	47	55'	40"	94	24'	24"	0	0
5/3/99 16:45	5/3/99 17:45	1:00	SC0	WG3	HP90	50	33'	32"	97	35'	57"	0	1
5/3/99 17:05	5/3/99 17:35	0:30	SC0	WG2	HP90	50	21'	12"	97	17'	15"	0	1
5/3/99 17.05	5/3/99 17.20	0:15	SC0	WG2	HP0	50	16'	10"	97	39'	19"	0	1
5/3/99 17:15	5/3/99 20:00	2:45	SC1	WG3	HP90	49	58'	42"	97	33'	1"	0	1
5/3/99 17:20	5/3/99 19:35	2:15	SC3	WG3	HP90	48	59'	15"	96	17'	49"	1	1
5/3/99 17:30	5/3/99 19:40	2:10	SC2	WG3	HP90	48	6'	45"	95	10'	17"	1	1
5/3/99 17:35	5/3/99 19:15	1:40	SC0	WG3	HP90	50	34'	58"	97	7'	42"	0	1
5/3/99 18:00	5/3/99 18:40	0:40	SC1	WG3	HP90	49	10'	50"	94	34'	6"	0	1
5/3/99 18:05	5/3/99 19:15	1:10	SC1	WG3	HP90	48	37'	26"	97	6'	56"	0	1
5/3/99 18:25	5/3/99 22:05	3:40	SC3	WG3	HP90	50	9'	9"	97	17'	44"	1	1
5/3/99 18:30	5/3/99 18:50	0:20	SC0	WG3	HP90	49	40'	24"	95	59'	40"	0	1
5/3/99 18:30	5/3/99 19:00	0:30	SC0	WG2	HP90	50	25'	5"	96	50'	51"	0	1
5/3/99 18:40	5/3/99 19:40	1:00	SC1	WG3	HP90	49	18'	32"	95	32'	7"	0	1
5/3/99 18:55	5/3/99 19:40	0:45	SC2	WG3	HP90	48	37'	18"	94	52'	55"	1	1
5/3/99 19:00	5/3/99 19:20	0:20	SC0	WG3	HP90	49	5'	52"	96	50'	15"	0	1
5/3/99 19:05	5/3/99 19:35	0:30	SC0	WG3	HP90	49	37'	45"	96	35'	22"	0	1
5/3/99 19:15	5/3/99 20:20	1:05	SC1	WG3	HP90	51	8'	39"	96	26'	27"	0	1
5/3/99 19:15	5/3/99 19:30	0:15	SC0	WG3	HP0	49	30'	48"	96	35'	41"	0	1
5/3/99 19:15	5/3/99 19:30	0:15	SC0	WG2	HP90	50	51'	3"	96	50'	11"	0	1

Cell_Ends

Figure 21: Event log imported into Microsoft Excel (Cell_Ends.Log) Note: provides information on severity levels and spatial location. Spatial location is separated into Degrees (D), Minutes (M), and Seconds (S).

characteristics of the cells. But benign cells may still characterize a portion of the database despite the removal of those not meeting severity level requirements.

Anomalous propagation is a problem often encountered when dealing with radar return archived data. Anomalous propagation occurs when radar waves are refracted either towards or away from the earth depending on the density of the atmosphere. When radar waves are refracted towards the earth they return and are sometimes interpreted as severe thunderstorm cells. When a radar transmits energy, targets on the ground, such as buildings, trees, cars, or other objects, may intercept part of it. The returned signals from these objects is called "ground clutter". Due to anomalous propagation many of the cells in the archive view demonstrate the minimum severity requirements but do not demonstrate other common characteristics of severe storm cells. Returns in the matched cell archive that are indicative of "ground clutter" are removed from the database

In summary, to remove cells not characteristic of severe storm cells, the following was done:

1. Matched cell archive was imported into a database application (Microsoft Excel 2000).
2. Cells were sorted according to severity level, duration, date and time.
3. Cells not meeting the minimum severity requirements were removed.
4. Cells with a duration of zero to five minutes were also deleted (severe storm cell last longer than five minutes on average).
5. Cells with a spatial location in Ontario, the United States, or in areas of extremely low population densities were removed.

Upon completion of this operation, the remaining cells can then be examined using the RDSS user interface.

3.2 On-screen Radar Volume Scan Analysis

Upon the examination and exclusion of cells detected by RDSS that failed to meet the examination criteria, we are left with cells which are worthy of further examination. The completion of the previous step allows the progression from the examination of the "cell_ends.log" database to the interaction with the RDSS user interface. The following section will concentrate on the use of on-screen visual observation of the detected storm cells, and the steps required to analyze this information and proceed to the "surface validation" process.

The first step required to use the RDSS user interface is to load the RDSS archived view program. This application allows the user to gain access to historical radar data catalogued by the RDSS. The user is prompted for such information as: 1) the radar range of interest, 2) the starting date and time of the storm cell, 3) the end date and time of the storm cell, 3) and the method the user would prefer the system to analyze the archived data (manual or automatic).

After this information is accepted by RDSS, it begins a "volume scan" of the data of interest, and consequently presents the information visually, allowing the user to interact with, and analyze the available information. When the RDSS client is started up, the first window displayed is the "Main Window" (Figure 22).

The RDSS Main Radar View is the section of the main window most important to the verification exercise. This feature is the most useful, because it gives an overview of

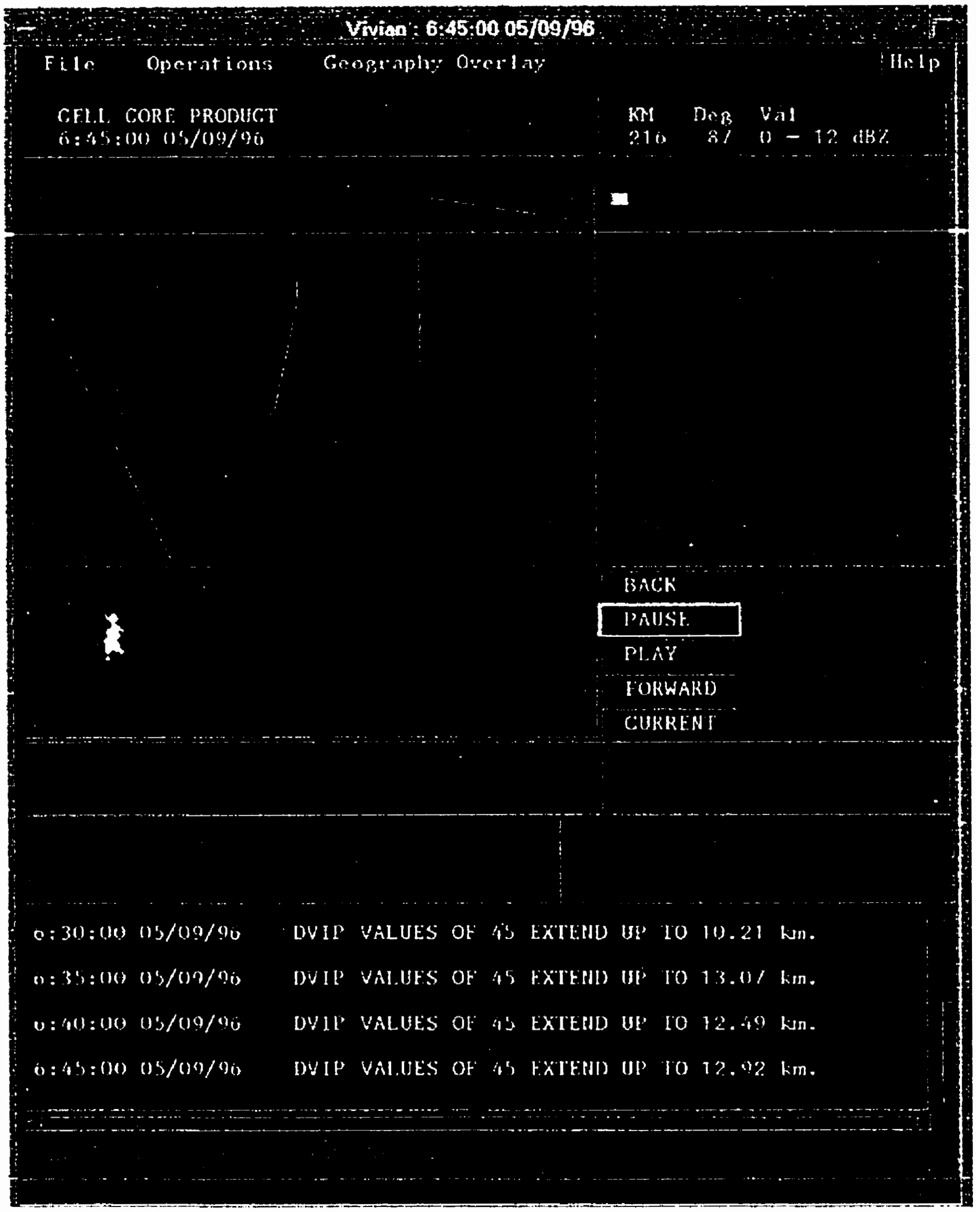

Figure 22: RDSS main window. Note: Section depicting storm cell and geographic overlay is the main radar view.

all other image products. The Main Radar View of the RDSS Main Window was used as the central control panel for the spatial analysis of severe storm cells within a radar space. One important feature in the Main Radar View was the cursor position and value display. The cursor position and value display area were used to display the location of the storm cell respective to the Vivian radar station location. Data are offered in a distance and degree format. When a cell of sufficient severity was located, and brought up on the Main Radar View, the cursor was placed on the cell boundary and the range values (km, degrees) were noted. Generally the progression of a sufficiently severe storm cell could be viewed as an animation and important range values would consequently be recorded for each frame in the animation.

To attain more detail or the current spatial location and reflectivity characteristics of the cell, the user can simply "click" on the cell of interest in the main radar view. A more detailed view of the cell is then made available. If the RDSS algorithm characterizes the cell as having downburst potential, then the Wind Gust View will open (Figure 23). If the cell is characterized by reflectivities indicative of a supercell, then the supercell window will open (Figure 24).

3.3 Surface Validation Procedure

One of the most important aspects of verifying severe weather events is the planning of the surface validation exercise. Hours, if not days can be saved through the careful planning of this step. When a severe storm cell is identified by the RDSS event log, and is brought up on the user interface, it must be tracked from the point of origin to the point of its expiration. These points are then be entered into a GIS environment and visually

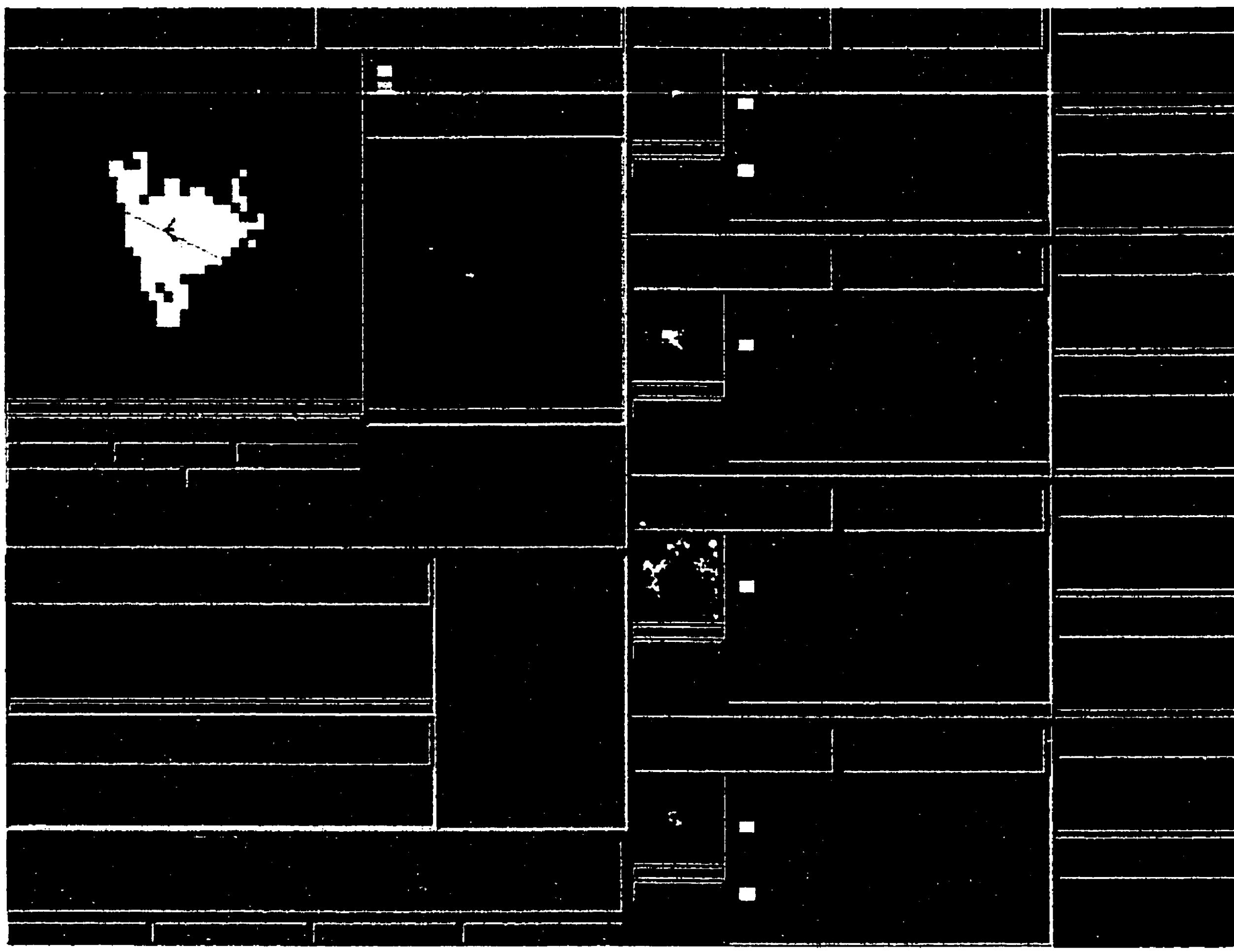

Figure 23: Wind-gust potential screen. Note: Provides information to meteorologist on VIL, BWER, max-R height, wind gust potential, and echo top.

