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AN OPERATIONAL ANALYSIS OF THE SEVERE THUNDERSTORMS OF AUGUST 4TH 1994

BY

PIERRE VAILLANCOURT
SPÉCIALISTE AU TEMPS SÉVÈRE/SEVERE WEATHER METEOROLOGIST
BUREAU DES SERVICES MÉTÉOROLOGIQUES ET ENVIRONNEMENTAUX DE MONTRÉAL METEOROLOGICAL AND ENVIRONMENTAL SERVICES OFFICE

Introduction

Quebec Province, southern sections of it in particular, is the site of severe weather events caused by summer meso-scale convection. On average, around 100 confirmed cases[1] of damages are reported each summer over the whole province with heavy downpours and downsbursts being the main cause. Although, these events are in general of a lesser extend and in smaller numbers than in the American Mid-West, they are of the same nature.

In 1994, we had an exceptional year with double the amount of severe events and an amazing 17 confirmed[2] cases of tornadoes. That summer, we had a good conjunction of unstable air-masses with synoptic dynamic features crossing the province during the maximum of daytime heating. The result was well organized squall lines and numerous super-cells.

In this paper, I will be describing the main event of that summer which happened on August 4th. On that day, a low pressure brought warm unstable air from the Gulf of Mexico to southern Quebec and triggered super-cells that were to produce 5 tornadoes ranging from F0 (wind less than 120 km) to F2 (winds of 180 to 250 km) on the Fujita scale.

The first section will describe the tools used by the Quebec Weather Center for convective predictions and warnings. In the second one, I will describe the synoptic situation on August 3 rd leading to the severe events and the predictors used for the issuing of warnings on the 4th. In the third part, I will show the unfolding of events over the coverage area of the J.S. Marshall Weather Radar Observatory. Finally, I will give some later meso-scale analysis.

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[1] P. Vaillancourt et al. «Rapport de temps violent estival pour la saison 1994», *Note technique Région du Québec 95N-001*, p 30

[2] Idid, p 17

1- Forecasting Tools

1.1- Analysis.

1.1.1- Surface and upper air.

The hourly, synoptic and special observations for North America are collected and distributed by the CMC (Canadian Meteorological Center). They are issuing plots of surface data every 6 hours and for 850 mb, 700 mb, 500 mb and 250 mb altitudes every 12 hours.

The Quebec Weather Center has the possibility of making analysis of those data every hour plus receive climatological data from Quebec Forest Service twice a day and from the department of Agriculture once a day.

1.1.2- Satellite

North America is covered by two geostationary satellite GOES-8 and GOES-9 which send every 15 minutes Infra-Red (IR) pictures all day long and Visible (VIS) pictures every 15 minutes of day-light. These pictures can be obtain every 7.5 minutes when a rapid acquisition cycle is initiated by NOAA (National Oceanographic and Atmospheric Administration) at the cost of a reduced coverage on latitude.

1.1.3- Radar

Quebec is covered by 4 conventional radars giving volume-scan of reflectivities. The J.S. Marshall McGill radar has data for reflectivities and for radial speed of the precipitations (Doppler Effect).

1.1.4- Lightning detection

In collaboration with Hydro-Quebec, the Quebec Weather Center has access to a network of lightning detectors to track the movement of thunderstorms. It is especially useful in remote areas not covered by radar.

1.2- Numerical Models

The CMC is computing two operational models but there has been some change since 1994 and I will talk here about the ones used at that time. The first one was a finite element type called RFE with resolution of 35 km in the horizontal. The second one is a spectral type called Global.

Data from these models are available as maps issued on circuit and as derived fields available on workstations used at the Quebec Weather Center. For severe weather forecasting, prognosis of synoptic features are important but derived field on airmass stability such as Relative Helicity Index and Severe Storm Index (SSI) are critical.

1.3- Tephigram analysis

The significant sounding are plotted on Tephigrams in Canada. At the Quebec Weather Center, this is done on a program called STRATUS. This program, not only plot the data, but do calculation about the stability of the airmass, the available energy and its potential of giving severe convection.

Here are some concepts and indexes routinely used operationally and that are calculated by STRATUS:

1.3.1- Convective Available Potential Energy (CAPE)

The CAPE is the total positive energy available to a parcel that reach the Level of Free Convection either by heating and humidification in lower levels or drying and cooling in upper levels. This is calculated by adding the positive difference in potential temperature between the environment and the parcel throughout the layer between LFC and the equilibrium:

$$CAPE = \int_{LFC}^{EQUILIBRIUM} g \frac{(\theta_{ENV} - \theta_{PARCEL})}{\theta_{ENV}} DZ \qquad \text{(in J/Kg)}$$

1.3.2- Convective Inhibition (CIN)

The CIN is the amount of energy that has to be added to the lower atmosphere in order for a parcel to be able to reach LFC. Basically, it is the area on a tephigram between the parcel lifted from surface along dry adiabate until saturation and then along moist adiabate until LFC compared to the environment:

$$CIN = \int_{SURFACE}^{LFC} g \frac{(\theta_{PARCEL} - \theta_{ENV})}{\theta_{ENV}} DZ \qquad \text{(in J/Kg)}$$

This feature is easily seen on a tephigram by an inversion above the surface that form a capping for convection. The larger is the capping, the more it helps accumulate buoyancy until surface temperature has reach the value were CIN is zero. Then, convection can be released all at once producing more devastating effects.

1.3.3- Severe Storm Index(SSI)

A study done by Rasmussen and Wilhemson[3] shows, and case studies done at the Quebec Weather Center confirm, that a thunderstorm needs a mix of Energy and Shear to develop into a severe event. If one is weak the other must compensate.
On the a graph below[4], severe and non severe events are plotted according to their CAPE and MEAN SHEAR below 4 km , we can see that all the severe cases involving large hail (triangles

[3] E. N. Rasmusssen and R. B. Whilhemson, 1983 "Relationship between storm characteristics and 1200 GMT hodograph, low level shear and stability". 13th Conf. on Severe Local Storm, AMS

and inverted pentagons), damaging winds (stars) and tornadoes (T and TT) are above the line of IN=100.

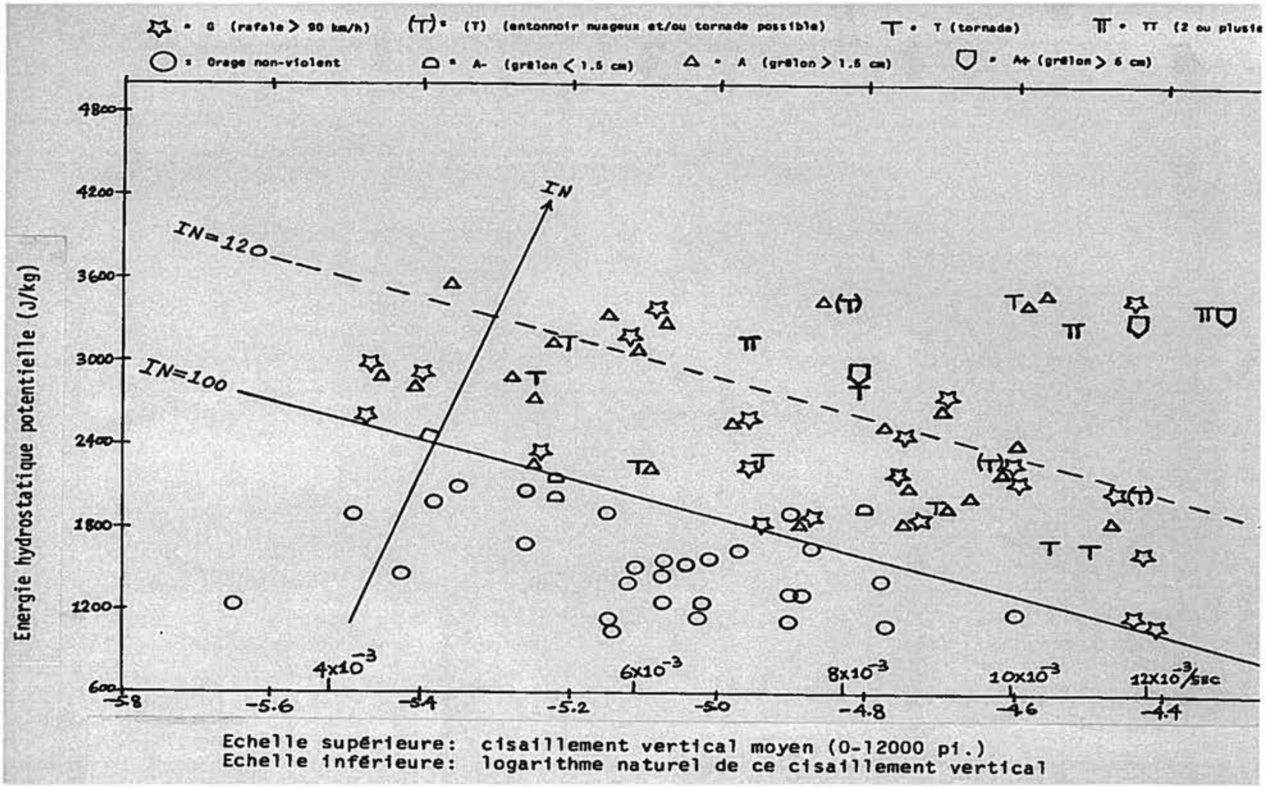

Figure 1 Study of thunderstorms events in Quebec in a CAPE vs SHEAR (below 6 km) plot

This line has been defined as the Severe Storm Index threshold and is routinely analyzed. Its normalized value is:

$$SSI = 100 \times [2 + 0.276(\ln SHEAR(0\text{-}6KM)) + 2.011\times10^{-4} \times CAPE]$$

And is interpreted as:

- SSI < 95 — no severe weather expected
- 95 < SSI < 100 — severe weather possible
- SSI > 100 — severe weather expected
- SSI > 120 — severe weather expected with risk of tornadoes if SHEAR is high

1.3.4- Relative Helicity(RH)

Tornadoes are due to the conversion of horizontal vorticity into a vertical one by a strong updraft in a thunderstorm. The tilting/twisting term of the shallow water equation :

$\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}$ is indicative of the rotation created by this conversion.

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[4] V. Turcotte et al. «Étude de cas de temps violents au Québec », *Note technique Région du Québec 87N-001*

A way of evaluating the percentage of the horizontal vorticity transformed into vertical one is to calculate the proportion of the storm motion parallel to the horizontal vorticity. This vorticity being caused by shear in low levels winds:

$$RH = \int_{SURFACE}^{Z=h} (\vec{V}_{STORM} - \vec{V}_{ENVIRONMENT}) \bullet \hat{k} \times \frac{dV_{ENV}}{dZ} \qquad \begin{cases} Horizontal\ Vorticity = \hat{k} \times \frac{dV_{ENV}}{dZ} \\ \vec{V}_{STORM} = Storm\ motion \\ \vec{V}_{ENVIRONMENT} = Environmental\ winds \end{cases}$$

On the tephigram, this equation is calculated from surface to 3 km. STRATUS is using automatically for $\vec{V}_{STORM}$: 70% of the mean wind below 6 km on the tephigram **or** we can input any speed and direction manually. The larger RH, the longer the storm will last because the winds of the storm are closer to the direction of rotation of the tilted vortex and help to maintain it.

Values of RH are used to predict the possible generation of tornadoes:

- RH from 150 to 299... possible Tornadoes of F0 to F1 strength
- RH from 300 to 449... possible Tornadoes of F2 to F3 strength
- RH from 450 and more... possible Tornadoes of F4 and F5 strength

1.3.5- Energy Helicity Index (EHI)

The Helicity can be related to the available CAPE of the storm to give an index of the possibility of tornadoes and of their strength. This index is more reliable as it takes into account not only the enhancement of the rotation by the storm wind but the CAPE which give a proportion of the updraft strength too.

Most of the shear in the wind happens in the lower levels of the atmosphere so this index is calculated for the layer from surface to 2 km above ground:

$$EHI = \frac{RH(0-2KM) \times CAPE}{160000} \qquad \begin{cases} 5 > EHI > 1 & Tornadoes\ F1\ to\ F3\ Possible \\ EHI > 5 & Tornadoes\ F4\ or\ More \end{cases}$$

1.3.6- Wet Microbursts

When the environment is dry at mid-level, some of the dry air can be sucked into the thunderstorm by the air turbulence and precipitations. This dry air has a lower potential temperature 2_e than the air in the cloud. A negative buoyancy is then created that develops into a downdraft.

We know that the maximum speed created by such a difference in 2_e is equal to the square root of 2 time the negative buoyancy between the temperature curve of the environment at the dry level and the temperature of the clouds. This energy can be estimated in calculating $)2_e$ between the driest part of tephigram and that of a parcel lifted from LFC.

- $)2_e < 13$ — no damaging Downburst
- $13 <)2_e < 19$ — possible damaging Downburst (30-45 knots)
- $2_e > 19$ — damaging Downburst (50 knots or more)

1.3.7- Hail Index

One of the important severe phenomenon is hail. Hail is formed in storms with large vertical extension, strong updraft and high humidity. The water vapor in the updraft condense into water droplets and later into ice particle if it reach a temperature cold enough. To become hail these particles need to stay long enough in the updraft to agglomerate until too heavy and then begin to fall. After falling below the freezing level, the hail stones begin to melt and what is left of it when it reaches the ground is the unmelted part.

To estimate the probability of producing hail one must evaluate the strength of the updraft which is proportional to the CAPE and the melting which is proportional to the time the hail stone passes at temperatures above zero (proportional to the freezing level height).

Experience has shown that the balance can be estimated by looking at the difference in temperature at the mean freezing temperature (between the environment and the particle) versus the height of that mean freezing temperature. The equation below calculate the difference and is corrected by a term that take into account the freezing level.

$$SPRED = (T_{PARCEL} - T_{ENV}) - \left(\frac{\left[\frac{FL}{1000} - 10.7 \right]^2}{4.12} \right) + 5 \quad \begin{cases} FL = Average\ height\ of\ freezing\ level \\ between\ parcel\ and\ environment \end{cases}$$

With CAPE > 1600 J/Kg:

- SSI > 100 and SPREAD >= -.5 .... Hail diameter less than 2 cm
  OR 95 < SSI <100 and SPREAD >= - .3
- SSI > 100, CAPE > 1600 J/Kg and SPREAD >= - .3 .... Hail diameter greater than 2 cm possible
  OR 95 < SSI <100 and SPREAD >= 0
- With SSI > 100, CAPE > 1600 J/Kg and SPREAD >= 0 .... Hail diameter greater than 2 cm likely

1.3.8- Flash Flood

The potential for sudden heavy downpour from a thunderstorm is directly proportional to the amount of moisture available in the cloud. This can be easily calculated by the precipitable water content in the convective parcel:

$$PCPTW = \int_{SURFACE}^{TOP\ OF\ CLOUD} W\, dP \qquad \text{(in mm/m}^3\text{)} \qquad \begin{cases} W \text{ is mixing ratio} \\ P \text{ is pressure} \end{cases}$$

With SSI >100 and PCPTW > 30 mm, flash flood is likely.