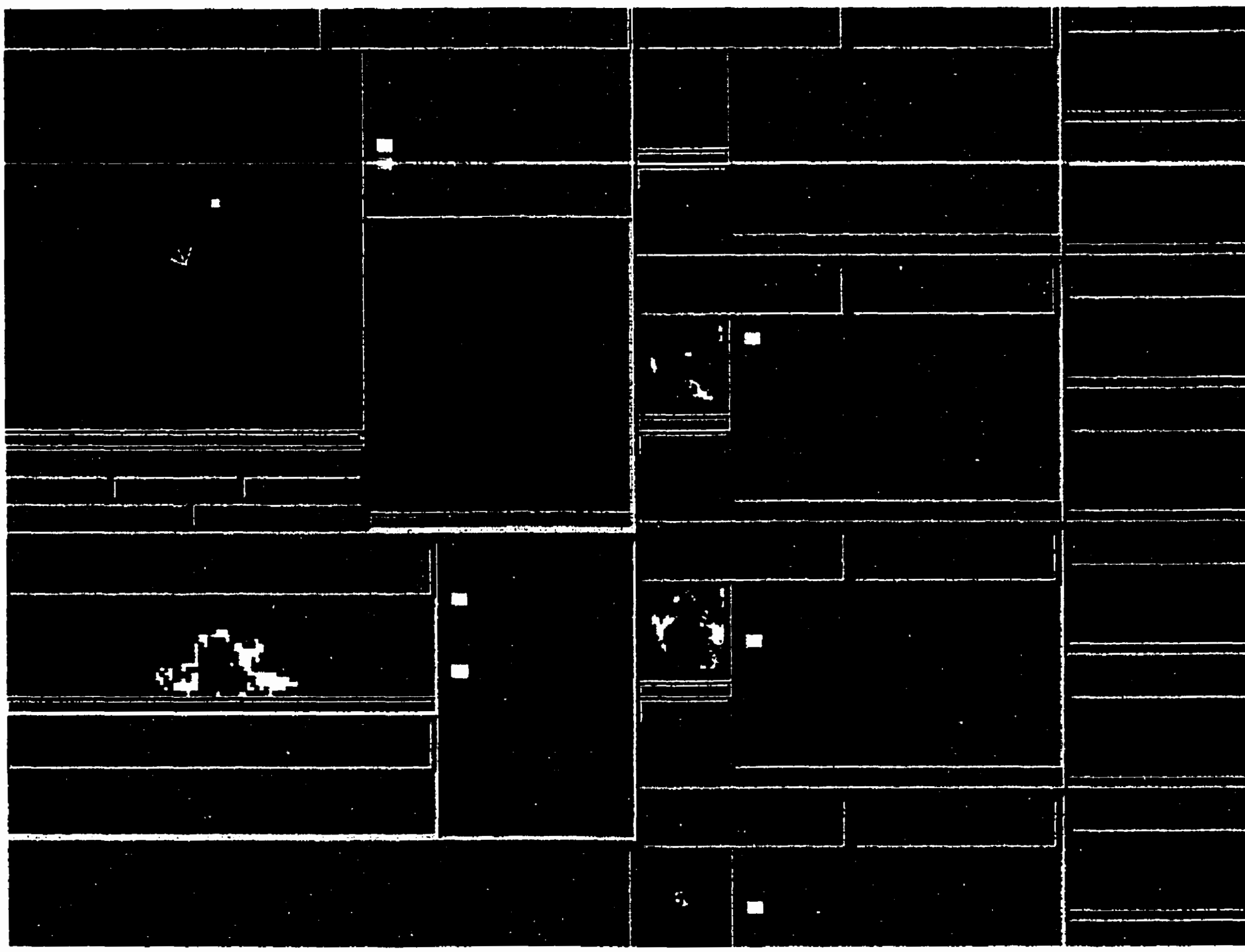

Figure 24: Supercell assessment screen: Note: Provides information to the meteorologist on VIL, gradient, overhang/BWER, and spatial location of cell.

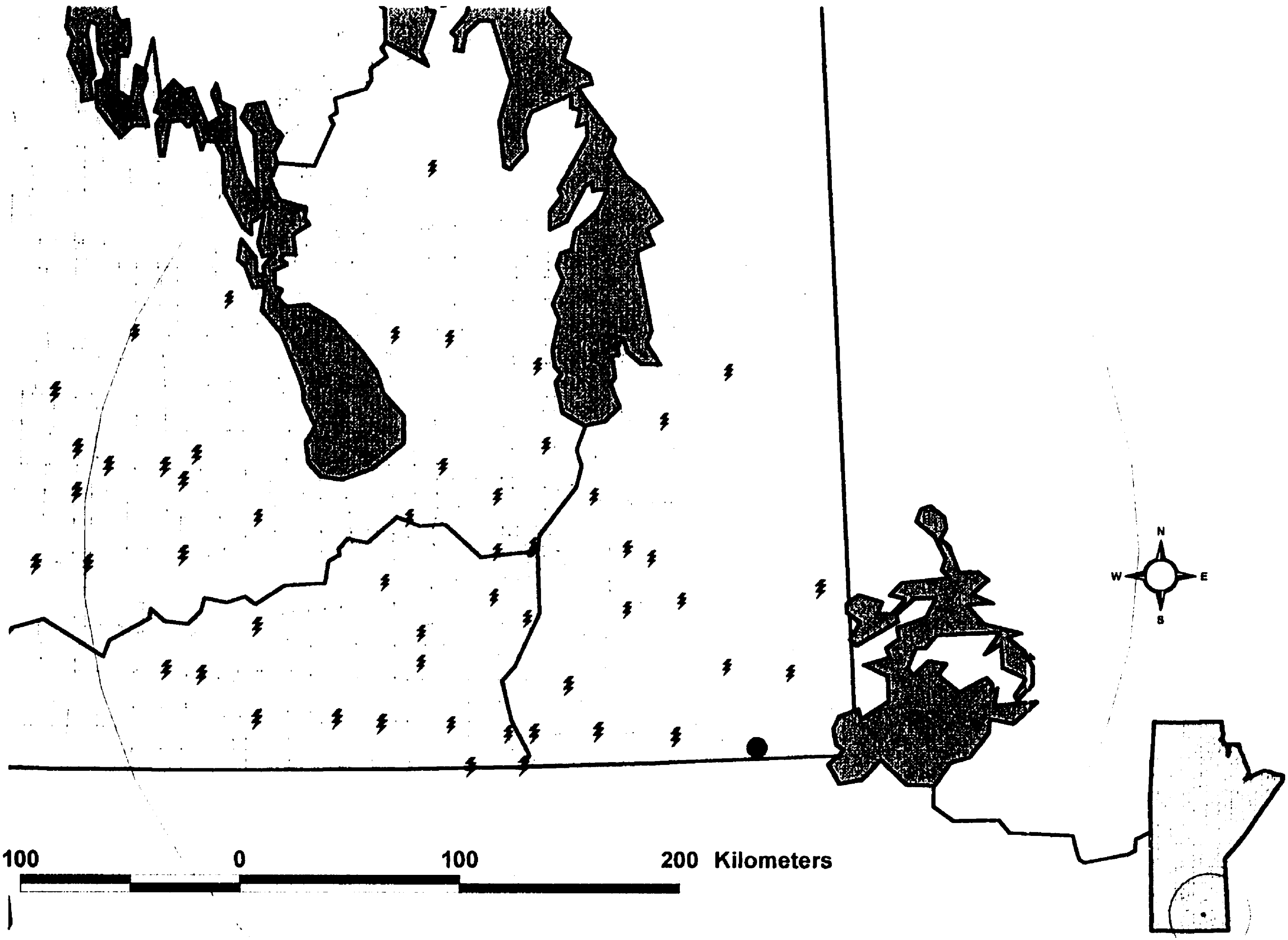

Figure 25: RDSS storm locations georefernced into a Geographic Information System (GIS)

depicted along with towns, rivers, lakes, land class and population density (Figure 25). A visual representation of the storm track, along with its spatial location relative to terrain not conducive to human habitation, allows the elimination of areas from the surface validation procedures.

Once all cells that are not conducive to the study are removed, the trip can be planned in a fashion that would allow for the most interviews in the shortest amount of time. Figure 25 illustrates how a RDSS radar animation can be georeferenced into a GIS environment to aid in planning of the surface validation exercise.

The Interview Questionnaire

The primary goal of the questionnaire was to provide surface validation of severe weather events, determined by RDSS to have passed over the interviewees' location, as well as subjective suggestions, complaints, and anecdotes concerning Environment Canada's summer severe weather warning dissemination techniques.

Before the project could be initiated, the questionnaire was subject to the Natural Resources Institute's Ethical Review Process. The ethical review is designed to ensure that the questionnaire conforms to acceptable standards for scientific research and is ethically sound.

The criteria used to select which individuals were to participate in the RDSS study were as follows:

1) the individual's residence is located in the immediate vicinity of the detected severe weather event are identified,

2) individuals present at their residence during the severe weather event. If there was more than one person at the residence, the group was interviewed, or an individual could represent the group.

3.4 Questionnaire

The questionnaire (Appendix A) produced information on the time and date of the event, the observed severity of the event, and subjective views and perceptions respondents hold of severe weather and aspects of Environment Canada.

The respondents were led through a logical series of questions beginning with simple closed-ended questions concerning the severity of the event, to open-ended questions concerning experiences, observations and opinions. The closed-ended questions were important in the verification of RDSS algorithms, while the open-ended questions provided important information on personal observations and exposure to severe weather experiences.

The closed-ended questions were adapted from the Environment Canada severe weather report forms used in the meteorological office during the convective season. Questions were quantitative in this section, focusing on weather observations and measurements such as hail size (mm) and wind speed (km/hr). The second part of the questionnaire used open-ended questions that allowed respondents to express their opinions on certain subjects. The main objective of this section was to document the views and perceptions Manitoba residents had of severe weather and of Environment Canada's severe weather dissemination techniques. Following a model used in a similar study (Clyde, 1981), questions proceeded from factual questions to questions requiring opinions and thought.

The first version on the questionnaire was pre-tested on colleagues in an effort to remove any ambiguous questions that may mislead the respondent. Modifications were made to the question format, resulting in a final questionnaire ready for distribution.

The responses to the questionnaire were digitized and results were generated and are presented in the results sections. The answers to the closed-ended questions were digitized and analyzed and tables and graphs were generated.

3.5 Data Analysis

The Probability of Detection (POD), false alarm ratios (FAR) and credibility (CRED) will be deciphered for each verification technique using a 2X2 contingency table. The Probability of Detection (POD) is a verification measure of forecast performance equal to the total number of correct event forecasts (hits) divided by the total number of events observed. Simply stated, it is the percent of events that are forecast. FAR is the percent of events that are forecast by RDSS but do not occur. The credibility is a measure which indicates the likelihood that a RDSS detection will make a reliable forecast. The following formulas will be used, and the resultant information will be arranged in a contingency table similar to Table 4.

POD = Probability of Detection = $x / (x + y)$ and

FAR = False Alarm Ratio = $z / (z + x)$, where

CRED = Credibility = $1 - FAR = x / (x+z)$

x represents correct Severe Thunderstorm (STS) forecasts or "hits",

y represents unverified STS forecasts, or "misses"; and

z represents "false alarm STS detection's" (Alfrod, 1998)

Table 4: Adapted from Alfrod, 1998

	RDSS severe weather forecast (yellow-red)	No RDSS severe weather forecast	
Severe Weather observed in verifying area	x (RDSS forecast hits)	y (RDSS forecast misses)	**POD =Probability of Detection = x / (x + y)**
No severe weather observed in verifying area	z (RDSS unverified forecast)	n_{ts} (difficult correct null detection)	**FAR = False Alarm Ratio = z/ (x + z) CRED = 1-FAR = x / (x+z)**

The "X" table entry is the number of event forecasts that correspond to event observations, or the number of hits; entry "Y" is the number of event forecasts that do not correspond to observed events, or the number of false alarms; entry "Z" is the number of no-event forecasts corresponding to observed events, or the number of misses; and entry "N" is the number of no-event forecasts corresponding to no events observed, or the number of correct rejections. Alfrod's modified POD/FAR table (Table 4), the utility of each verification technique will be determined with subsequent recommendations for each. The credibility (CRED) of the measure is of particular interest to the operational meteorologist. This calculation indicates the prospect of a correct RDSS forecast in a particular situation. If the credibility of the forecast is low, the operational meteorologist may delay on putting out a warning. Conversely, if the credibility of the RDSS forecast is high, the meteorologist may decide to immediately put out a warning. Credibility is inversely correlated to FAR, thus as the credibility of RDSS forecasts increased, the FAR decreases. The POD and FAR are important to the public, on account of the need for of accurate warnings. If the POD is high and the FAR is high, then issued warnings would hold little use to the public. On the other hand, if the POD is high and the FAR is low, then the public would have more confidence in the weather warnings.

Upon completion of the data collection, the quantitative database of information collected will be examined by the field researcher and the performance of the RDSS and verification techniques will be determined. As well, the qualitative information collected will also be analyzed. Both quantitative and qualitative data will be used to provide recommendations for improvements in EC's severe weather warning system. An interim report was also prepared outlining the preliminary discoveries and performance characteristics of the RDSS algorithms and validation techniques.

4 Results and Discussion

4.1 RDSS Severe Weather Forecast Results

4.1.1 Introduction

The severe weather detection algorithms were evaluated in terms of their ability to detect severe wind, hail, and tornadic events. Although hundreds of cells were tracked across the prairies, those events falling within the Vivian Radar Range in southern Manitoba were used as the dataset of concentration.

In this section the Probability of Detection (POD), False Alarm Ratio (FAR) and Credibility (1-FAR) were computed for the Hail Probability Algorithm (HPA), the Wind Gust Detection Algorithm, and the Supercell Automatic Severity Rating. It is important that these values are computed correctly due to the nature of severe weather meteorology. The HPA was assessed in detail through the use of two value thresholds. The relationship between the probability of detecting severe hail and the size of hail observed was also examined. As well, the Supercell Automatic Severity Rating was examined in terms of its relationship to the occurrence of severe weather such as wind and hail. Furthermore, tornadic events were examined in terms of their association with RDSS Supercell and Windgust automatic severity ratings. Through the examination of the results, recommendations were made to improve the validity and reliability of the RDSS's severe weather detection algorithms.

Environment Canada considers a storm to be "severe" if any of the following are associated with the event;

a) Surface winds greater than 90km/hr, approximately 50 knots;
b) Hail diameter of 20mm, about ¾ of an inch;
c) Rainfall accumulation rate greater than 50mm/hr or 75mm over three hours.
d) One or more tornado or waterspout.

These conditions are directly observed at meteorological recording sites or reported by weather watchers. It is common practice to use evidence of damage related to severe weather to estimate the intensity of the event (EC, 1982)

RDSS Severe Hail Forecasting Results

Numerous large hail events (hail 20mm in diameter or more) were studied across the range of the Vivian radar during the summer of 1999. The RDSS Hail Probability Algorithm (HPA) uses a straightforward comparison of Vertically Integrated Liquid (VIL) density values against threshold values. The thresholds for 50% and 90% probability of hail were examined through the comparison of RDSS forecasts and validated severe hail events. Due to the small sample size for the 50% threshold, it would not provide any significant information thus it has been removed from the analysis. It was found that for this verification exercise, useful relationships could be obtained when a range of possible thresholds, from low to high is examined. Previously, dime sized hail (18mm) was considered to be "severe" by Environment Canada but this definition has since been changed to 20mm. With this in mind, the analysis was done twice, with the threshold for severe hail set at 18mm (dime), and 20mm respectively.

Currently there are two value thresholds used by the RDSS. The first threshold (A) is associated with a 50% probability of large hail, while the second threshold (B) is associated with a 90% probability of large hail. If RDSS detects a VIL density value of

Table 5: RDSS Hail Potential 90 forecasts and their surface validation statistics. HP90 uses a VIL density of 4.0 g/ m^3 as the value threshold.

		RDSS Hail Potential 90	
		Yes	No
Reported severe hail occurrence at surface	yes	13	35
	no	16	*

Table 6: Performance results of the HP90 threshold.

	POD	CRED
HP90 Performance	45%	27%

Table 7: RDSS forecast statistics for incremental hail size.

	18mm-20mm (dime)	20mm-22mm (EC threshold)	22mm-26mm (nickel)	26mm-38mm (quarter)	38mm +
X= hits	16	13	13	9	4
Y =misses	12	11	11	10	2
Z= false alarms	19	19	2	4	1
POD	57%	54%	54%	47%	67%
CRED	46%	41%	87%	69%	80%

3.5 g/m^3 in a cell, then the condition for threshold A is met, and if RDSS detects a VIL density of 4.0 $g/^3$ or greater, then the condition for threshold B is met.

Cells examined exhibiting the RDSS HPA conditions for a 90% probability of severe hail (n=29), disclosed a POD of 45% and a CRED of 27% (Figure 26; Table 6).

The sensitivity of the HPA was examined through the use of incremental hail size and the POD and CRED associated with this size increase (Figure 27; Table 7). From the data it is not clear that any trend exists. As hail size increases, the probability of detection remains fairly constant until the larger (38mm and larger) are considered. The POD at hail size 18mm is 57%, as hail size increases to 38mm (ping-pong ball), the POD increases to 67% (Table 7, Figure 27). These results are not surprising considering a large amount of work has been done develop methods that may better predict severe hail occurrence, but there has yet to be an extremely reliable one.

As a supplement, the POD and CRED of former EC criteria for severe hail (18 mm), was compared to current criteria (20 mm) using the 90% probability of hail data (Figure 27. When using previous EC severe hail criteria, the POD is 57%; the CRED is 46%. When current EC severe hail criteria are examined, the POD remains constant at 54%, with CRED decreasing slightly from 46% to 41%. But when 20 mm hail is compared to 22 mm hail there is a large increase in CRED, from 41% to 87%. This is an interesting result that warrants further examination due to its possible ramifications on future severe hail size.

RDSS Severe Wind Forecasts

During the summer storm season, RDSS detected many storms meeting the criteria necessary to produce severe wind gusts. Within RDSS, Wind Gust Potential (WGP) is a measure of the maximum downdraft that can occur in a pulse type thunderstorm as a result of cloud top penetrative downdrafts. RDSS provides an automatic severity rating for storms based on characteristics that can be associated with wind gusts. Severity level one indicates that the storm has the potential to create moderate wind gust if part of the cell core were to descend. The wind speed threshold is 60 km/hr for severity level one. Severity levels two and three both have a wind speed threshold of 90 km/hr, the difference being that severity level three must meet three of four wind gust conditions (Table 8). For the purposes of this study, only severity levels 2 and 3 will be considered.

Verifying actual wind speeds proved to be challenging during this project. Assessing property damage and observer reports added an obvious subjective variable to the project. Because of these challenges, and because wind measurements are not generally available, algorithm performance was related to the physical damage observed at the site. Using EC's wind damage requirements, assessments were made based on damage done to trees and structures that met the expected damage due to 90km/hr winds. Despite these limitations, the wind gust detection algorithm displayed a high probability of detecting damaging wind gusts. The probability of detecting severity level three wind gusts (>90km/hr) was the highest of the three detection algorithms at 95%, the CRED was also the highest with a value of 91% (Table 8).

Supercell Assessment

RDSS provides an automatic severity rating for storms based on supercell characteristics. Severity level one (green) indicates that the storm is large but lacks the structural characteristics of a really severe storm or that it potentially has structure, but lacks size. Level two (Yellow) indicates that the storm is large and potentially has structure indicating a more severe storm. Level three (Red) indicates that there is a significantly large Bounded Weather Echo Region (BWER) in the storm. This indicates a tendency towards very strong updrafts, which is often associated with the worst kind of storms. For the purposes of this study, the supercell severity ratings were examined in terms of their relation to severe weather events such as damaging wind, and severe hail.

In this section of the study, the POD and FAR will be calculated in terms of the supercell's severity rating and its relationship to severe wind/hail or tornadic events (Table 10). If the supercell severity level reached two or higher along with a minimum hail potential rating of 50 and/or a minimum wind gust severity two, then it was considered a correct detection (hit). If the supercell severity rating reached two or higher without any associated severe weather events, then it was considered a false detection (miss). Using these criteria, the probability detecting a supercell associated

Table 8: POD/FAR and credibility of RDSS wind detection algorithms.

		RDSS Supercell Severity 2/3 Forecast		
		POD	FAR	CRED
RDSS Severity Level	2	58%	42%	58%
	3	95%	9%	91%

Table 9: RDSS Supercell Forecasts and their association with observed events.

		RDSS Severe Supercell Forecast	
		Yes	No
Reported Severe Weather?	Yes	56	68
	No	28	*

Table 10: POD and CRED values for RDSS cells associated with any severe weather phenomenon (hail, wind, and tornado).

	POD	CRED
RDSS Severe Weather (Hail, Wind, Tornado)	45%	62%

Table 11: Statistics for tornadic events and correct RDSS forecasts using Wind Gust and Supercell severity levels two and three.

		RDSS Level 2, 3	
		Yes	No
Reported Tornadic Event	Yes	6	4
	No	*	*
	POD	60%	

with severe weather is 45%, and the CRED is 67% (Table 10). It should be qualified that the frequency of storms with a supercell severity level of two made up 80% of the total sample. Of the storms chosen for verification, only two had a severity level of three.

Tornado Detection

In the summer of 1999, several funnel clouds and tornadoes were observed. As a supplement to the previous data interpretations, it was also of interest to determine if the occurrence of tornadoes or funnel clouds were related to any RDSS severe weather detections. As a preface to any data interpretation, it must be qualified that the frequencies of occurrences of tornado or funnel cloud observations were low. Of the many observer reports about severe weather, only ten reports of tornadoes or funnel clouds were within the Vivian Radar range (Table 11).

Of the ten reports, four were not associated with any RDSS severe weather detection, but three of the four tornado producing cells were tracked by RDSS. A cell that is tracked may not have the components to be considered "severe", but it may have achieved an intensity level that warrants the attention of an operational meteorologist. Tornadic cells are occasionally not particularly intense, funnels and waterspouts can develop from cumulus clouds. The remaining six observations were associated with a wind gust severity level three, and a supercell severity level two (Table 11).