2- Weather Situation Prior to the Severe Events

2.1- Synoptic situation at 00 GMT on the 4th of August 1994

At surface (fig. 2), a low pressure in the northern part of Lake Michigan is associated with a maritime warm sector with dew points of 18 to 20 degrees reaching a maximum of 22 degrees about 120 miles ahead of the cold front. An arctic cold front is coming down from James Bay area, too.

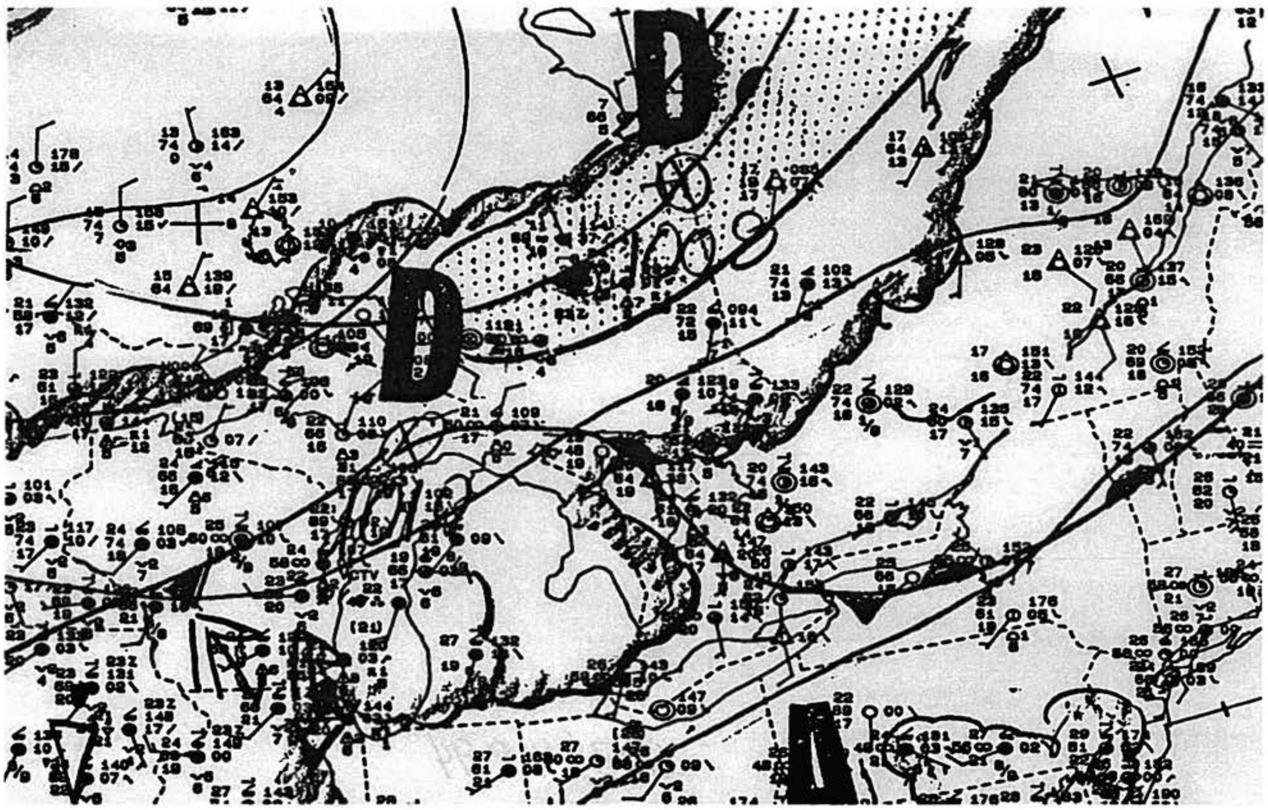


Figure 2 Surface Map of 00 GMT for August 4, 1994

The flow of air is generally from the south in the warm sector but turns to the southwest near the moister area (also known as the moist tongue) giving an area of convergence at surface. Surface temperatures are near 23 degrees in the cloudy area ahead the cold front but as high as 28 along the southeastern edge of it, creating a flow of air toward the clouds were we notice thunderstorms.

At 850 mb (fig. 3), there is generally a southwesterly flow of about 20 knots (40 km/h) over the same area which is not yet organized into a low level jet. The dew point depression is 3 degrees or less showing the high saturation in low levels.

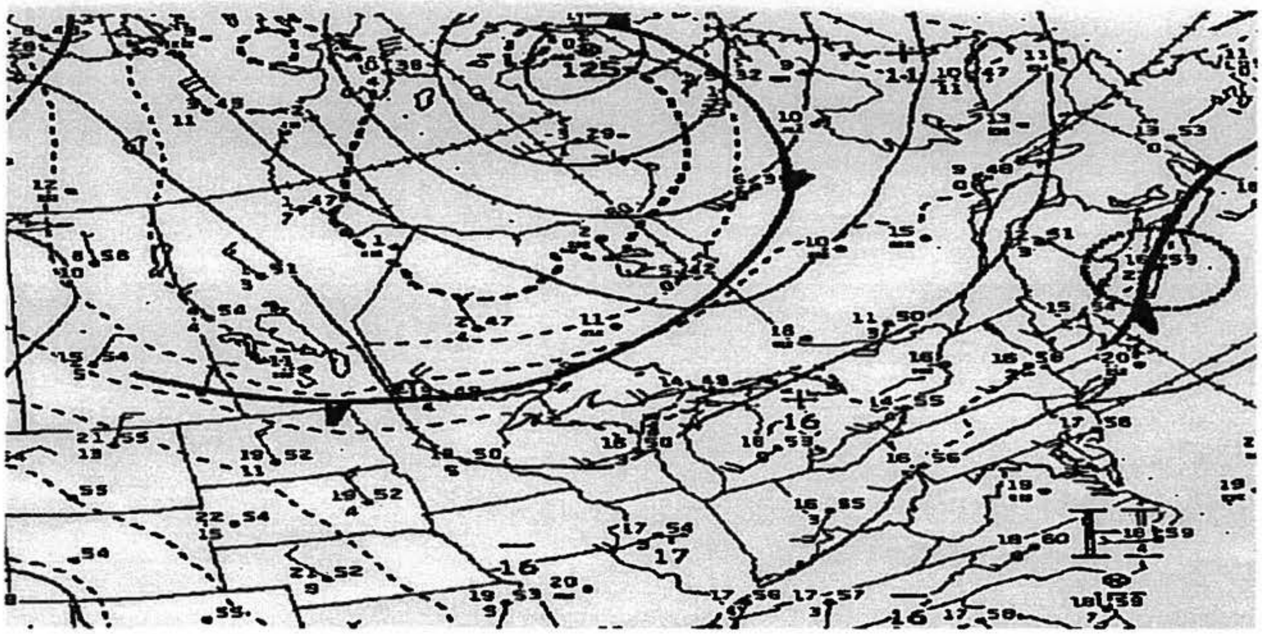


Figure 3 Altitude 850 mb at 00 GMT on August 4,1994

At 700 mb (fig. 4), we have the same flow but the dew point depression is 16 to 23 degrees over southern Michigan while only 1 degrees in northern parts near the surface cold front. The air becomes very dry north of Lake Superior. This shows that the air is only moist at mid levels near the cold front and that an injection of colder and drier air is coming from the northwest, possibly making the air more unstable.

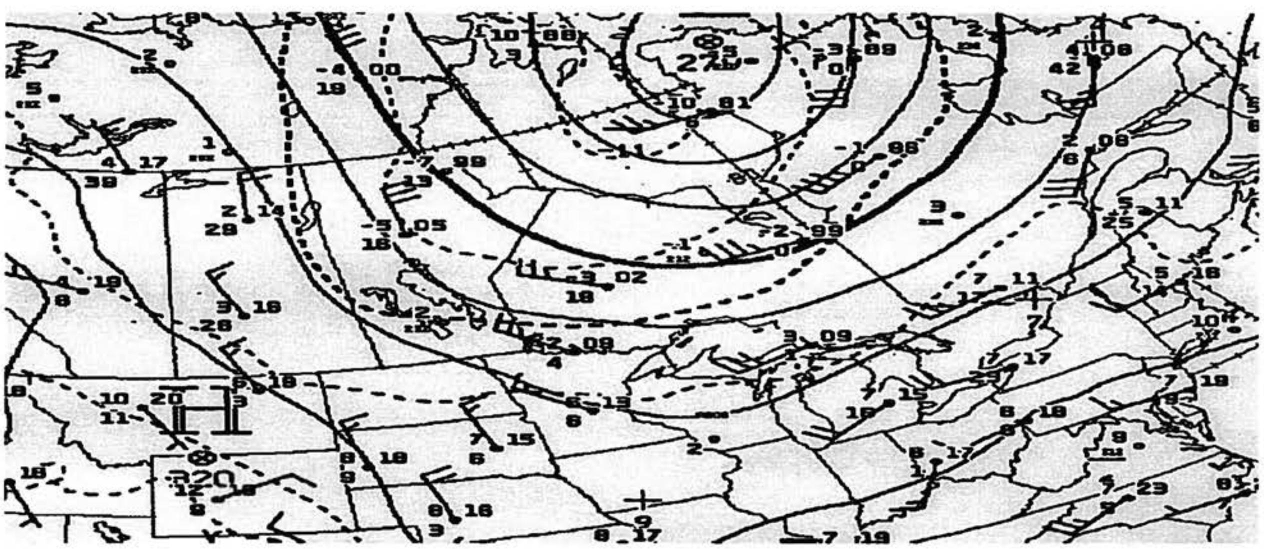


Figure 4 Altitude 700 mb at 00 GMT on August 4 ,1994

At 500 mb (fig 5a and b), there is a short-wave from Iowa toward Sault-Ste-Mary supporting the cold front. Another stronger short-wave is coming down from Northwestern Ontario and is associated with an influx of cold air (-21 degrees).

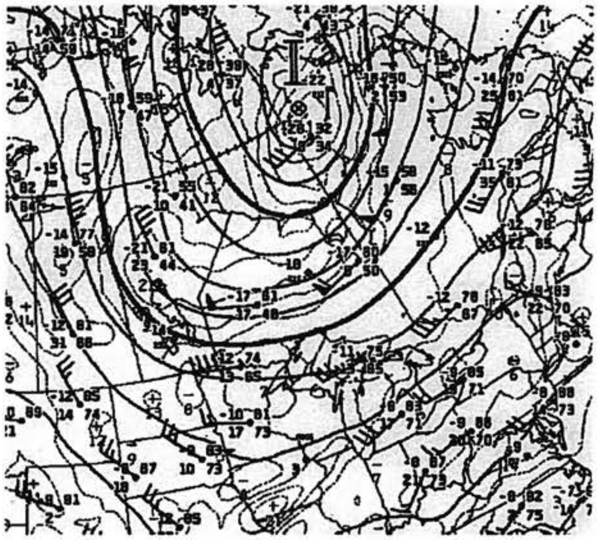


Figure 5a Vorticity at 500 mb on August 4,1994

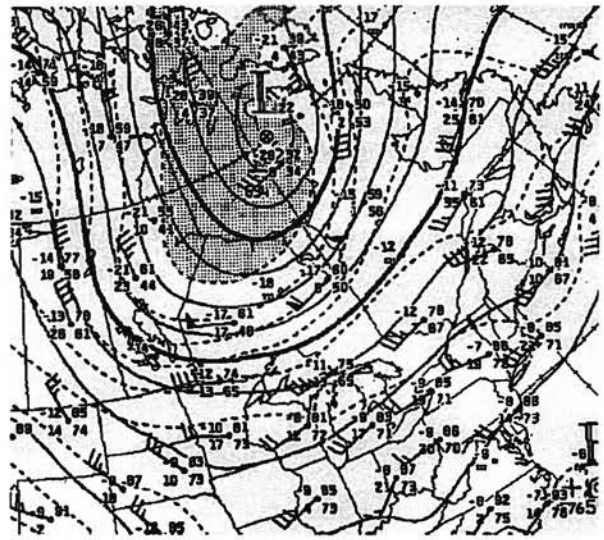


Figure 5b Thickness at 500 mb on August 4,1994

Finally at 250 mb (fig. 6), there is a Jet-Stream of 99 knots at the base of the trough, not really yet in a good position to enhance the surface low.

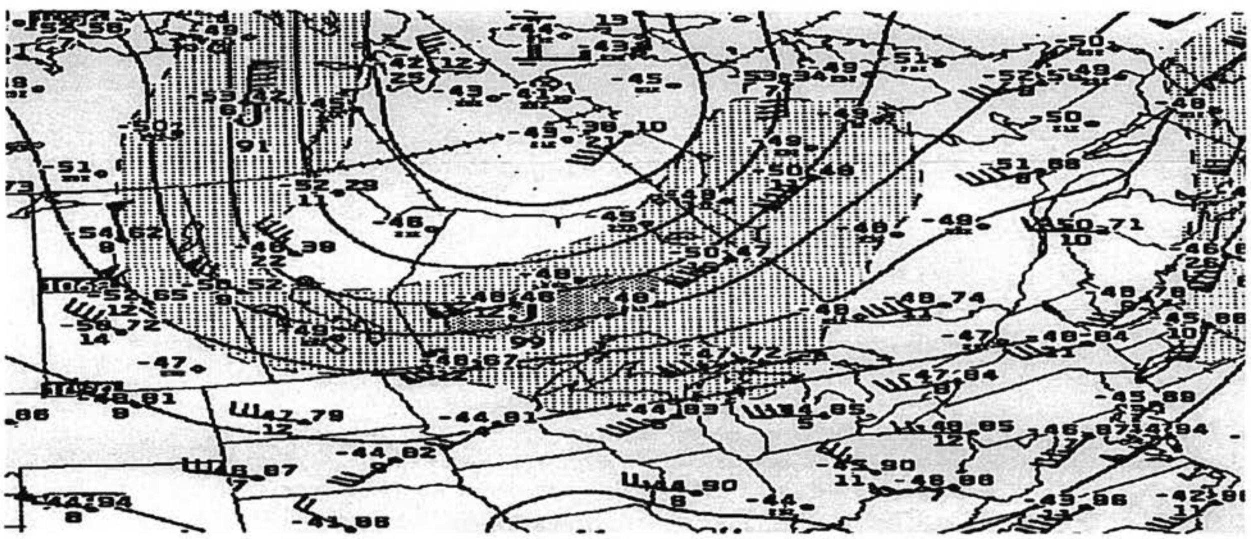


Figure 6 Altitude 250 mb at 00 GMT on August 4,1994

2.2- Thermodynamics

The tephigram of Flint, Michigan (fig. 7a), is the most characteristic of the clear air in the warm sector. It is important to use clear air sounding that have not been yet modified by convection for evaluation of the thermodynamic potential.

The shaded area is the energy balance of a parcel in convection with temperature of 27 degrees Celsius and dew point of 22, characteristic of the warm sector. The tephigram shows a rather unstable airmass, quite dry in mid levels with possible Cumulo-Nimbus(CB) tops of 45 to 50 thousands feet.

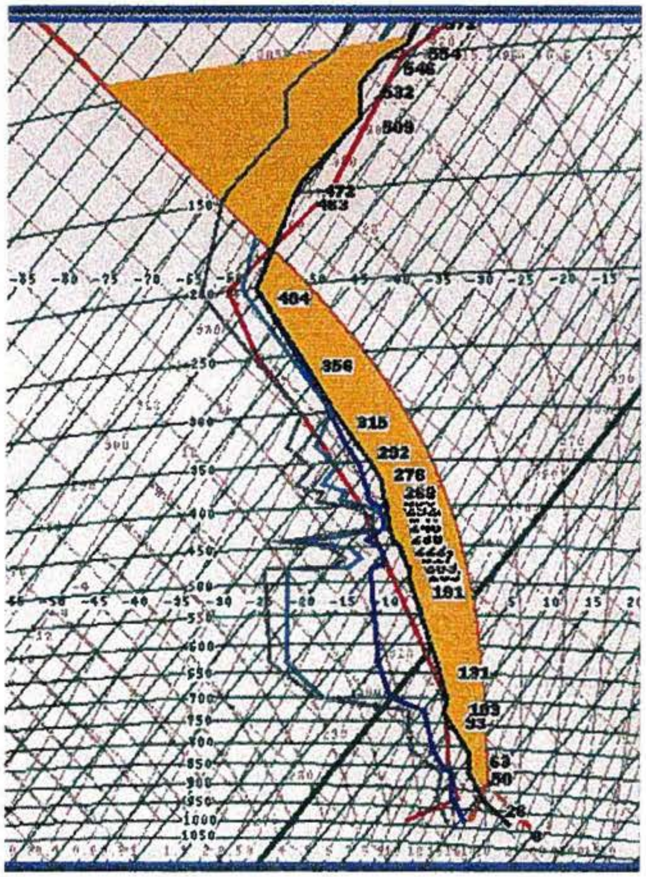


Figure 7a Tephigram of Flint, Michigan at 00 GMT

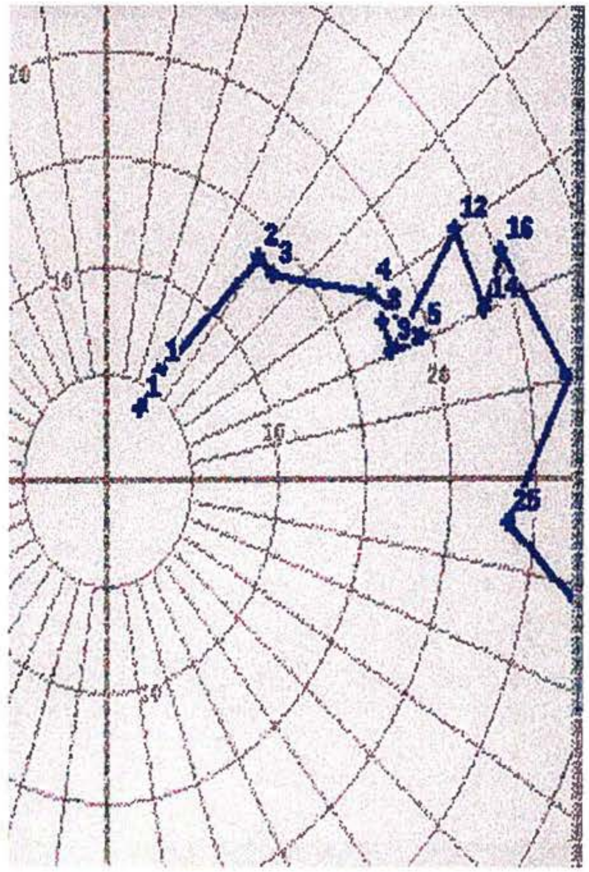


Figure 7b Hodograph

The hodograph (fig.7b), show a slightly clockwise rotation shear up to 16 thousand feet and rotating more above that. This is favorable to supercells, too.

The total CAPE is 2200 J/kg with a SHEAR of 4.8 x 10^{-3} /sec giving a SSI of 98. So the thermodynamics are marginally favorable to severe weather. The analysis the other indexes shows possibility of heavy downpour (PCPTW = 32 mm/m^3), strong to damaging downdraft ()2_e=18) but only a slight possibility of small hail. The motion of the stronger cells should be 275 degrees at 30 m/s.

If the same tephigram is redone but with a temperature of 29 degrees (2 degrees more than before), the CAPE increase to 2800, SSI to 109 and EHI gives a possibility of an F2 tornadoes. So the surface maximum temperature is quite a sensitive variable in this case.

The situation in that warm sector is very unstable with thunderstorms having a marginal potential for severe weather. One of the key element missing is a strong low level jet.

2.3- Forecast

The multi-panels (fig 8) of the RFE model shows that the surface low would slightly deepened to 1008 mb and move to Lake Huron for 1200 GMT on the 4th ,supported by the short-wave at 500 mb coming from the American Mid-West. The stronger short-wave from northwestern Ontario is accelerating toward the low, too.

By 00 GMT on the 5 th, the low pressure is northwest of Montreal, under a stronger double short-wave at 500 mb and moving the warm sector over southwestern Quebec. The multi-panels (fig 9) show that the Jet-Stream would be 128 knots by that time and that the low would be under the right entrance to the jet, quite a good position for development.

Finally, a low level jet of 45 knots was expected to develop by 1200 GMT in the warm sector and move to be along the St.-Lawrence Valley from Trois-Rivières to Windsor by 00 GMT.

The figure 10 shows a composite map of the dynamic factors at 00 GMT the 4th and their forecast position (fig. 11) at 1800 GMT. This shows a great potential for severe weather in the warm sector northwest of the low level jet during the afternoon of the 4th.