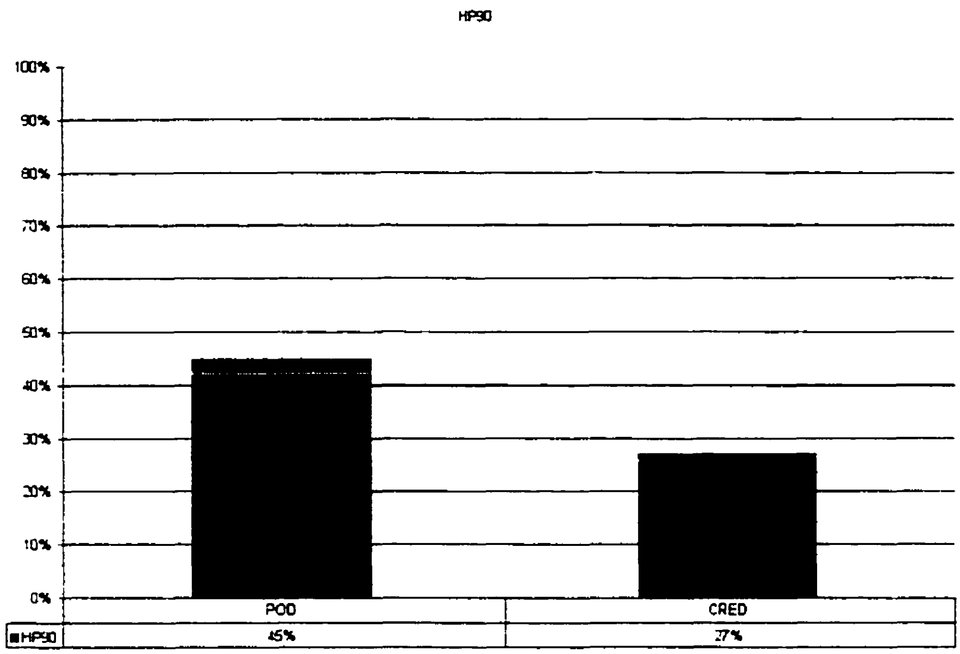

Figure 26: POD and CRED of detecting severe hail using VIL density thresholds. HP50 uses 3.5g/m^3 and HP90 uses 4.0g/m^3.

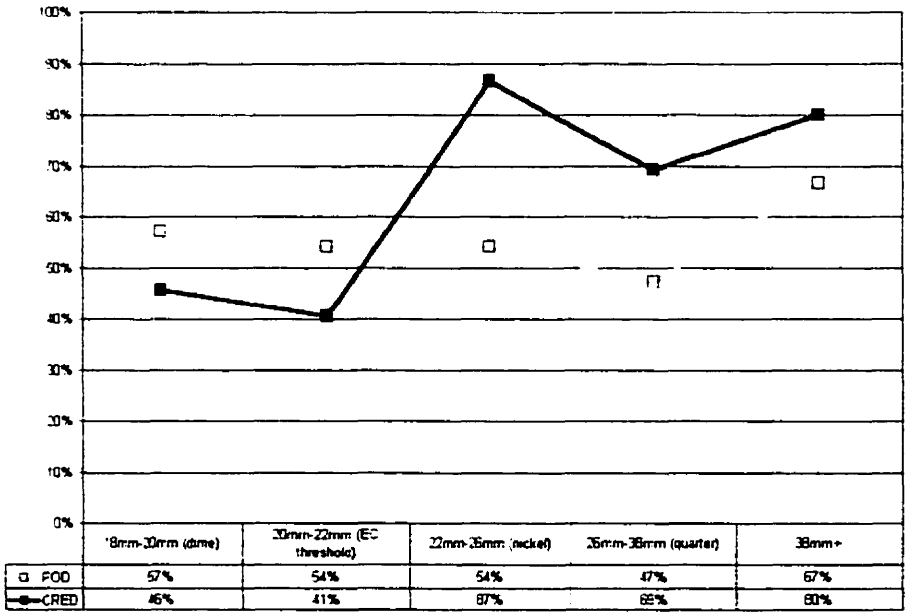

Figure 27: Depiction of POD and CRED values with incremental hail size. Note: Values calculated using VIL density of 4.0g/m^3.

4.2 Questionnaire Results

This section introduces the results of the questionnaire survey and reports the perceptions of the relative importance of the three severe weather hazards in question (hail, wind, tornadoes), to farmers. As well this section reports farmers use of severe weather warnings, their perception of the dissemination techniques, and their observations of apparent changes in weather patterns.

Relative Importance of Hail, Wind, Rain, and Tornado to Farmers

Table 12 shows that of 229 respondents, 64 viewed hail as the most damaging to crops and this exceeds that of any other severe weather occurrence. 58 of the respondents viewed rain as the second most damaging to crops, and 31 viewed wind as the most damaging. Interestingly, the option for "other" hazards was the highest at 76. When asked what the "other" severe event was, almost all respondents responded with "standing water". In hindsight, this would appear to be a logical answer considering much of southeastern Manitoba was flooded past the maximum seeding date during the spring and summer of 97.

Table 13 addresses flooding and standing water more effectively than Table 12 due in part to the separation of flooding and severe weather. This question addresses the main disadvantages farmers have of farming in southern Manitoba. Respondents in southern Manitoba found flooding to be the biggest disadvantage, with 104 (45%) respondents. Second to flooding, farmers found frost to be the next largest disadvantage (24%), with severe weather coming next with 19 respondents.

Table 12: What do you perceive as the greatest hazard to your crops? Note: This question inquires as to the hazard that affects the crops the most, in terms of damaging affects.

Greatest Hazard	Number of Responses
Hail	64
Wind	31
Rain	58
Tornado	0
Other	76
Total	229

Table 13: Main disadvantages of farming in southern Manitoba as perceived by respondents.

Disadvantage	Number of Responses
Too Dry	21
Frost	56
Floods (Standing water)	104
Insects	10
Severe Weather	19
Others	20

Table 14: Main disadvantages of farming in southeastern Saskatchewan as perceived by respondents. Source: Questionnaire Survey, 1978.

Disadvantage	Number of Responses
Too Dry	134
Frost	85
Floods	33
Insects	23
Severe Weather	19
Others	68

Table 15: Has water been a more frequent problem in the 1990's than previous decades?

Responses	Number of Responses
Yes	161
No	38
Do not Know	29

The prevailing anomalous weather appears to have an extremely large impact on the respondents. In a previous farmer perception study conducted by Clyde in 1981, Saskatchewan farmers perceived drought as the greatest disadvantage to farming in Saskatchewan (Table 14). Southern Manitoba springs have been characterized as wet from 1997 (IJC, 2000), with predominant flooding and standing water. During the Saskatchewan farmer study, standing water and flooding was not a significant factor in the late 70's. Excess water was a significant factor in the mid-70's (Clyde, 1981), and the results may have been different, had the study been conducted at this time.

Drought in fact was the experience of many Saskatchewan farmers in 1977-1980, and these memories may have been fresh in the minds of the respondents (Table 14). When we compare the Manitoba study to the Saskatchewan study, we can see that the prevailing weather conditions were different, which may have led to the differing opinions. As mentioned earlier, questioning these data is very important. Why have farmers changed in their views concerning disadvantages to farming?

- Weather conditions are different during both of the studies in question. The prevailing weather conditions could be characterized as wet during the Manitoba study, and dry during the Saskatchewan study.
- Farmers from different geographic locations may have different views and perceptions based on environmental, cultural, or economic factors.

Hail

This section is an attempt to determine the respondents' experience and perceptions of hail as a hazard in southern Manitoba. Property damage due to hail varies from year to year, but is estimated that it accounts for nine percent of the annual Canadian total property damage (LaDochy, 1985). Although hail events do account for property damage, the reason why severe weather is not reported more frequently continues to be of interest to Environment Canada (McCarthy, 1999). In previous studies, it appeared that many respondents were not reporting the occurrence of a "few" hailstones as 'hailfall' (Clyde, 1981). In order to gain information on the experience and opinions of the respondent, numerous questions were included in the questionnaire.

1. What they consider to be a "hailstorm".
2. Why they choose to report or not report a particular hail event.
3. If they perceive the frequency of hailstorms in the 1990's to be higher or lower than in previous decades. (In view of the attention paid to climate change over the previous decades, the perceived frequency of severe hailstorms is also of interest).

The first question asks respondents how they define a severe hailstorm. Modeled after a question in the Clyde (1981) study, the objective was to gain insight into the reason why farmers fail to report severe hail. Respondents tended to consider a storm benign unless damage occurred to property and crop. Of the 229 respondents only three considered a hailstorm to consist of a few hailstones. As the severity of the hailfall increases, so does the percentage of farm operators who consider it a "hailstorm". 118 of 229 respondents considered it a hailstorm if the ground was covered, while 104 (45%) considered it a hailstorm if buildings were damaged. When crop-loss was used as the defining variable, 111 of the 229 (48%) respondents considered it to be a severe hailstorm (Table 16). This is interesting in that it shows the importance of the crop to the farmer. The number of responses dropped off for the remaining options (Table 16). The results of the question pertaining to the instance of hail being a more frequent occurrence in most recent decade, than decades before revealed some interesting results. In Clyde (1981), the majority of respondents (67.4%) felt that hailstorms were not more frequent in the 1970's than in previous decades. In this study, 87 of 229 (38%) respondents felt that severe hail was a more frequent occurrence in the 1990's than in previous decades (Table 17). The last national hail climatology of Canada was based upon the 1951–1980 time period. From 1977 to 1993, many more stations reported days with hail than prior to 1977. However, Manitoba stations reported a slight decrease in average hail days from 1977 to 1993 (Figure 28). The reliability of this hail data is questionable due to the differing collection methods over the previous fifty years. Unfortunately, after 1993 the observing network began to be replaced by automatic stations that do not report hail, and therefore an analysis can only effectively use the time period of 1977–1993.

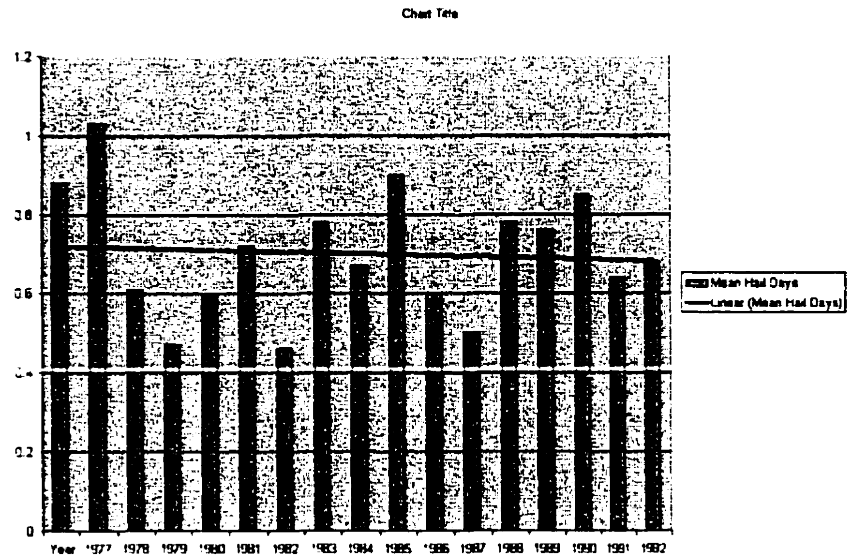

Figure 28: Average Manitoba hail frequency. Only stations with a full period of record were used, in order to create a homogeneous data series. Note that these numbers do not represent average hail frequencies for the province, but only of the available stations.

Table 16: What do you consider a hailstorm to be? Note: Columns one and two are grouped as one set of options and column two and three are grouped as second set of options (respondents answer once for each set).

Parameter	Number of Responses	Parameter	Number of Responses
A few hailstones	3	1-30% crop damage	111
Ground covered by hail	118	30-70% damage	78
Buildings damaged	104	70-90% damage	29
Hail fell, but no crop loss	4	100% damage	12

Table 17: Has hail been a more frequent problem in the 1990's than in previous decades?

Responses	Number of Responses
Yes	87
No	65
Do not Know	77

Wind

Even though most respondents had just experienced a severe wind event in the previous 24 hours, the majority did not feel that wind events were more prevalent in the 1990's (Table 18). This is interesting due to the results obtained with severe hail events. Using White's (1974) guidelines it can be understood that perhaps farmer perceptions were not modified by the wind event, because of minimal monetary loss.

When addressing wind damage, 51% of respondents felt that severe wind damage had not increased in the most recent decade over previous decades. When asked if tornadoes were a more frequent occurrence in the most recent decade than in previous decades, the great majority of respondents felt that they were not (54%). In addition, a large proportion "did not know" if there had been an increase in tornado activity, but many shared their anecdotes about previous tornado activity (Table 19). Figure 29-34 are some examples of the damage caused by severe weather hazards over the summer of 1999.

When asked what they felt was the greatest threat to crops, the majority (47%) felt that increased amounts of rain is the most threatening. Severe weather, was the second most threatening with 28% of respondents replying (Table 19). Upon examining the Clyde (1981) results along with these, it becomes evident that the farm operators' have certain perceptions based on recent experiences and how those experiences are tied to their livelihoods (White, 1974)

Table 18: Has wind damage been a more frequent problem in the 1990's than in previous decades?