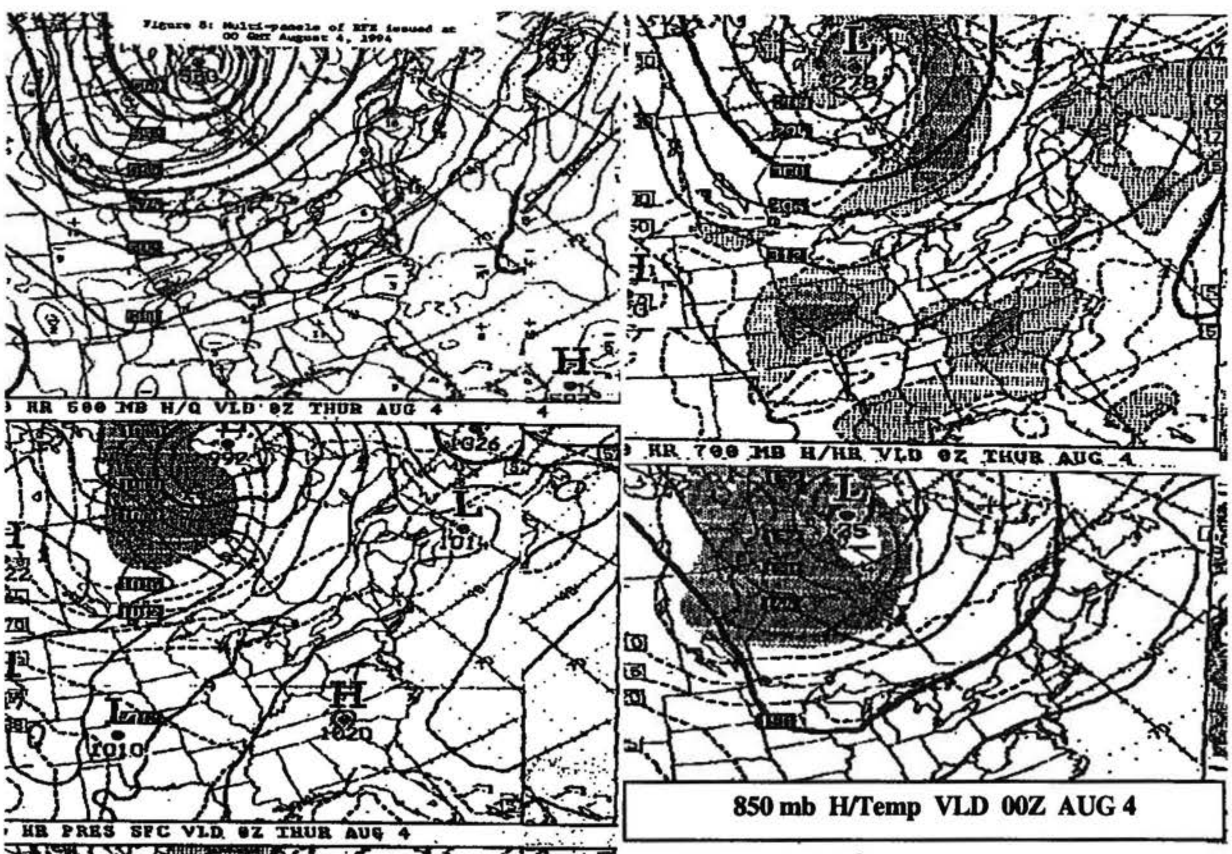


Figure 8a : RFE analysis at 00Z on August 4th 1994

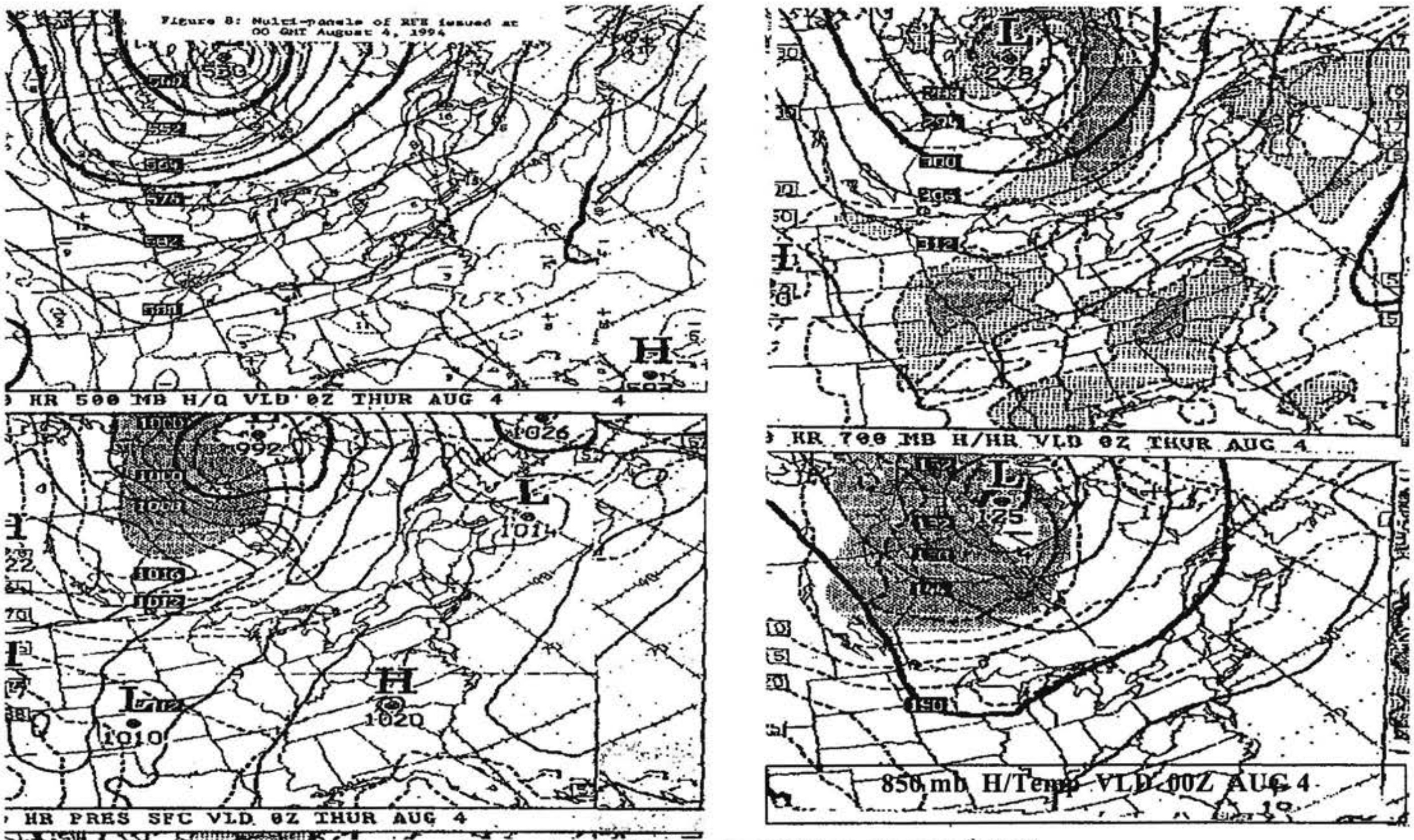


Figure 8a : RFE analysis at 00Z on August 4th 1994

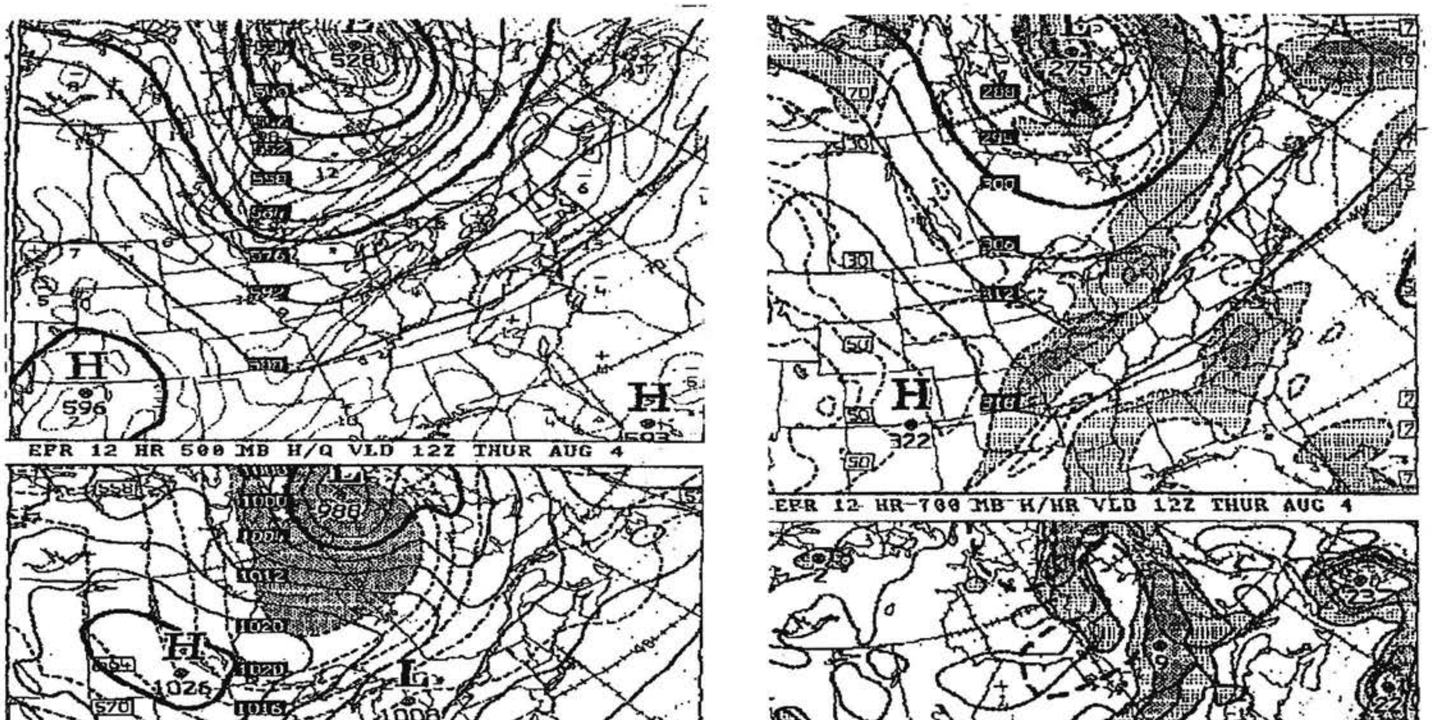


Figure 8b : RFE prognosis for 12Z on August 4th 1994

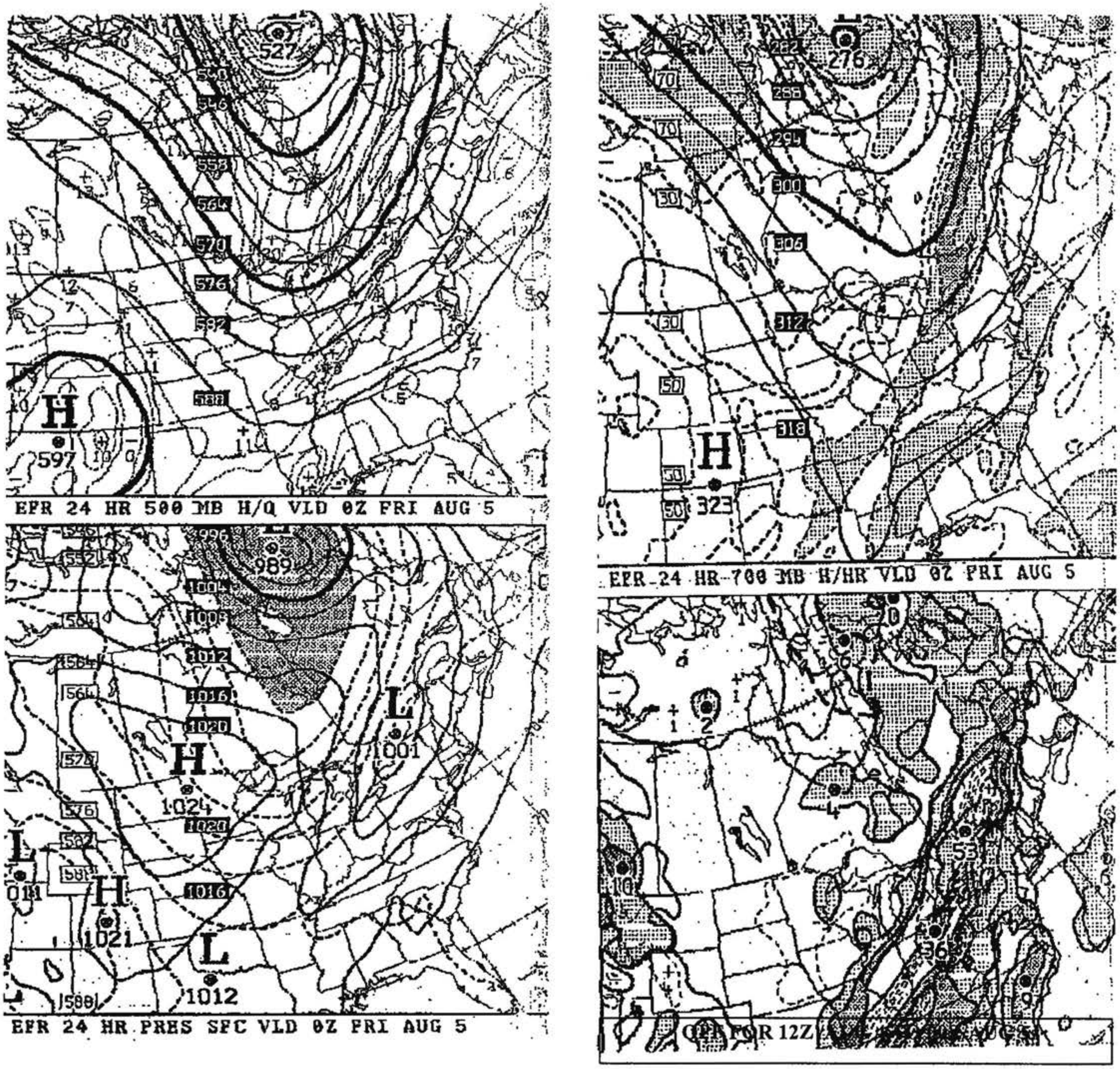


Figure 8c : RFE prognosis for 00Z for August 5th 1994

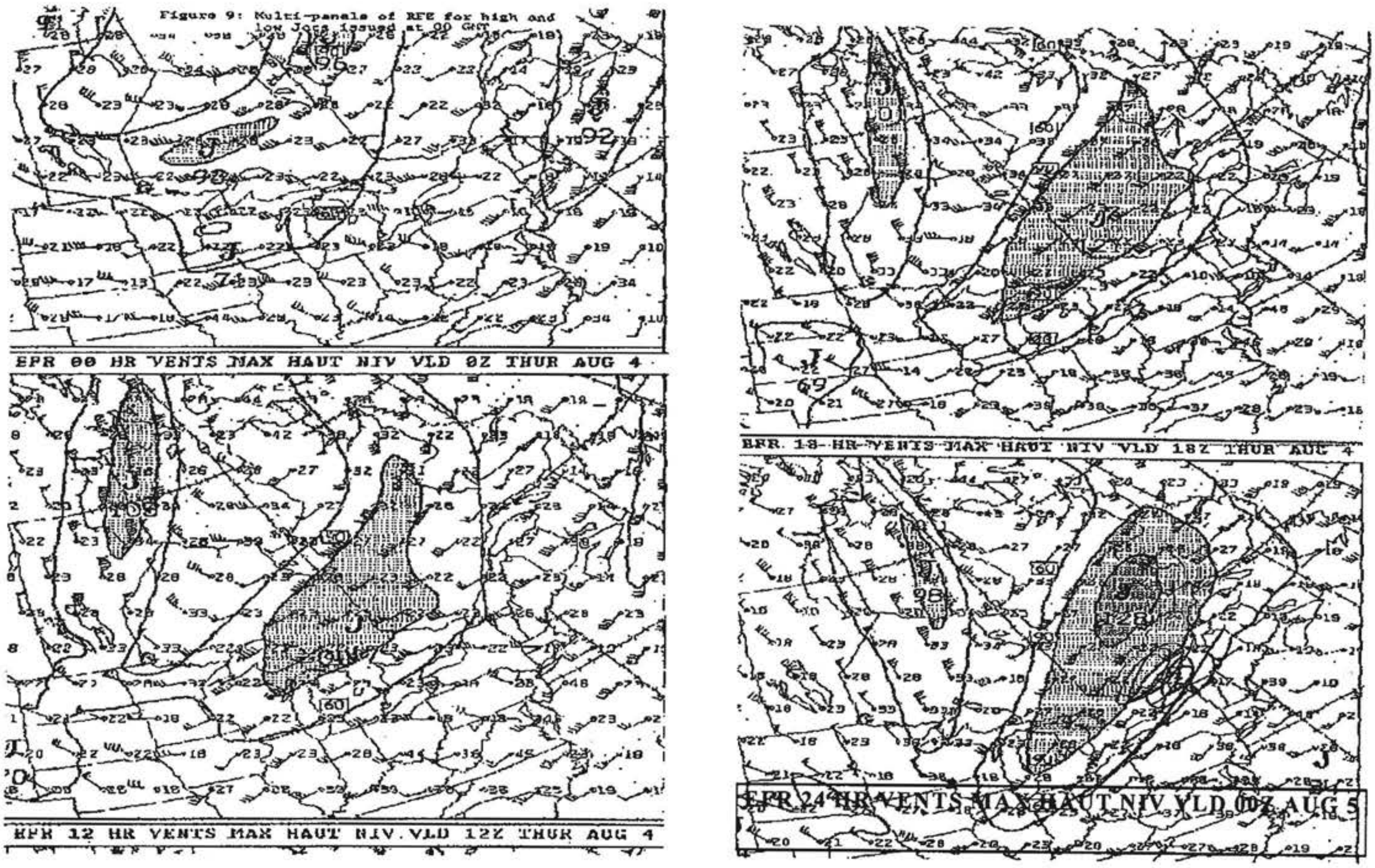


Figure 9a : RFE prognosis for Max Winds at High Levels (Jet-Stream) for 00hr, 12hr, 18hr and 24 hr

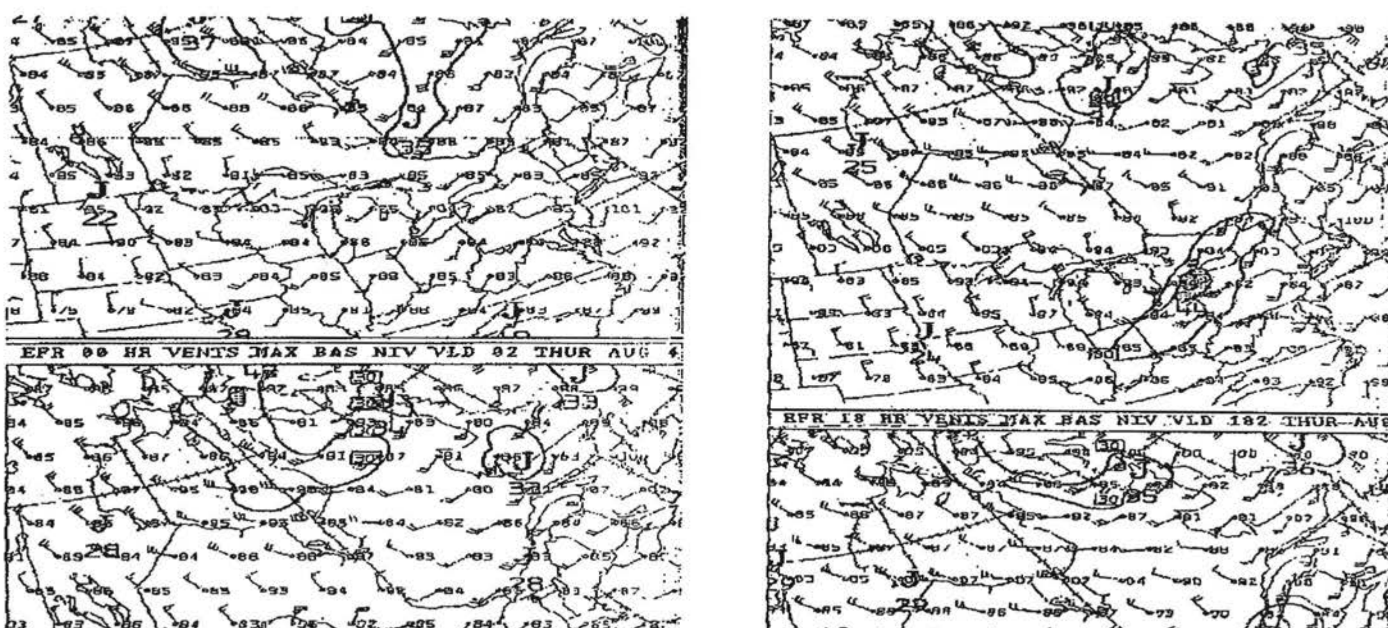


Figure 9b : RFE prognosis for Max Winds at Low Levels for 00hr, 12hr, 18hr and 24 hr

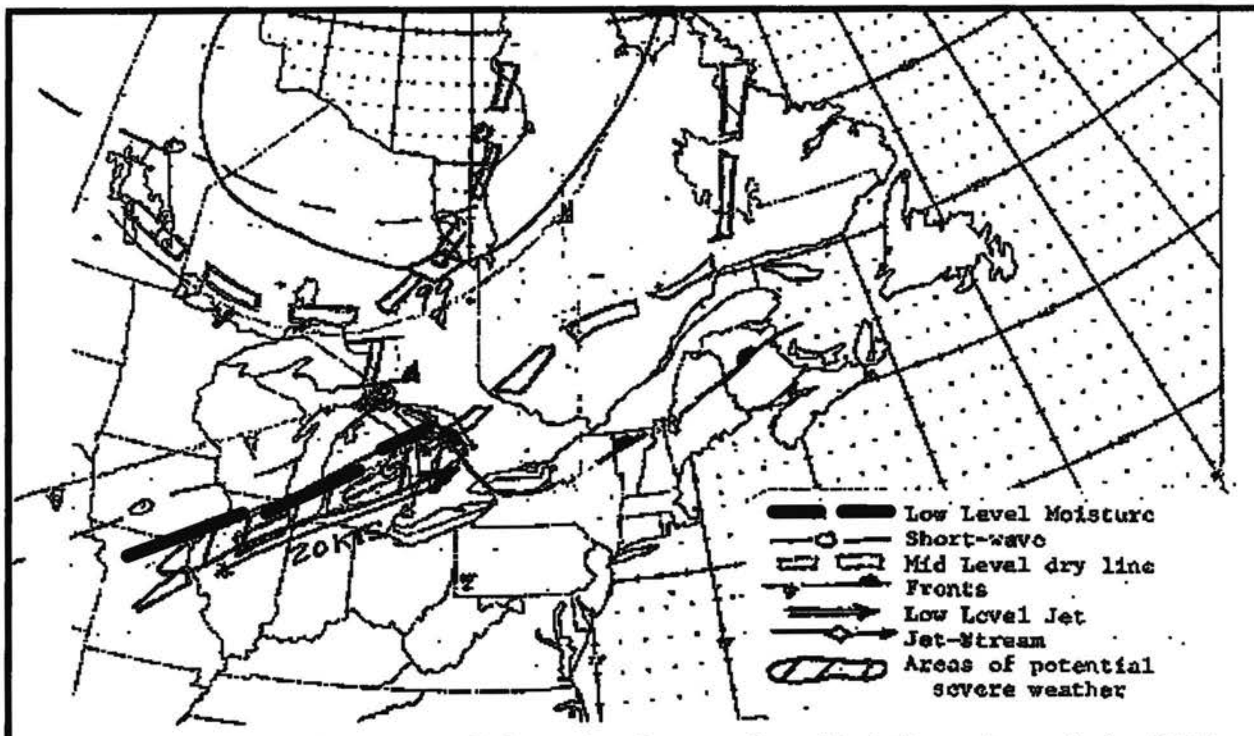


Figure 10: Composite Map of dynamic factors for 00 GMT on August 4, 1994

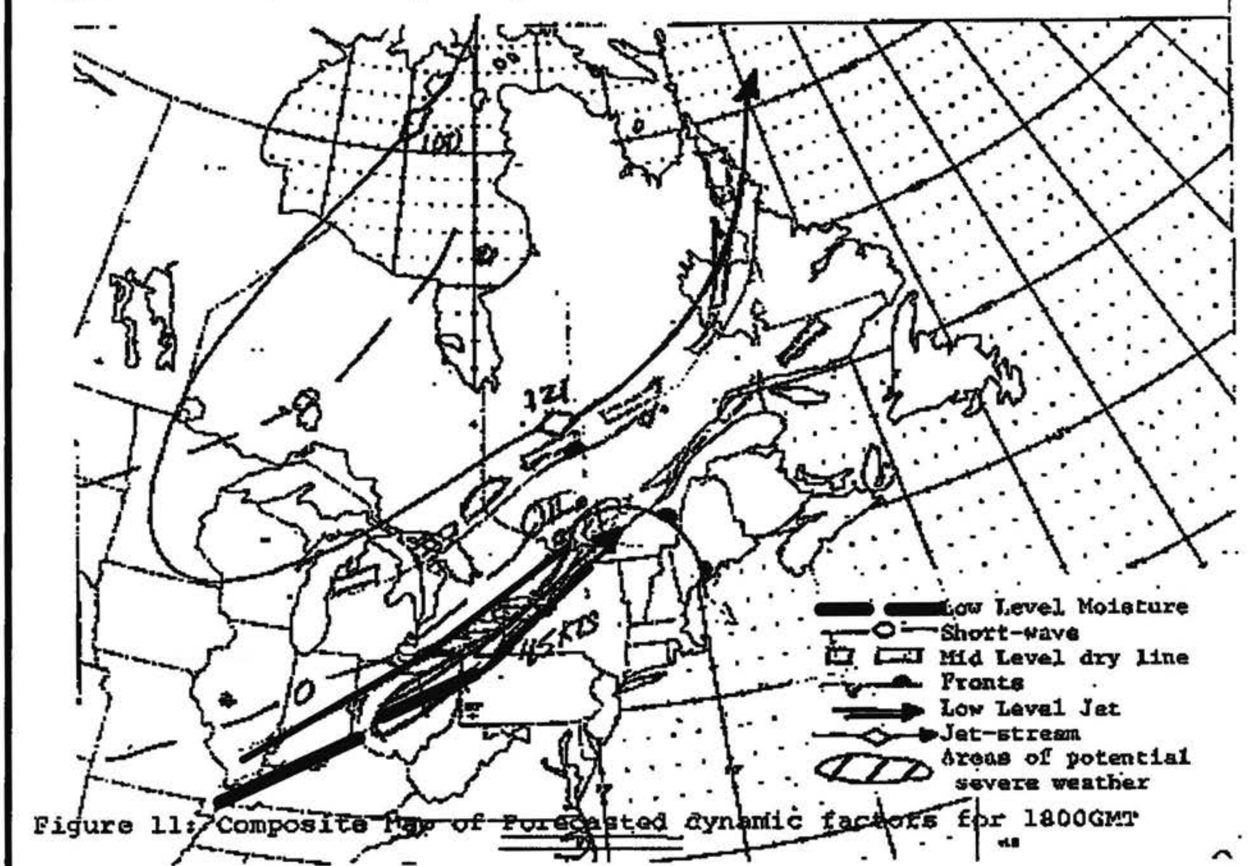


Figure 11: Composite Map of Forecasted dynamic factors for 1800GMT

- Situation on morning of the 4th

3.1- Synoptic situation

Figure 12, surface map at 1200 GMT, shows that the low pressure has moved as predicted to Georgian Bay/Northern Lake Huron with the maritime warm front along the Ottawa river and the cold front extends toward Chicago.

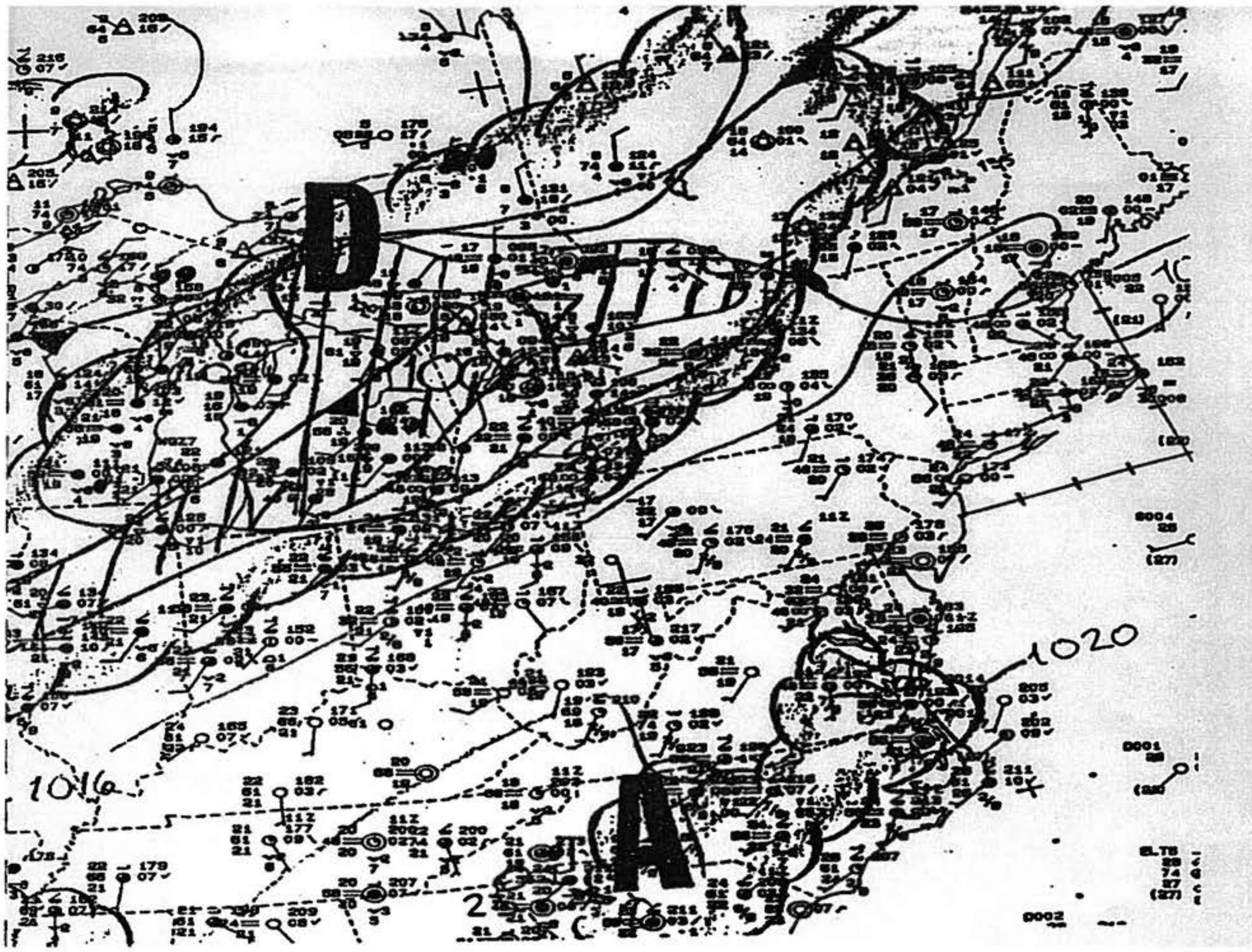


Figure 8 Surface Map of 1200 GMT on August 4,1994

The arctic cold front is now south of Val d'Or giving quite a strong temperature contrast between the maritime warm sector (temperatures of 20 to 22 degrees dropping to 8 degrees within 120 nautical miles). This configuration of fronts is giving a convergence of winds along the warm front that is quite favorable to a lift in the lower levels of the atmosphere.

The clouds (fig. 13) are covering most of central and southern Quebec ahead of the arctic front and quite a good part of the maritime sector. The southern edge of the clouds is more or less along a line from Lake Erie to Montreal then Bagotville. There is a band of showers, locally moderate, that has survived the night in the warm sector. It proves that the dynamic is quite strong.

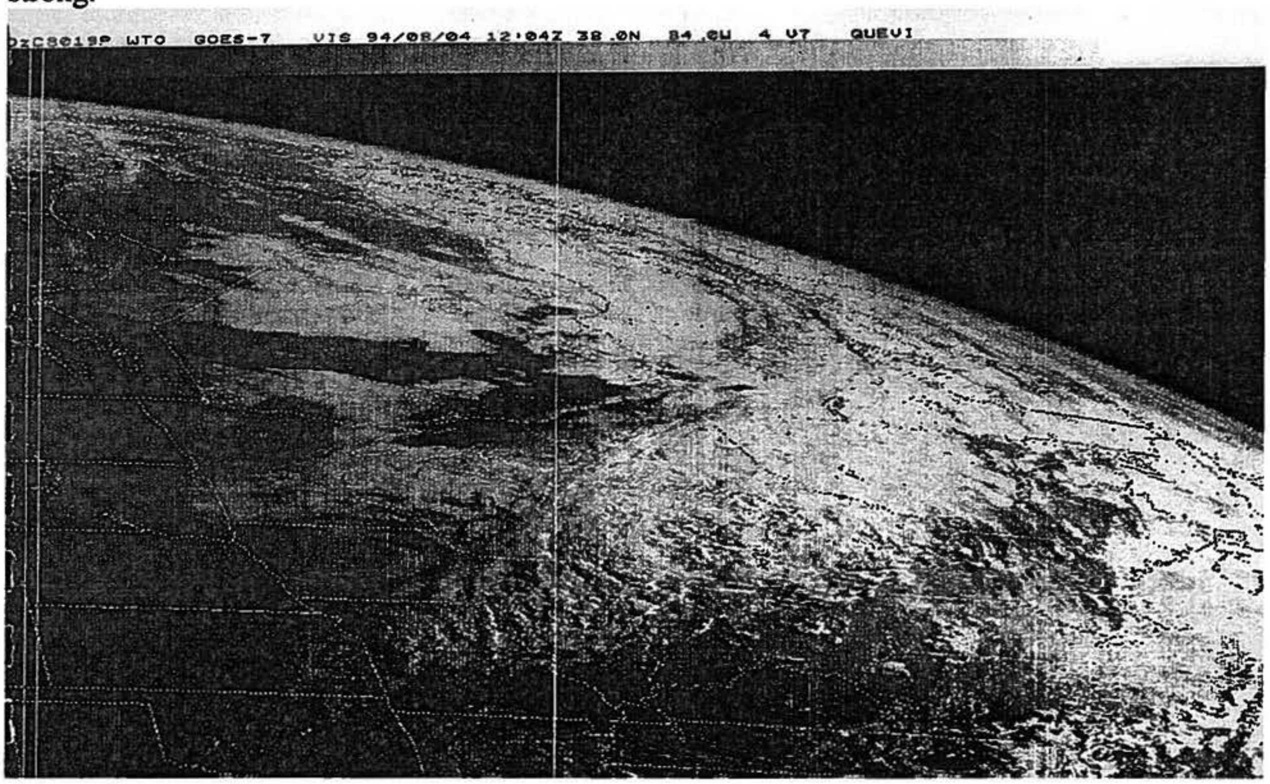


Figure 9 Visible Satellite Picture of 1200 GMT on august 4,1994

Figure 14 (850 mb) shows that the winds have now reached 45 knots, as expected, in the maritime warm sector. The air quite saturated (dew point depression of 1 to 3 degrees).

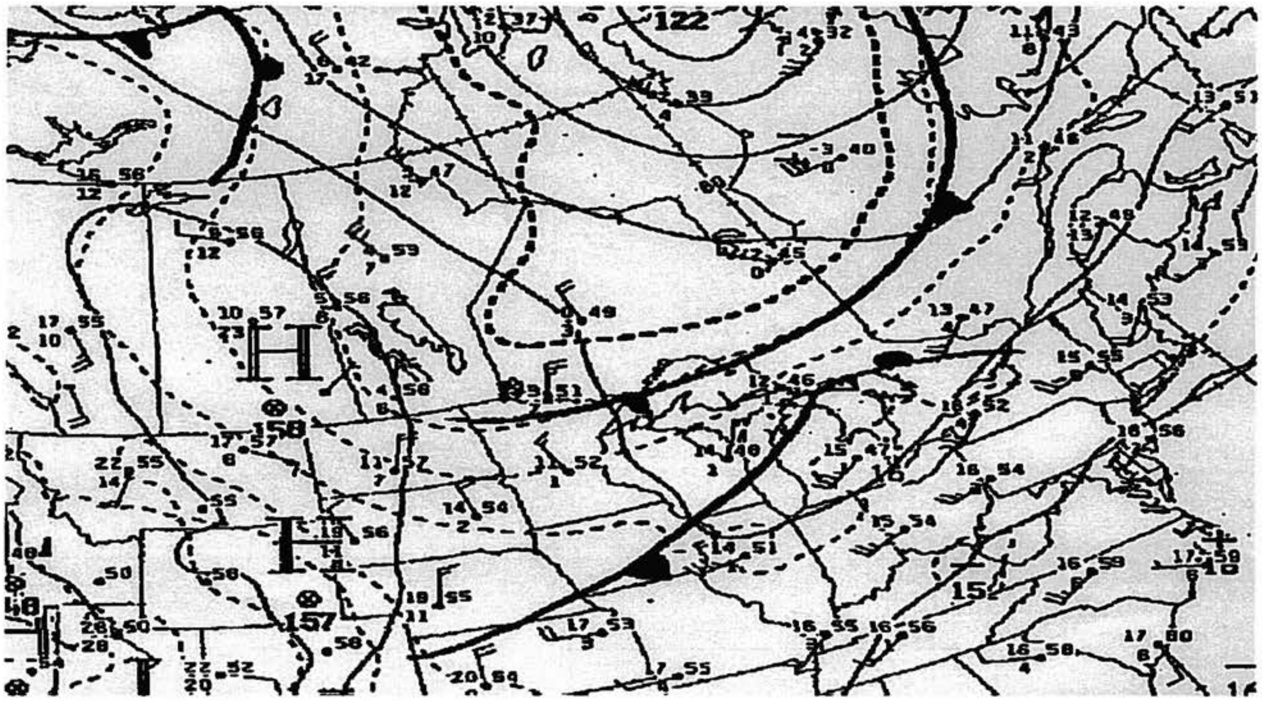


Figure 10 Altitude 850 mb at 1200 GMT on August 4,1994

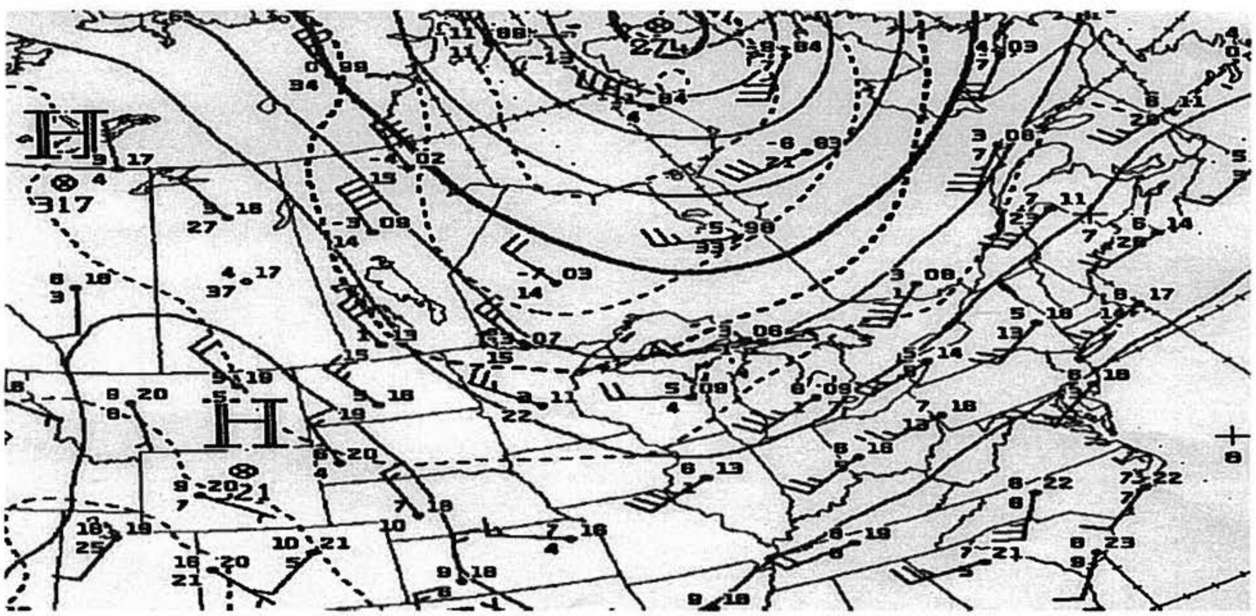


Figure 11 Altitude 700 mb at 1200 GMT on August 4,1994

At 700 mb (fig. 15), the cold and dry air from northern Ontario is pushing over Lake Superior, coming toward the maritime warm sector. This helps the development of the surface low.