Responses	Number of Responses
Yes	60
No	118
Do not Know	51

Table 19: Have tornadoes been more of a problem in the 1990's than in the past?

Responses	Number of Responses
Yes	12
No	87
Do not Know	63

Figure 29: Hail damage to Canola crop Southwest of Morden Manitoba.

Figure 30: Hemp crop destroyed by hail and strong winds. Southeast of Morden Mb.

Figure 31: Wind damage to Oak tree. Emerson Manitoba

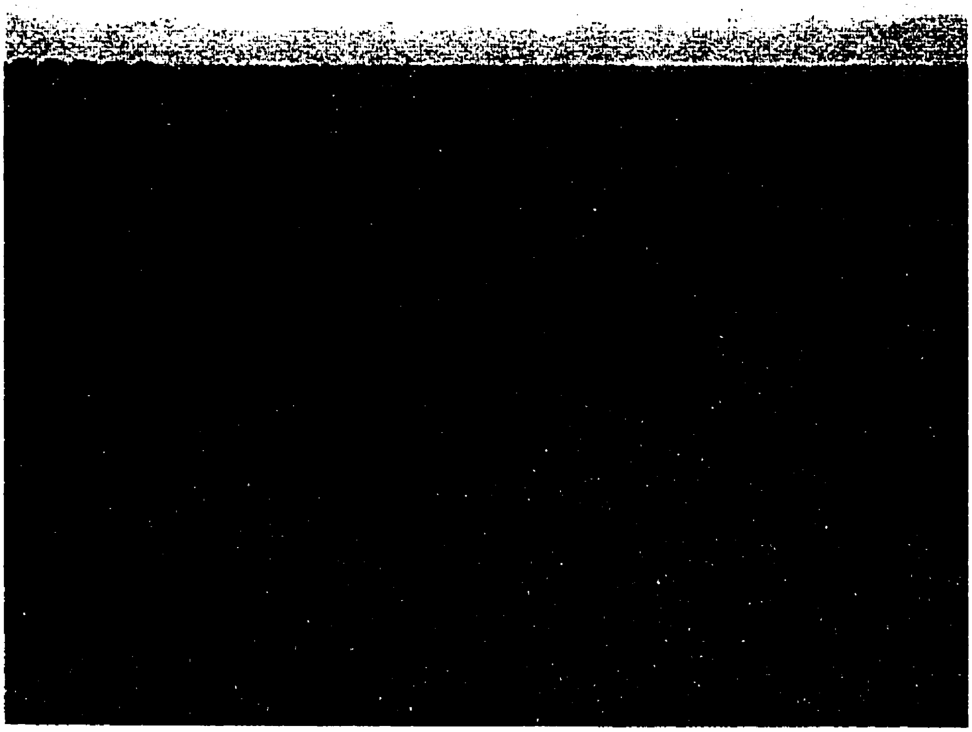

Figure 32: Crops flattened by strong winds. Near Piney, Mb.

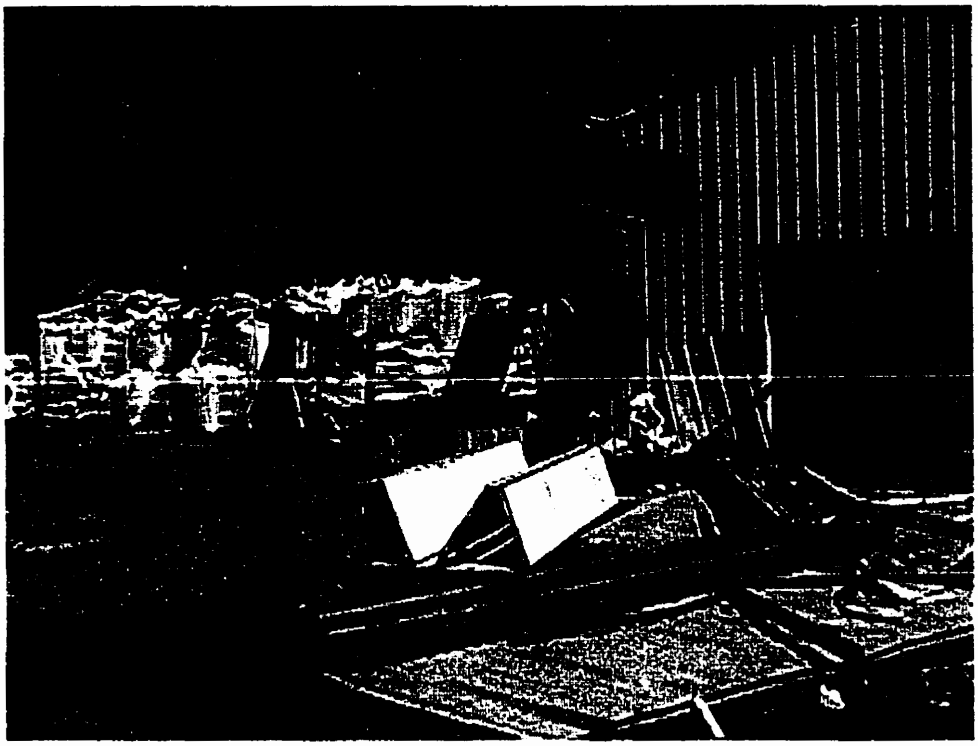

Figure 33: Tornado damage to 1200sq. ft. steel shed. Note: White bags of seed at left of photo were inside shed before shed was destroyed away by the tornado. The shed was found 200 yards away in a field.

Figure 34: 1200 sq ft steel shed dropped 200 yards away from its original position.

When asked how they obtain weather data, there was almost an even split between television and radio (Table 21). Many respondents replied that they do not really have a preference between the television or radio, but all respondents had never used the Internet for severe weather information.

When individuals were asked how they felt about the accuracy of Environment Canada's warning system, most respondents were positive. 122 of 229 (53%) respondents rated the performance of the warning system between satisfactory and excellent. Along with the positive feedback, numerous expressed negative feelings of EC's weather warning dissemination techniques. 108 of 229 (47%) respondents rated the warning performance as poor (Table 22). Evidently from much of the feedback received from respondents, problems may exist in the weather warning system. It must be qualified that many respondents believed EC and the media as a single entity. The negative comments included:

- I often find myself checking the American stations, because EC does not show that weather crosses the border, and that most of the weather begins in Montana.
- I swathed my hay yesterday because the forecast did not mention any chance of rain or a storm, and a huge storm came through and blew all of my rows away. Every day I check the forecast to see if it is a good time to swath, this seemed like a good time, but it was not. Can you do something about this?
- I never check the EC forecast, I always check the US forecasts, because they are usually right, and they have better weather shows. They have little maps showing where the storm is going to hit... I like that.

- I phone my daughter in Winnipeg to tell me about the weather, because the radio station out here is not very good.
- You know, I really get frustrated when I have to wait to find out the weather. You always put the weather at the end of the show. If you guys keep putting the weather at the end of the show, I will put in a complaint.
- I don't know why the government puts any money into projects like this. If there is one thing I know, it is that you can't predict the weather. They are good at giving me the temperature, but they aren't good at predicting storms. If this is what you are doing, then I think you are wasting your time.

The final question asked respondents about their future likelihood to use the Internet in ascertaining weather data (Table 24). Over the past decade, the use of the Internet has increased markedly, especially in areas of information dissemination and e-commerce. Environment Canada has a web site (www.ec.gc.ca), which includes information on current weather conditions and advisories, five-day forecasts and long-term forecasts, allowing Canadians and individuals worldwide to query Canadian weather conditions. Weather warning information is also available, but its use for those in the agricultural community is questionable. When asked if they will use the Internet for weather information in the future, 64 respondents said yes, 24 said no and 141 did not know (Table 24). Although not an overwhelming majority, 30% of farmers suggesting future use of internet weather data may warrant further development of the internet as a warning dissemination technique.

Table 20:What weather phenomenon do you perceive as most threatening to crops in the future?

	Number of Responses
Weather Conditions:	
Changing Climate	4
Severe Weather (more frequent)	65
Increased amounts of rain	107
Increased amounts of snow	44
Heavy run-offs	9

Table 21: How do you obtain weather data?

Method	Number of responses
Television	115
Radio	103
Internet	0
Other	6
Total	224

Table 22: How would you rate the accuracy of Environment Canada's Severe Weather Warnings?

Answer	Number of responses
Excellent	29
Good	47
Satisfactory	46
Poor	79
Terrible	29
Total	229

Table 23: Do you have an Internet connection?

Responses	Number of Responses
Yes	27
No	202

Table 24: Do you see yourself using the Internet for weather information in the future?

Responses	Number of Responses
Yes	64
No	24
Do not Know	141

This result appears promising, considering at the time of the interview only 11% of respondents had Internet connections (Table 23). As rural dial-in servers become more commonplace, allowing rural users the ability to dial in without long-distance charges, the use of the Internet for weather information could be expected to increase.

Some of the responses accompanying the related questions were:

- I didn't even know you could get that kind of information. I still need a computer though.
- I don't have an Internet connection because it is too expensive. We would have to dial into Winnipeg to get the service, and that would cost us long-distance.
- I have a connection, but what is the EC website? I will check it out.

Of the 27 respondents that had an Internet connection, one person had used it for weather related information. Many of the farm operators who had an Internet connection mentioned that they rarely use it, and that it is used almost exclusively by their kids. Figure 35 provides an example of the information provided by US news stations and the National Weather Service. Websites such as that provided by WRAL-TV allow the user to interactively view Doppler radar scans while simultaneously receiving weather-warning information. The EC website also provides the user with a user-friendly display, but does not provide the user with live radar volume scan animations.

Unlike the radar information the NOAA provides free of cost, "real-time" meteorological information is commercialized and unavailable to the Canadian public. Figure 36 is the display the user encounters when querying weather-warning information.

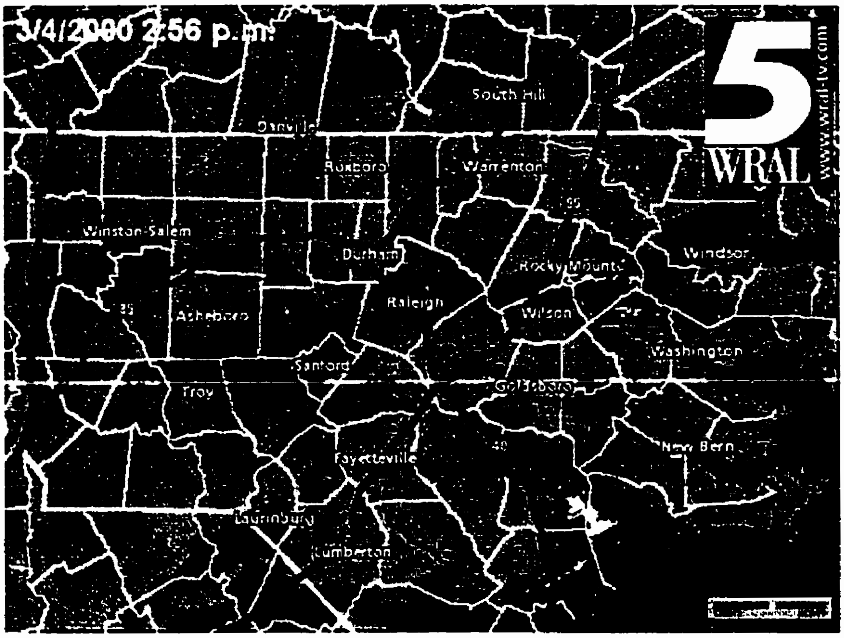

Figure 35: Example of online weather information available in the US. Note: Many news sites provide up to the minute Doppler radar volume scans. (Source: www.wral-tv.com)

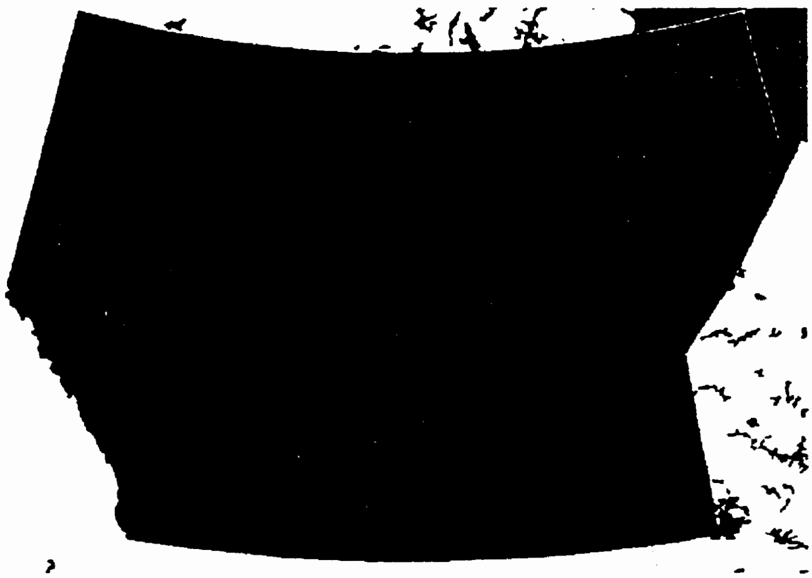

Figure 36: Example of Canadian Online Weather Warning System. Note: Each blue dot represents a warning districtSource: http://www.mb.ec.gc.ca/ENGLISH/WEATHER/WARNINGS/Warnings.html

The user is then prompted to 'click' on the area they are interested in, resulting in a display that lists the warnings for that particular area. Although useful, the coarseness of the map (Figure 36) does not provide a live view of their area of residence. From the interview questionnaire it is evident that farm operators hunger for the availability of live radar scans for their own interpretation. The EC web site is currently undergoing revisions that will provide more resolution for its users, and there is a possibility that radar images may be available during weather warning and watches in the future.