Finally at 500 mb (fig. 16), the two short-waves are converging and the Jet-Stream is strengthening . Everything is proceeding as expected.

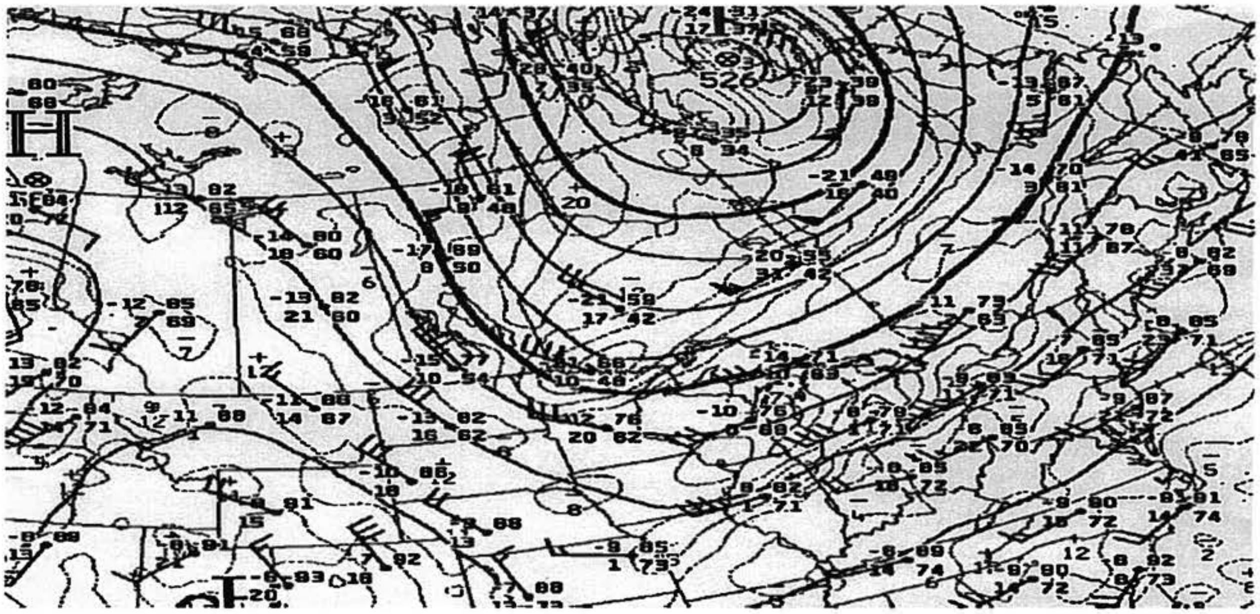
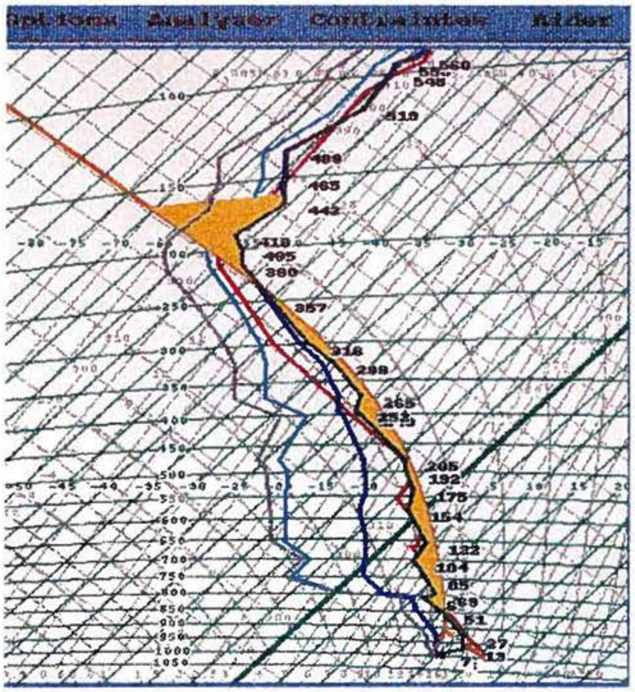


Figure 12 Altitude 500 mb at 1200 GMT on August 4,1994

3.2- Thermodynamic

There is no tephigram fully satisfying to look at on the morning of the 4th. The clouds are covering Maniwaki; Buffalo and Albany are south of the low level Jet and have some subsidence effects. Here are some points we can analyze however:

- The tephigram of Albany (fig. 17a) shows a subsidence from 400 to 800 mb, forming a weak capping for the convection at 500 mb. To compound that, there is an inversion below 950 mb the temperature must reach 30 degrees to be brake it.



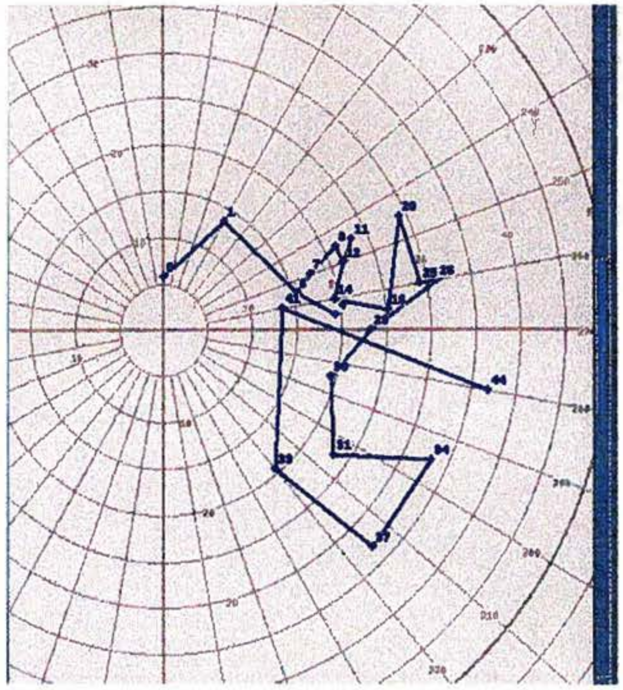


Figure 13a Tephigram of Albany, NY, at 1200 GMT   Figure 17b Hodograph

The analysis of the indices by STRATUS gives an SSI of 72 with the expected maximum of the day of 26 to 28 degrees. CAPE is only 600 J/kg but on the hodograph (fig. 17b) the SHEAR of 6.4×10^{-3}/sec is moderate and with a clockwise rotation.)2_e is 18.

Although, this tephigram is not conducive to severe weather, it would be if the capping was broken. The region to the north of the Jet should have enough convergence in the low levels to do the trick.

- The tephigram of Maniwaki (fig. 18a) is just north of the warm front. It is completely humid showing that it is in the clouds up to 40 thousands feet. The hodograph (fig. 18b) has a relatively linear SHEAR up to 8 thousand feet but then make a loop between 8 and 20 thousand feet.

The temperature follows more or less the pseudo-adiabate of a convective cloud. The shaded area shows the modification if we raise the temperature to 24 degrees and the dew point to 20 as in the warm sector. This will happen with the push of the warm front over Maniwaki.

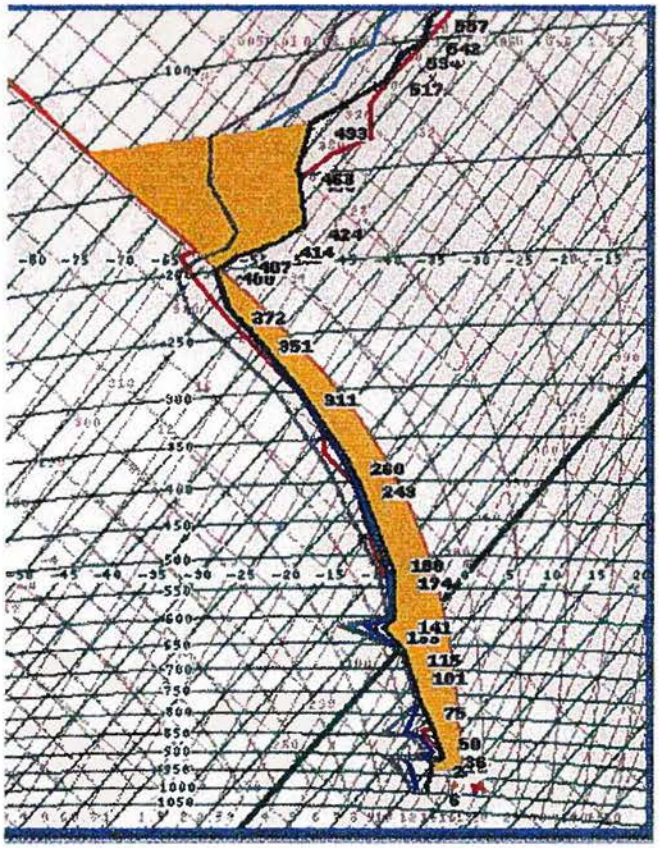


Figure 14a Tephigram of Maniwaki,Qc, at 1200 GMT

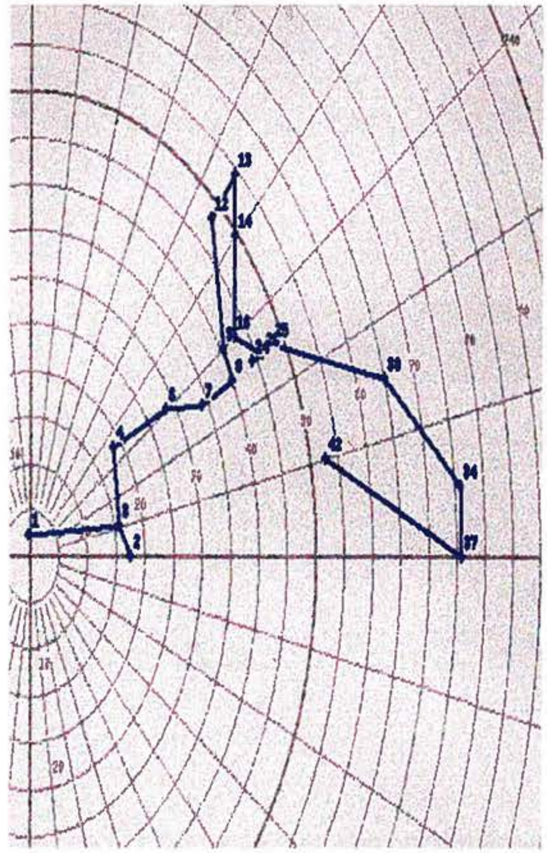


Figure 18b Hodograph

This modification gives a CAPE of 1800 J/kg with a strong SHEAR of $10x10^{-3}$/sec, bringing the SSI to 109. The possibility of heavy downpour (PCPTW of 37 mm/m^3), large hail and F2 tornadoes (EHI of 1.12) are threatening. Since the airmass is so moist ()2_e is only 2), damaging downdrafts are unlikely.

In conclusion, these tephigrams shows that the warm sector has increased its potential for severe weather but that there is two different possibilities:

1. Along the southern edge of the clouds in the warm sector where warming and the low level Jet could cause a destabilization of the airmass characterized by the tephigram of Albany. This would give damaging downdrafts and local heavy downpours.

2. Along the warm front itself where convergence at surface and the low level jet would give convection typical of Maniwaki's tephigram. Heavy downpours, some hail and a strong possibility of a tornado are to be expected.

3.3- Forecast

By 1400 GMT, a watch has been issued that morning for the potential of severe weather of southwestern Quebec for all the areas were the warm sector would pass.

4- The severe events

4.1-Radar criterias for detection of severe weather

4.1.1- Reflectivity Overhang:

The theory shows that in a storm a core of precipitation is formed by the updraft and eventually a region of weak echo will develop under this precipitation if the upward movement is very strong. Experience has shown that severe weather is associated with a core of 50 dBZ or more at 7 km or above with a slope in the reflectivities that give an overhang.

4.1.2- Meso-cyclonic circulations:

The meso-cyclonic circulations are associated with transfer of horizontal vortex to a vertical one by the updraft. Studies show that in 90% of cases where meso-cyclone has been detected there has been some damaging winds reported and in 50% of those cases there was a tornado.

4.1.3- Shear in low levels:

Downdrafts fan out when they reach the ground and such a shear can be analyze from Doppler radar output.

4.1.4- Vertical Integrated Liquid Content (VIL) and associated GUST:

The summation of reflectivities in the vertical can be converted to the total amount of liquid water in the cloud:

$$\text{VIL (Kg/m}^2\text{)} = G\, Z^{4/7} \text{ (dBZ of Reflectivity)}$$

This water will eventually fall as precipitation and push air toward the ground. One can associate a maximum gust to that downdraft. IT depends on VIL and the vertical extend of the cloud (its top) as:

$$\text{Max GUST(m/s)} = [(20.6 \times \text{VIL}) + (3.1 \times \text{ET}^2)]^{1/2}$$

Such an algorithm is available on the McGill Doppler Radar.

4.2- The events

4.2.1- Aylmer

By 1800 GMT, a strong cell was developing northwest of Ottawa near the low pressure and along the warm front (fig. 19). It gave a F2 tornado over Aylmer, a Quebec suburb of Ottawa, at 1900 GMT causing heavy material damages but no lost of life. This cell was out of range for the McGill radar.

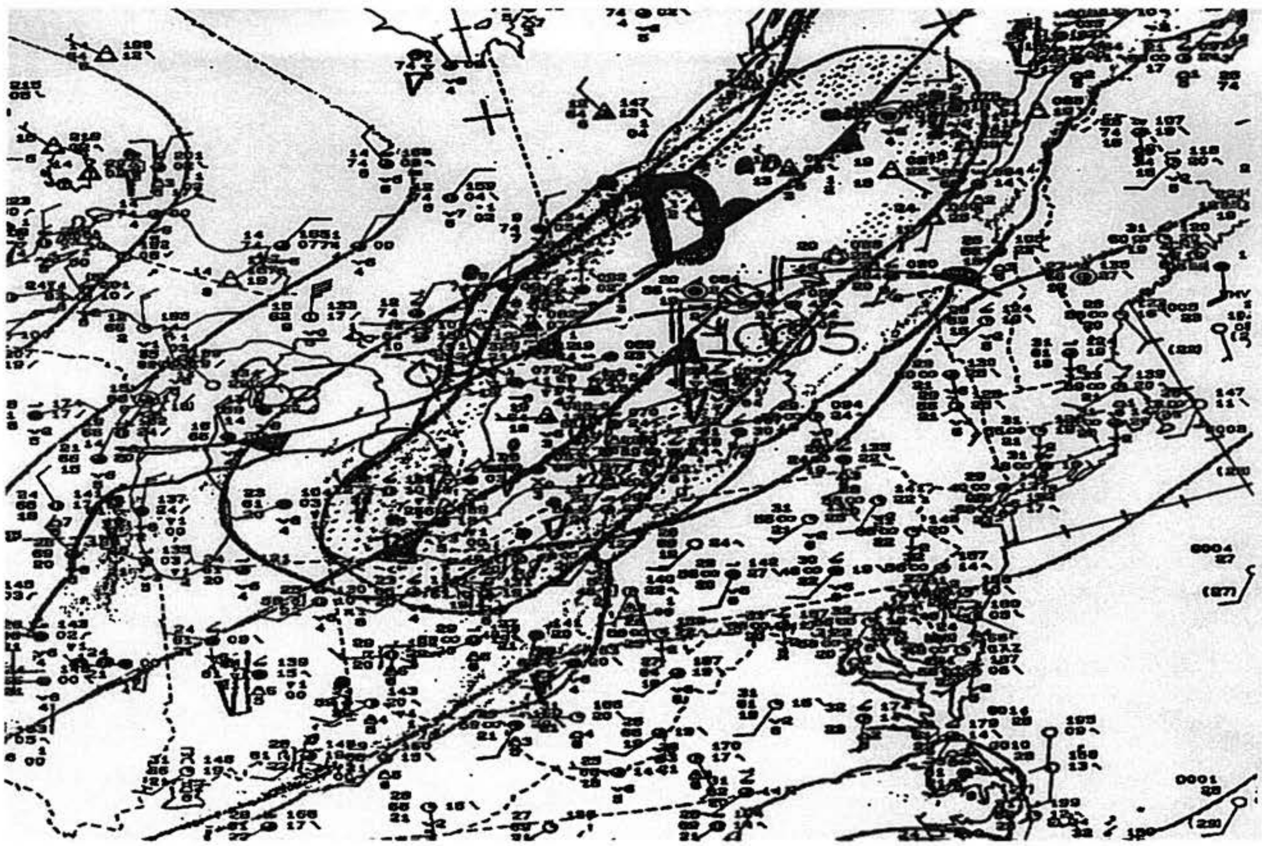


Figure 15 Surface Map at 1800 GMT on August 4, 1994

4.2.2- Laurel, Rawdon, Maskinongé

At 1801 GMT, the radar (fig. 20) show another cell near Papineauville (mid point between Ottawa and Montreal) with reflectivities of 50 dBZ (50 mm/h) at an altitude of 2.5 km which is already quite strong. You can see that is has formed along the warm front just on the edge of the clouds were the heating contrast is higher. Figure 21 shows a cross section of that cell in the direction of its motion. We can see that it extends up to 8 km above ground but that the core of the reflectivities is below 6 km and the gradient of reflectivities is beginning to show a slope in the direction of motion.

The cell developed rapidly. By 1825 GMT (fig. 22), a cross section in a direction perpendicular to its motion shows a core of more than 62 dBZ at 6 km, a top at 10 km and a slope in the reflectivities characteristic of a weak echo region at low altitude. Figure 23 is a view of the field of radial velocities for the same time with correction to make them relative to the storm. We can see in the square box a doublet of velocities (+18 m/s and -10 m/s) characteristic of a meso-cyclone. Both of those facts point clearly to a severe supercell moving across the lower Laurentians.

Figures 24 give the trace of rain of the Papineauville cell from 1800 GMT to 2100 GMT and from two other supercells that passed during the same time over the Laurentians. The total amount of rain that those cells (the yellow and red traces) left over a line more or less 20 kilometers wide is up to 50 mm.

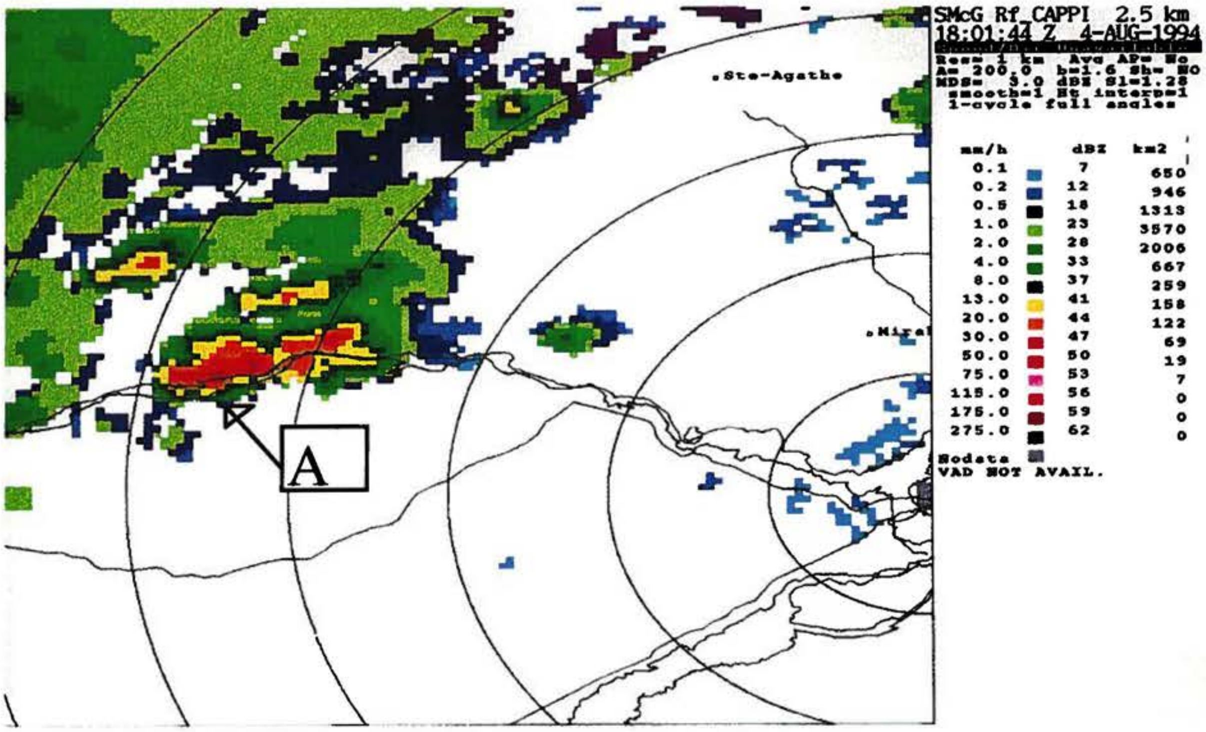


Figure 16: **CAPPI at 2.5 km for reflectivity (1801 GMT). The cell pointed by "A" is the Papineauville supercell.**

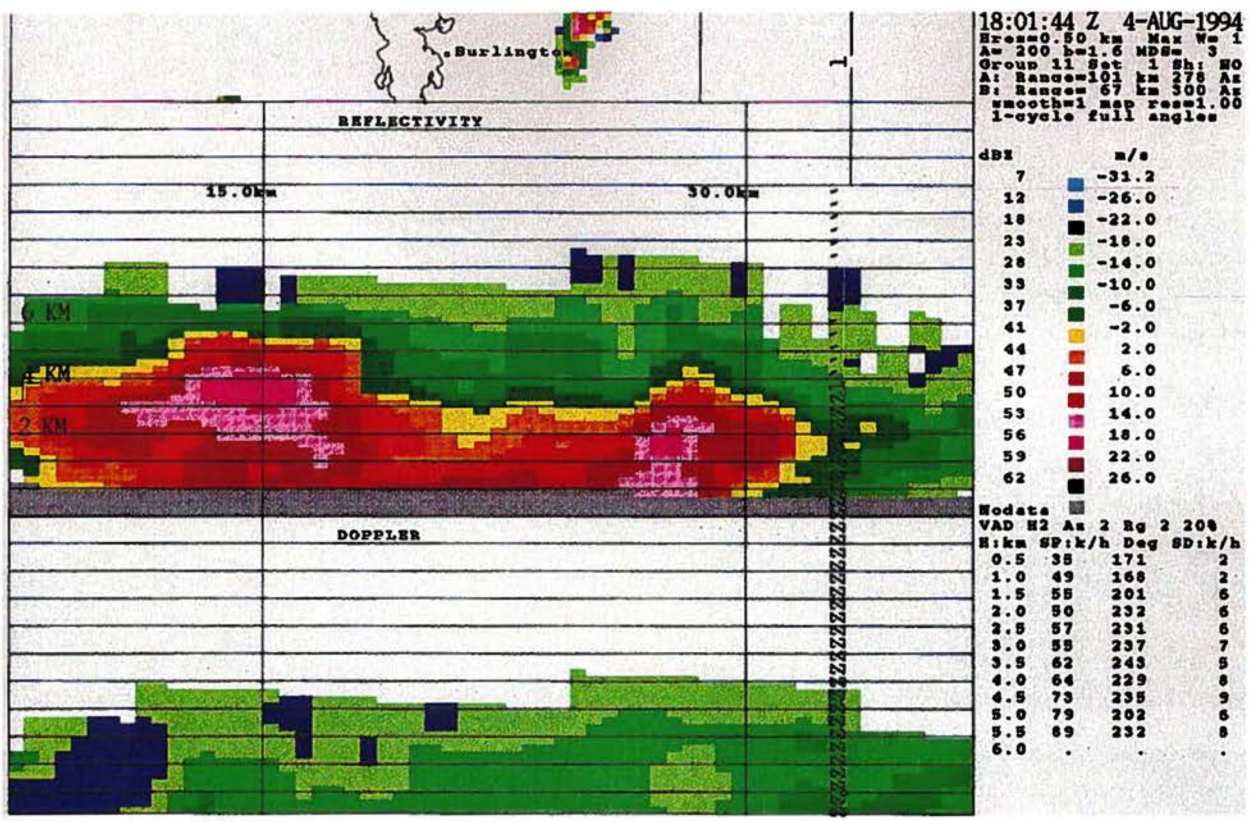


Figure 17: **Vertical cross-sections of reflectivities and velocities for Papineauville supercell at 1801 GMT**

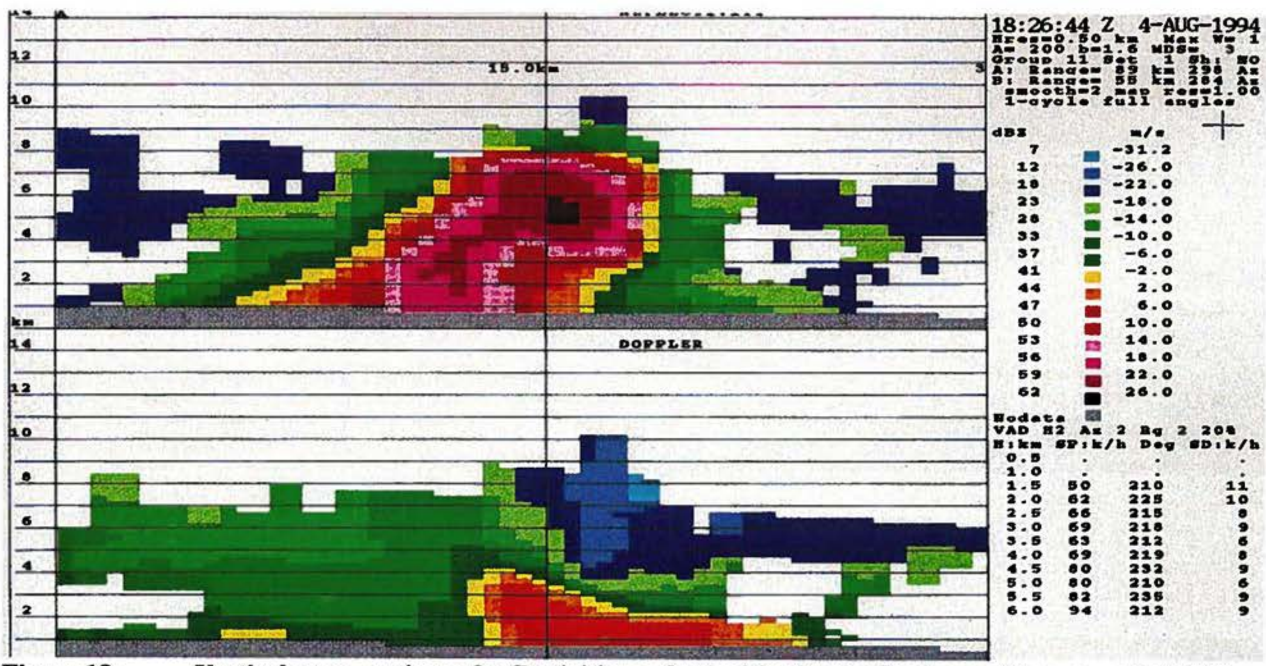


Figure 18: **Vertical cross-sections of reflectivities and velocities for the Papineauville supercell at 1826 GMT**