5 Summary, Conclusions and Recommendations

5.1 Summary

This document has focused on two main areas of interest to Environment Canada. The main objectives of this research were to verify the utility of the RDSS severe weather detection algorithms, and to document and analyze the views and perceptions Manitoba farm operators hold of severe weather, Environment Canada and aspects of weather warning dissemination techniques. The thesis was separated into two main sections, each concentrating on related objectives. The objectives relating to the verification of the RDSS severe detection algorithms were addressed through the use of statistical techniques common in meteorology. The results uncovered the strengths and weaknesses associated with most aspects of the detection procedure, allowing researchers the ability to improve the RDSS verification algorithms, user-interface and verification operations. The objectives related to the documentation of farmer perceptions were addressed through the use of systematic interviews. The views and perceptions collected from farm operators on severe weather, Environment Canada, and weather warning dissemination techniques, may guide Environment Canada or other Federal departments in related projects in the future.

5.2 Conclusions

This thesis conducted a limited study of the performance of the RDSS severe detection algorithms for the 1999 summer convective storm season. The successful collection and analysis of available RDSS logged data, radar animations, damage assessments, and questionnaire contents have delivered encouraging performance results for the severe weather detection algorithms. Obtaining detailed ground truth verification data proved critical in determining the RDSS algorithm's true performance. Examining all cases showed that the algorithm over-forecasted the occurrence of severe hail, with a Credibility (CRED) of 27%. RDSS detected severe wind gusts (>90km/hr) with the highest efficiency; the wind gust algorithm was found to be superior in POD and CRED compared to the other algorithms. The supercell algorithm also performed satisfactorily with the lowest POD (45%) and the highest CRED (67%). A lack of ground truth observations in areas of low population density and lack of ground truth data in the U.S. may have contributed to these results. As well, the high frequency and large spatial difference of these storms made it difficult for a single person to verify every severe weather event that occurred within a 24-hour period. Furthermore, it should be noted that the sample size used in this study was relatively small and the results presented here are preliminary.

Farm operators' views and perceptions of severe weather events in southern Manitoba were also successfully documented. During lengthy interviews, farm operators discussed freely their personal experiences and the perceptions they have of severe weather. Do farm operators fear severe weather? The definitive answer was no, but the majority of farm operators had experienced monetary loss due to severe weather events, and most had negative comments related to these events. The most serious damage resulting from these hazards was delivered by hail and standing water. Commentary and anecdotes offered by most respondents related to hail or lightning events that had occurred on their property or neighbors. Several noted different lightning patterns that had been occurring over the most recent summers. When asked what severe event they perceive as the most threatening in the future, the majority of farm operators chose increased amounts of rain and snow, but many wondered why drought was not an option. Interestingly, climate change was not perceived as a future threat to agriculture in Manitoba with many farmers citing a longer growing season as the reason.

This study also successfully documented farm operators' perceptions and views concerning current severe weather frequency patterns. The majority of farm operators felt that hail events had been more frequent occurrence in the most recent decade than in past decades. As with the hail results, water was identified as a problem for many Manitoba farm operators in the 1990's, therefore it is no surprise that it was considered to be a more frequent event in the 1990's. Unlike the hail and water results, most farm operators felt that the frequency of severe wind events had not increased in the most recent decade. Similarly, the frequency of tornadoes was not seen as a more frequent event in the 1990's. Can, these opinions be verified? Considering the short and variable nature of weather data from year to year, it is difficult to discount the opinions provided by farm operators.

The research project also examined the views and perceptions that farm operators hold of Environment Canada and current weather warning dissemination techniques. The questions pertaining directly to Environment Canada spawned interesting reactions from respondents. Some provided a positive assessment of EC's severe weather warnings, while others displayed frustration and disdain. The balance of suggestions for improvement were generally reserved for the availability of weather information in a format which is easier to consume by farmers. Farm operators showed a preference towards information provided by the NWS over Canadian sources. In terms of weather warning dissemination techniques, the results showed a preference toward using television and radio. The use of the Internet for weather information by Manitoba farm operators was found to be still in its infancy with only one respondent having used it for weather related information.

The final objective, to make recommendations that may lead to the improvement of RDSS severe weather detection algorithms, Environment Canada's RDSS verification procedures, severe weather warning dissemination techniques, and understanding of Manitoba farm operators, is outlined below.

5.3 Recommendations

Although previous RDSS verification studies have been attempted, very little research has been published on how the Manitoba farm operator perceives and adjusts to severe weather hazards. Moreover, little has been done to document the views and perceptions that Manitoba farm operators hold of Environment Canada and current severe weather warning dissemination techniques. A study of this type will not only help EC improve the RDSS, but may also help assess the need for closer relations with Manitoba farmers. This study has several recommendations related to each individual objective.

In terms of improving RDSS, this study recommends that Environment Canada:

1. Use the results of this study to increase the validity and reliability of RDSS severe weather forecasts.

The results of the algorithm verification section of this study indicate that although the RDSS severe weather detection algorithms performed satisfactorily, improvements need to be continually made. In particular, the Hail Detection Algorithm (HDA) was found to "overwarn" the instance of severe hail, warranting further study and fine-tuning.

2. Develop VIL density guidelines specific to the Manitoba atmospheric conditions.

As described in the review of literature, VIL density has been commonly studied in research conducted by the NWS. One concern with using VIL density as a hail indicator, was that its performance is correlated to spatial location. Studies conducted further south generally had higher success rates. The probability of detecting severe hail could possibly be increased and the False Alarm Ratio could be decreased, if VIL density thresholds reflected the Manitoba climatology.

3. Increase EC severe hail diameter requirement from 20mm to 21.5mm (nickel sized).

From the results of this study there are indications that current EC severe hail measurement requirements are inadequate. Hail meeting current severe standards remains difficult for RDSS to detect with sufficient efficiency. If severe hail size were increased from 20mm to 21.5mm (nickel), the credibility of RDSS forecasts would increase from 24% to 82%. This increase in credibility is inversely correlated to FAR, thus as the credibility of RDSS forecasts increased, the FAR decreases.

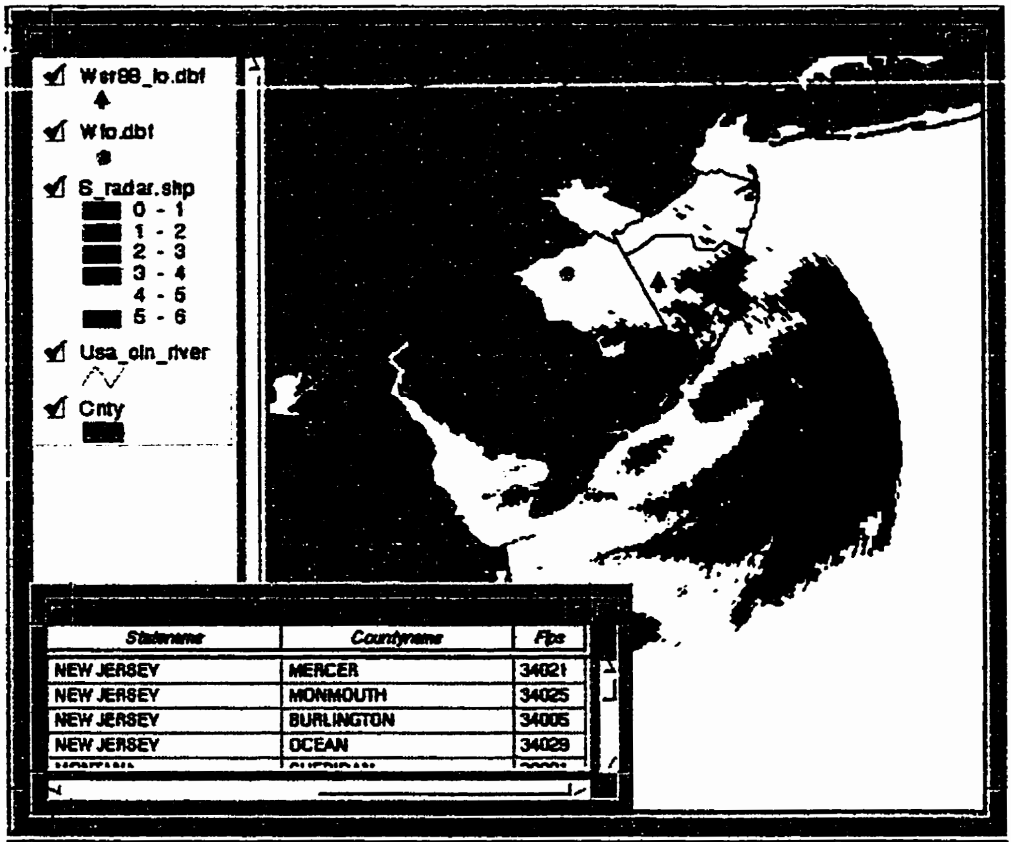

Figure 37: Nexrad Radar volume scan integrated into a GIS environment. Intrinsic GIS functions are also shown for user selection of county polygons and marking of the selected county records in an attached relational database. (Source: Shipley, et al. 1996).

4. Continue with RDSS verification, using an increased number of personnel.

The verification of the RDSS algorithms proved to be a daunting task for one field technician. In further verification projects it is recommended that on any severe weather day, at least three verification technicians should be used. To remain cost-effective, the team could be made up of one senior technician, and several summer students with interests in meteorology.

5. Environment Canada improve the RDSS user-interface by; a) conducting yearly feedback forums with severe weather meteorologists; b) enabling the seamless transfer of information to GIS application package (Figure 37).

The RDSS user-interface is relatively user friendly, but conversations with several severe weather meteorologists indicate that some drawbacks exist. It is recommended that an operational assessment be conducted, which includes a workstation assessment. Of concern to RDSS verification studies, it is recommended that radar volume scan animations be GIS compatible. Radar animations can currently be downloaded from RDSS in GIF89 format, which is not georeferenced.

In terms of citizen and farm operator involvement, this study recommends that:

6. Environment Canada increases the citizen and farm operator involvement in the development of severe weather dissemination techniques.

This thesis indicates that such programs would be well received by Manitoba farm operators. Although many provided negative feedback of EC's severe weather dissemination techniques, these individuals showed a willingness to help through their suggestions and comments. Developing relationships with Manitoba farm operators also stands to increase severe weather reporting. Other benefits and opportunities not mentioned in this study may also surface.

7. Environment Canada conduct a pilot study cataloguing Manitoba farmer's local knowledge and perceptions of severe weather

The results of this study indicate that Manitoba farm operators have specific concerns and perceptions of severe weather. Many feel that severe weather events have increased over the last decade and have had a negative impact on their livelihoods. Many farm operators feel that information on global climate change and their effect on Manitoba agriculture should be readily available. Research could be improved with personal interviews and a larger population sample. As well, the questioning could include areas of interest to Environment Canada. This could foster a better relationship between farm operators and government, resulting in mutually beneficial relationship.

8. Increase the availability of "real-time" radar volume scans to the public.

Interviews with Manitoba farm operators indicate a hunger for weather information. References to American weather data as "better" than Canadian was a common sentiment among farm operators in southern Manitoba. Farmers and public alike enjoy a sense of control. Seeing a severe cell coming towards ones area on the internet or television would not only give the public a sense of control through knowledge, but would give Environment Canada a level of credibility in their forecasts.

Note: Just prior to the publication of this document, Environment Canada released the following on their website.

OTTAWA – August 16, 2000 – Environment Minister David Anderson is pleased to announce that radar weather displays from the Meteorological Service of Canada (MSC), a branch of Environment Canada, are now available on the Internet.

Minister Anderson explained that "based on the public's interest to see weather systems for themselves, we developed a site providing this service to Canadians. The public wants this sort of information to make plans, whether it's playing golf or travelling or, more importantly, to take protective actions."

As of July 19, 2000, MSC has been uploading weather radar displays onto its Web site.

The system uses radar antennae, similar to the kind used for tracking airplanes, to detect raindrops and clouds. The antennae emit beams of microwave energy, which get scattered when they come into contact with weather phenomena such as rain, snow or ice particles. As the beams scatter, some of the energy is reflected back to the radar detector as an "echo". The "echo" is then picked up and the image is displayed on a radar screen. The radar system can determine a system's location based on the time it takes between sending the signal and receving the reflected signal back again. Radar can also help determine the severity of a weather system by the shape and intensity of the echo.

Canada has 22 radar stations across the country that provide weather data covering 90 to 95 percent of the population. Each station is capable of monitoring weather in a 240 kilometre radius.

The new service features hourly images taken from each radar station and posted to the Web site. A special feature allows visitors to click on an "animation" link which activates a playback of how a weather system has moved over the previous five hours.

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Appendix A: Questionnaire

Dear, Sir/Madam,

Attached you will find a four page survey. The purpose of this survey is to gather information about severe convective weather occurrences in southern Manitoba as well as information on the use of current severe weather reporting options. This information is needed to verify the utility and function of Environment Canada's (EC) newly developed Radar Decision Support System (RDSS), and to improve current severe weather warning methods.

In order to complete this survey please answer all questions as they pertain to your observations and experiences during the severe convective weather occurrence. This will take approximately five to 10 minutes. All personal information included in any responses will remain, at all times, confidential.

The survey is part of a thesis research through the Natural Resources Institute (NRI) in working toward the degree of Master of Natural Resources Management (MNRM). The study has received sponsorship from Environment Canada.

Additional information on this study, or a summary of the results of the survey may be obtained by contacting Ryan T. Tombs at either of the following locations:

Natural Resources Institute
University of Manitoba
70 Dysart Road
Winnipeg. Manitoba
R3T 2N2
Ph: (204) 474-8373

Or

Prairie Storm Prediction Centre (PSPC)
Environment Canada
Ph: (204) 983-8856

1. Name of observer:

2. Address:

3. Phone Number:

( ) -
( ) -

4. Time and Date of the Event:

5. Location:

6. Did you experience a severe weather occurrence? (Hail, Wind, Rain, Tornado)

a) Yes b) No c) I don't know

7. If yes, proceed with following questions

8. How did you determine the time of the event?

a) stopped clock b) power failure c) memory d) other time fixing event

Rain

9. Was there any rain?

a) Yes b) No c) I don't know

10. If yes, how much?

Estimation (cm)______ Measured (cm) ______

11. How long did it rain? (hr, min)

____

12. Do you have any additional remarks or comments about the rainfall?

a) Yes b) No

13. If yes, use space below

____

____

____

____

Hail

14. Was there any hail?

a) Yes b) No c) I don't know

15. If yes, how much?

Estimation (cm)_____ Measured (cm) _______

16. How big were the hailstones?

a) Pea b) Grape c) Walnut d) Golf ball
e) Tennis Ball f) Other g) Unknown h) Other

17. How long did it hail? (hr, min)

____

18. Do you have any additional remarks or comments about the hail storm?

a) Yes b) No

19. If yes, use space below

____

____

____

Wind

20. Did you experience any strong winds?

a) Yes b) No

21. If yes, what was the winds estimated speed?

____

____

22. In which direction was it blowing?

a) North b) East c) South d) West

23. How long did the winds last? (hr, min)

____

24. Do you have any additional remarks or comments about the strong winds?

a) Yes b) No

25. If yes, use space below

____

____

____

____

Tornado

26. Did you see a funnel cloud?

a) Yes b) No

27. If yes, was it touching the ground?

a) Yes b) No

28. In which direction was it moving?

a) North b) East c) South d) West

29. What shape was the tornado?

a) Multiple b) Smoke-like c) Columnar d) Cone e) Rope-like f) Unknown g) Other

30. Do you have any additional remarks or comments about the tornado?

a) Yes b) No

31. If yes, use space below

____
____
____
____

Severe Weather Views and Perceptions

32. What do you perceive as the greatest hazard to your crops?

a) Hail b) Wind c) Rain d) Tornado e) Other

33. What do you perceive as the main disadvantages of farming in Southern Manitoba?

a) Too dry b) Frost c) Floods d) Insects e) Severe weather f) Other

34. Has water been more of a problem in the 1990's than in previous decades?

a) yes | b) no | c) do not know

35. What do you consider to be a hailstorm?

a) A few hailstones
b) Ground covered by hail
c) Buildings damaged
d) Hail fell, but no crop loss

a) 1-30% crop loss
b) 30-70% damage
c) 70-90% damage
d) 100% crop loss

36. Has hail been a more frequent problem in the 1990's than in previous decades?

a) yes b) no c) I don't know

37. Has wind been a more frequent problem in the 1990's than in previous decades?

a) yes b) no c) I don't know

38. Have tornadoes been a more frequent problem in the 1990's than in previous decades?

a) yes b) no c) I don't know

39. What weather phenomenon do you perceive as most threatening to crops in the future?

a) Changing climate b) Severe weather (more frequent). c) Increased amounts of snow d) increased amounts of rain e) heavy run-offs

40. How do you usually hear of warnings?

a) Television b) Radio c) Internet d) other

41. Do you have an Internet connection?

a) Yes b) No

42. Do you see yourself using the internet for weather information in the future?

a) Yes b) No c) I do not know

43. Have you ever reported a severe weather occurrence?

a) Yes b) No

44. If yes, why?

____

____

____

____

If no, why not?

45. How would you rate the accuracy of Environment Canada's severe weather warnings?

a) Excellent b) Good c) Satisfactory d) Poor c) Terrible

46. How would you improve the way Environment Canada puts out severe weather warnings?

Appendix B: Glossary of Terms

Adapted from "Radar for Meteorologists", R.E. Rinehart. Copyright (c) 1991, Ronald E. Rinehart.

accuracy:

Degree of conformity of a measure to a standard or true value.

anomalous propagation (AP):

When nonstandard refractive index distributions prevail, "abnormal" or "anomalous" propagation occurs.

backing wind:

A change in wind direction in a counterclockwise sense representing cold air advection.

backscatter:

That portion of power scattered back in the incident direction.

Boundary layer:

The layer of a fluid adjacent to a physical boundary in which the fluid motion is affected by the boundary and has a mean velocity less than the stream value.

bounded weak echo region (BWER):

A core of weak equivalent reflectivity in a thunderstorm that identifies the location of a strong updraft. The updraft is so strong that large precipitation particles do not have time to form in the lower and mid-levels of the storm and are prevented from falling back into the updraft core from above. The weak echo region is bounded when, in a horizontal section, the weak echo region is completely surrounded or bounded by higher reflectivity values.

probability of detection (POD):

A verification measure of categorical forecast performance equal to the total number of correct event forecasts (hits) divided by the total number of events observed. Simply stated, it is the percent of events that are forecast. With respect to the 2x2 verification problem example outlined in the definition of contingency table, POD= (A)/(A+C).

false alarm ratio (FAR):

A verification measure of categorical forecast performance equal to the number of false alarms divided by the total number of event forecasts. With respect to the 2x2 verification problem example outlined in the definition of contingency table, FAR= (B)/(A+B).

bow echo:

Rapidly moving, crescent shaped echo that is convex in the direction of motion. Typically associated with strong, straight-line winds.

cell:

A compact region of relatively strong vertical air motion (at least 10 m/s).

clutter:

Echoes that interfere with observation of desired signals on a radar display. Usually applied to ground targets.

convection:

In meteorology, the ascent of air which is less dense than its surroundings, usually because of thermal (temperature) differences. Clouds and storms are known as *moist* convection because the condensation of water vapor releases latent heat, which further heats the ascending air and makes it more buoyant.

convergence:

A measure of the contraction of a vector field. In meteorology, usually refers to wind, or mass, convergence, when observed near the ground, it is associated with updrafts.

correlation:

A measure of the similarity between variables or functions.

critical success index (CSI).

Also called the threat score (TS), is a verification measure of categorical forecast performance equal to the total number of correct event forecasts (hits) divided by the total number of storm forecasts plus the number of misses (hits + false alarms + misses). The CSI is not affected by the number of non-event forecasts that verify (correct rejections). However, the CSI is a biased score that is dependent upon the frequency of the event.

contingency table.

A two-dimensional "square" table (with kxk entries) that displays the discrete joint distribution of forecasts and observations in terms of frequencies or relative frequencies. For dichotomous categorical forecasts, having only two possible outcomes (Yes or No), the following 2x2 contingency table can be defined:

		Event Observed	
		Yes	**No**
Event Forecast	**Yes**	A	B
	No	C	D

The "A" table entry is the number of event forecasts that correspond to event observations, or the number of hits; entry "B" is the number of event forecasts that do not correspond to observed events, or the number of false alarms; entry "C" is the number of no-event forecasts corresponding to observed events, or the number of misses; and entry "D" is the number of no-event forecasts corresponding to no events observed, or the number of correct rejections. This 2x2 table will be referenced in the definitions of a number of performance measures formulated for the 2x2 verification problem. These measures include percent correct (PC), probability of detection (POD), false alarm ratio (FAR), success ratio (SR), threat score (TS) or critical success index (CSI), Gilbert skill score (GS), Heidke skill score (HSS), and a categorical measure of bias.

dBZ:

A logarithmic expression for reflectivity factor, referenced to (1 mm^6 / 1 m^3). dBZ = 10 log (z / 1 mm^6 m^3).

divergence:

A measure of the expansion of a vector field. In meteorology, usually wind or mass divergence. When observed near the ground it is associated with downdrafts.

downburst:

A strong downdraft that induces an outburst of damaging winds on or near the ground.

downdraft:

Currents of air with marked vertical downward motion.

echo:

Energy backscattered from a target as seen on the radar display.

false alarm ratio (FAR).:

A verification measure of categorical forecast performance equal to the number of false alarms divided by the total number of event forecasts.

frequency:

The number of recurrences of a periodic phenomenon per unit time. Electromagnetic energy is usually specified in Hertz (Hz), which is a unit of frequency equal to one cycle per second. Weather radars typically operate in the GigaHertz range (GHz).

GPS:

Global Positioning System. A network of satellites which provide extremely accurate position and time information. Useful in remote locations or for moving platforms.

ground clutter:

The pattern of radar echoes from fixed ground targets.

isolated storm:

An individual cell or a group of cells that are identifiable and separate from other cells in a geographic area.

macroburst:

Large downburst with 4 km or larger outflow size, with damaging wind lasting 5-20 minutes.

mesocyclone:

A 3-dimensional region in a storm that rotates cyclonically (counterclockwise in NH) and is closely correlated with severe weather.

mesoscale convective system (MCS):

Precipitation systems 20 to 500 km wide that contain deep convection. Examples in mid-latitudes are large isolated thunderstorms, squall lines, Mesoscale Convective Complexes, and rainbands.

PPI:

Plan-Position Indicator. An intensity-modulated display on which echo signals are shown in plan view with range and azimuth angle displayed in polar coordinates, forming a map-like display. Each PPI is taken at a single, fixed elevation angle, and thus forms a cone of coverage in space. PPIs may be run in sequence, creating a "volume scan".

probability of detection (POD).: A verification measure of categorical forecast performance equal to the total number of correct event forecasts (hits) divided by the total number of events observed. Simply stated, it is the percent of events that are forecast.

propagation:

Transmission of electromagnetic energy as waves through or along a medium.

radar cross section:

The area of a fictitious, perfect reflector of electromagnetic waves (e.g., metal sphere) that would reflect the same amount of energy back to the radar as the actual target (e.g., lumpy snowflake).

radar reflectivity:

The sum of all backscattering cross-sections (e.g., precipitation particles) in a pulse resolution volume divided by that volume. The radar reflectivity can be related to the radar reflectivity factor through the dielectric constant term |K|^2, and the radar wavelength.

range:

Distance from the radar antenna.

reflectivity:

A measure of the fraction of radiation reflected by a given surface; defined as a ratio of the radiant energy reflected to the total that is incident upon that surface.

squall line:

A line or narrow band of active thunderstorms.

storm:

Any disturbed state of the atmosphere, especially affecting the Earth's surface, and strongly implying destructive and otherwise unpleasant weather. Storms range in scale from tornadoes and thunderstorms through tropical cyclones to widespread extratropical cyclones.

storm motion:

The velocity at which a storm travels.

supercell:

A large, long-lived (up to several hours) cell consisting of one quasi-steady updraft-downdraft couplet that is generally capable of producing the most severe weather (tornadoes, high winds, and giant hail).

wall cloud:

A local, abrupt lowering of a rain-free cumulonimbus base into a low-hanging accessory cloud, from 2 to 6 km (1 to 4 miles) in diameter. The wall cloud is usually located in the southwestern part of a severe thunderstorm in the main updraft to the southwest of the main precipitation region. Rapid upward motion and visible rotation may be seen in wall clouds from several km away. Almost all strong tornadoes develop from wall clouds.

weak echo region (WER):

Within a convective echo, a localized minimum of equivalent reflectivity associated with the strong updraft region.

WSR-88D system: The summation of all hardware, software, facilities, communications, logistics, staffing, training, operations, and procedures specifically associated with the collection, processing, analysis, dissemination and application of data from the WSR-88D unit.

critical success index (CSI).: Is a verification measure of categorical forecast performance equal to the total number of correct event forecasts (hits) divided by the total number of storm forecasts plus the number of misses (hits + false alarms + misses).

Appendix C: RDSS User Interface

Note: The following user-interface description was compiled by Anthony Keck (1998).

The RDSS user interface consists of two window types ...

1. Main Radar View: This window is used to show full radar views showing the locations of storm cells. It is also used to display general product information. The user can use this window to select a storm region or cell, upon which detailed region data analysis results will be shown in an appropriate storm cell window.

2. Storm Cell Window: This type of window is used to display detailed results from storm cell analysis.

All windows have a title made up of the name of the radar source and the time associated with the latest radar scan obtained.

Main Radar View

The "Main Radar View" window consists of two main viewing areas, a set of pull-down menus, and a scrolling text area. The viewing areas can be used to display single views of radar data as well as animation loops showing how radar data is changing over time. One of the views is used for displaying the locations of storm cells, which are color-coded according to their perceived level of potential for causing severe summer weather events. The other view is used for displaying "Product" information. The user can use the mouse to select a storm cell from the first view, upon which a "Storm Cell Window" will appear with information about the selected cell. Both windows have the following elements.

Title - identifies the type of information being displayed and the time it was obtained from the radar,

Radar Image - a color-coded or gray scale image or movie loop showing radar data and product information,

Geography Overlay - an optional geography overlay, which is mapped onto the radar image,

Color Key - a color key explaining what colors used in the radar image display represent,

Image Save Controls buttons for saving images and animations in GIF and animated GIF format files; individual images can be saved in GIF or animated GIF files using a right mouse click (GIF) or modified (shift, ctrl, or lock) right click (animated GIF) on the image to be saved,

Movie Controls - buttons used for pausing and resuming movie loops, stepping forward and backward in movie loops, and skipping to the end of movie loops,

Progress Gauge - shows the location of the current movie frame in the movie loop,

Mouse Location/Value Reporting - the user gets a report in a display field that identifies the location and data value associated with the current mouse pointer location,

Mouse Based Geography Report - the user gets a report in a display field that identifies cities, towns, airports, and possibly other important landmarks that are close to the current mouse pointer location.

The pull-down menu includes options for changing the radar source, selecting specific volume scans, requesting specific product information, and for turning on and off geographical overlays.

The scrolling text area is used for reporting non-pictorial information and supplying other status information.

Storm Cell Window

When the user uses the mouse to select a storm cell from the "Main Radar View" window, a "Storm Cell Window" will appear. "Storm Cell Windows" provide more detailed information about the selected storm cell. "Storm Cell Windows" have been designed for two types of analyses; super-cell analysis, and wind gust analysis.

"Storm Cell Windows" have the following elements;

> Cell Core / Composite Product View - a view containing an image or movie loop showing the relative locations of the storm cell core and product-based features, as well as storm tilt and motion vectors,
>
> Product Image Views (Figure 0-1) - views containing images or movie loops showing product information in the region of the storm cell,

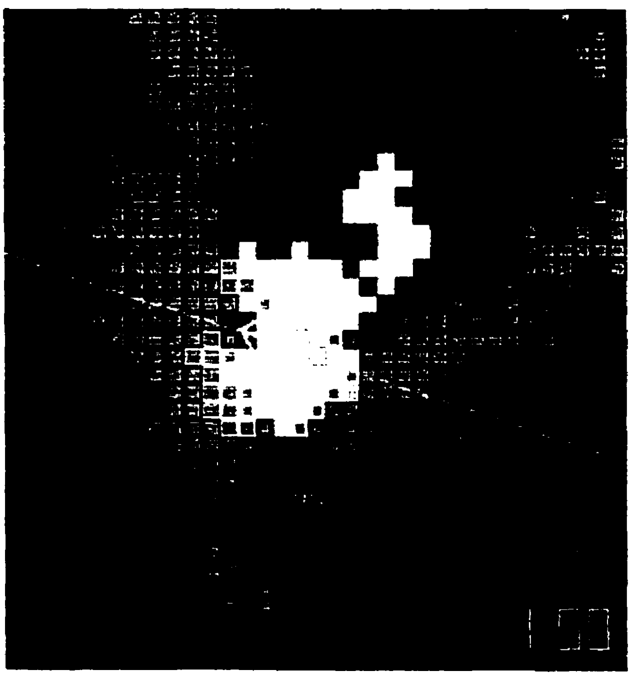

Figure 0.1: Storm cell composite image.

> Cell Profile View (Figure 0-2)- a view containing two profile image displays; an image or movie loop showing automatically selected

vertical profiles of product data taken in the direction of the cell's tilt vector, and a display for user selected profiles,

Figure 0.2: Cell Profile View.

Storm Parameter vs. Time Graphs (Figure 0-3) - time profiles of important storm cell parameters,

Figure 0.3: Time Graphs

Image Save Controls ñ buttons for saving images and animations in GIF and animated GIF format files; individual images can be saved in GIF or animated GIF files using a right mouse click (GIF) or modified (shift, ctrl, or lock) right click (animated GIF) on the image to be saved,

Movie Controls - buttons used for pausing and resuming movie loops, stepping forward and backward in movie loops, and skipping to the end of movie loops,

Mouse Based Geography Report - the user gets a report in a display field that identifies cities, towns, airports, and possibly other important landmarks that are close to the current mouse pointer location,

Mouse Pointer Linkage - the location of the mouse pointer when it is over an image display is mirrored in all of the other image displays to help the user correspond locations of product features,

Storm Selection Display - a miniature display of the full radar field, complete with all storm cells that can be used to select other storm cells using the mouse.

The "Cell Core / Composite Product" view, "Product" image views, and "Cell Profile" view all have the following elements;

> Title - identifies the type of information being displayed and the time it was obtained from the radar,
>
> Color Key - a color key explaining what colors used in the radar image display represent,
>
> Progress Gauge - shows the location of the current movie frame in the movie loop.

The "Cell Core / Composite Product" view and "Product" image views also have the following elements;

> Mouse Location/Value Reporting - the user gets a report in a display field that identifies the location and data value associated with the current mouse pointer location,
>
> Zoom Button - can be used to obtain an enlarged view of the image or movie loop contained in the view.

Appendix D: Algorithm Condition Statements

Super Assessment

RDSS provides an automatic severity rating for storms based on supercell characteristics. These are applied to each CellSnapshot. A rating between 0 and 3 is assigned using a two step process.

Step 1

The following conditions are evaluated and assigned a value of True or False.

- Condition 1: Volume of cell core above height 7.0km AGL (above ground level) > 20km3 and Cell core area at height 7.0 km AGL > 10 km2
- Condition 2: Volume of cell core above 7.0km > 150km3
- Condition 3: Echo top within 2km of highest echo, overhang, low level gradient > Z, occur within 2km.
- Condition 4: BWER footprint covers area > 10km2

The above section can be interpreted as follows. Condition one is used to make sure the reflectivity core meets the minimum requirement that it have enough of its cell core above the minimum altitude. Condition 2 is used to determine whether or not the cell can be considered to have a large amount of cell core above the minimum height (Threshold C is typically set much higher than threshold A). Condition 3 is used to determine if the storm cell has the sort of structure where high echo tops, reflectivity overhangs, and strong low-level reflectivity gradients occur in close proximity. This implies that the storm might have the kind of structure related to strong supercells, as indicated by Lemon. Condition 4 provides as much indication that a very strong updraft is feeding the storm.

Step 2

A severity rating is assigned through the prograssive application of a set of logical expressions involving the above conditions. The highest level of which the associated expression evauates to TRUE will be assigned to the storm cell.

- Level 0: Default
- Severity Level 1: Condition 1 AND 2 OR condition 1 and 3
- Severity Level 2: Condition 1 AND condition 2 AND condition 3.
- Severity Level 3: Condition 1 and 4

  - The above ratings can be interpreted as follows. Level 0 indicates that the cell is not large enough to be considered a supercell. Level one indicates that the storm is large but lacks the structural characteristics of a really severe storm or that it potentially has structure but lacks size. Level 2 indicates that the storm is large and potentially has structure indicating a more severe storm. Level 3 indicates that there is a significantly large BWER in the storm, which tends to indicate a very strong updraft, which is often associated with the worst kids of storms.

Wind Gust Assessment

The following conditions are evaluated and assigned a value of TRUE and FALSE.

- Condition 1: Wind Gust Potential (Stewart) > 60km/hr
- Condition 2: WGP (Stewart) + Storm Cell Velocity > 90km/hr
- Condition 3 Decreases in Maximum VIL > 10kg/m2
- Condition 4: Decreases in height of Ma-R > 2km

Condition one involves only the most recent cell snapshot. It is assessed using the maximum wind gust potential that appears in the region of interest used to create the wind gust product for the cell snapshot. Threshold A is chosen so as to represent a moderate wind gust potential.

Condition 2 assumes that any downdraft that would occur would add to the wind caused by the motion of the cell itself. It is used to assess whether the combined wind would exceed a high velocity, either because the downdraft wind could be large an/or the wind from the cell motion is large.

Condition 3 and 4 are calculated using the latest cell snapshot and the previous cell snapshot and are used as indicators that the storm cell core might be in descent, indicating that a downdraft could be occurring. Condition 3 is assessed using the maximum VIL that occurs anywhere in the region of interest used to create the VIL product for each cell snapshot. Condition 4 is assessed using the maximum height of all Max-R values over 45dBz tat occur in the region of interest used to create the MAX-R and Height product for each cell snapshot.

<u>Step 2</u>

A severity rating is assigned through the progressive application of a set of logical expressions involving the above conditions. The highest level for which the associated expression evaluated to TRUE will be assigned to the storm.

- Severity Level 0 : Default

- Severity Level 1: Condition 1
- Severity Level 2: Condition 1 AND Condition 2 OR Condition 1 and Condition 3 OR Condition 1 and Condition 4.
- Severity Level 3: Condition 1 AND Condition 2 AND Condition 3 OR Condition 1 AND Condition 2 AND Condition 4

The above ratings can be interpreted as follows.

Level 0 indicates that the cell is not likely to cause to cause strong wind gusts in the near future.

Level 1 indicates that the storm has potential to create a moderate wind gust if part of the cell care were to descend.

Level 2 indicates that one of several scenarios could exist. They are that the storm has the potential to create strong wind gusts if part of the cell were to descend, he cell is moving fast and has the potential to produce a strong wind due to the addition of a moderate downdraft, or that the potential for a moderate gust due to a downdraft has been detected and there is an indication that the cell core might be descending.

Level 3 indicates one of two things; the potential for a strong wind gust due to a downdraft has been detected and there is an indication that the cell core might be descending, or the cell is moving fast, has the potential to produce a strong wind due to the addition of moderate downdraft and there is an indication that the cell core might be descending.

Hail Probability Algorithm (HPA)

RDSS provides indicators for the possible presence of large hail. The algorithm consists of the straightforward comparison of VIL density values against threshold values. The greater the VIL density, the higher the probability of severe hail occurring. Currently there are two threshold values being used by RDSS. The first threshold (A) is associated with a 50% probability of large hail, while the second threshold (B) is associated with 90% probability of large hail.

Hail indicators are produced for each Cell Snapshot, and consist of a set of flags that are used to indicate whether or not the thresholds are exceeded.