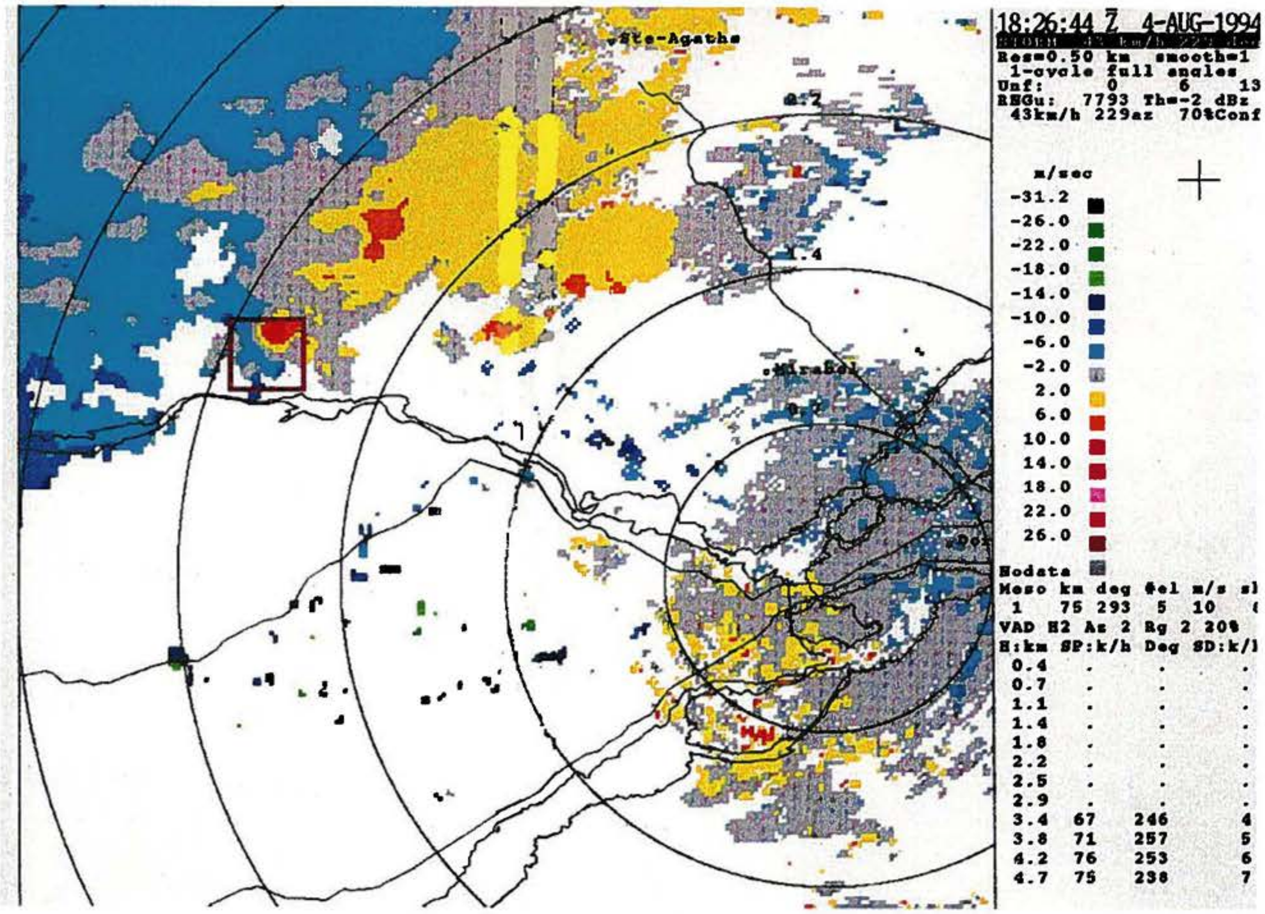


Figure 19: **Storm-relative view of the velocities at 1826 GMT. Meso-cyclone detected in the red square box at elevation no. 7(around 2.7 km above ground at this distance from the radar.**

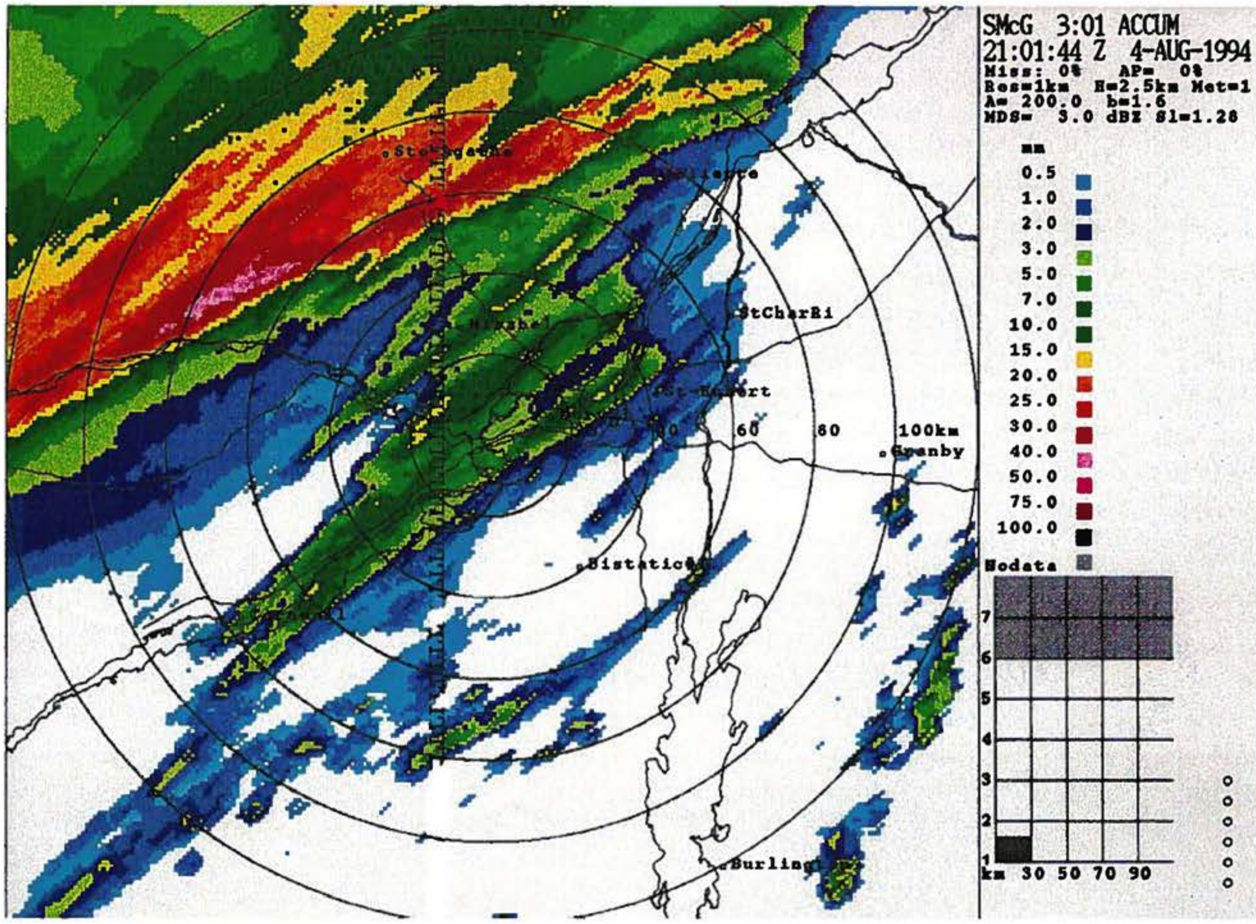


Figure 20: **Accumulation of precipitations from 1800 to 2100 GMT on August 4, 1994. The Papineauville supercell passed along the southern track of 30mm or more.**

We can see a westerly motion of those cells by the trace they left but the general motion of the other precipitations has been more southwesterly. That is characteristic of right mover supercells.

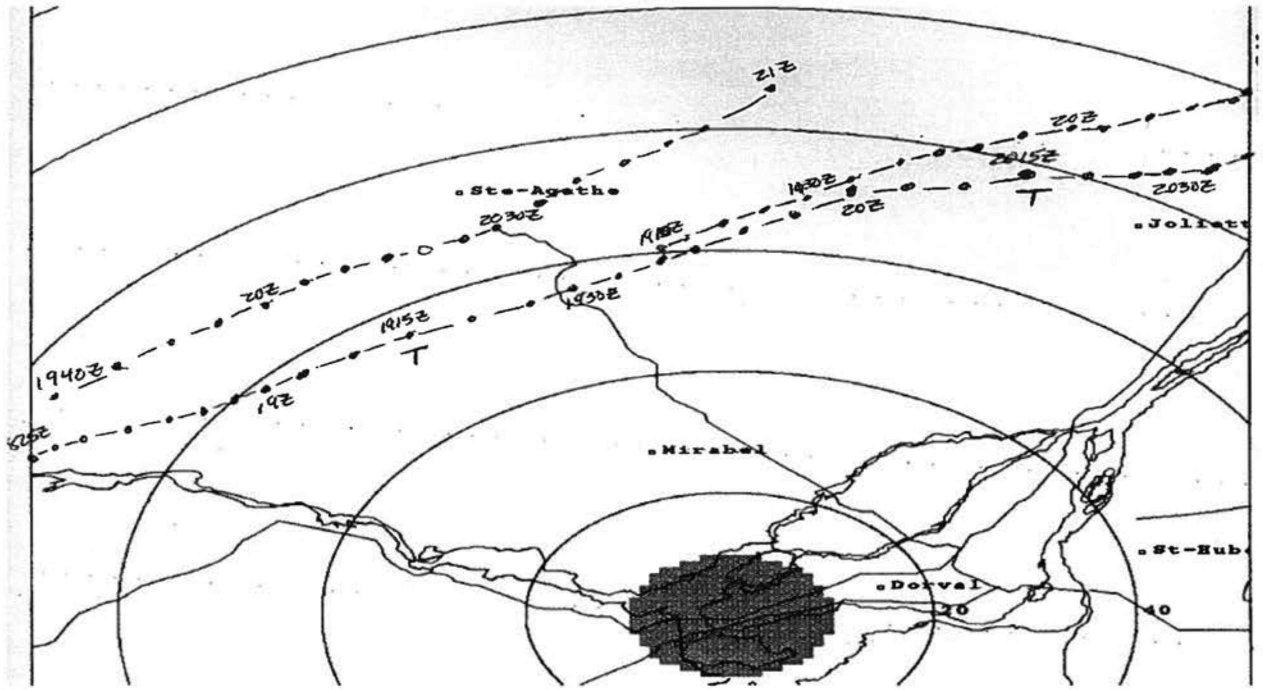


Figure 21 Path of meso-cyclonic circulations of three super-cells

Figure 25 is a trace of the meso-cyclones associated with those supercells. The most southern trace is the one associated with the Papineauville. It gave two confirmed tornadoes (points were there is a "T"): the first in Laurel (F1-2) and the second in Rawdon (F0-1); and a possible third in Maskinongé out of the Doppler radar coverage(by 21Z). No damages were reported by the other two supercells but they passed in sparsely populated areas.

These supercells were quite exceptional for southern Quebec, not by their strength but by the length of time that they lasted, especially their meso-cyclonic signature. A meso-cyclone is usually reported for periods that last from 5 to 20 minutes but the Papineauville cell had one for two hours and a half!

4.2.3- Alexandria

By 2150 GMT, another set of two cells had formed in the warm sector on the edge of the clouds. These cells (fig. 26) moved on each side of the 417 highway that link Ottawa to Montreal. They originated from the same cell. The squares and dots represent the trajectories (each five minutes) of those cells from 2150 to 2330 GMT. The squares are when meso-cyclonic circulations were detected. It is to notice that this detection has been sporadic.

We notice that the two cells are moving apart and the one to the south is credited for a weaker tornado in Alexandria at 2215 GMT. This behavior is characteristic of supercells splitting where the right moving cell is favored for severe weather.

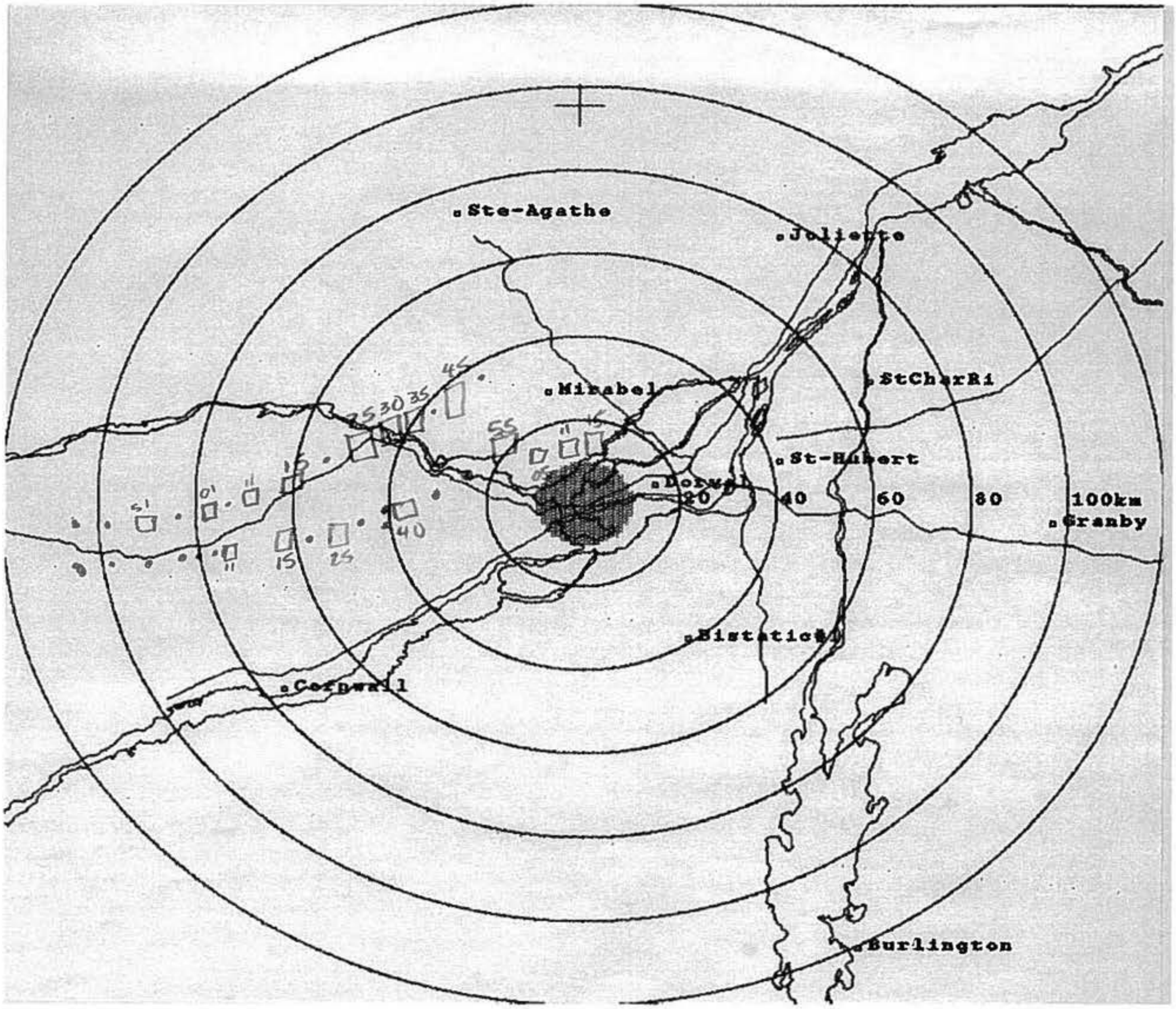


Figure 22 Path of two supercells. The southern one giving a tornado in Alexandria,On,

On figure 27, (2215 GMT at 2.5 km altitude) the reflectivities shows the meso-cyclonic circulations detection (the black square on the center-right of the figure) just at the moment of the tornado. Visible is a certain coma shape of the stronger echoes that is characteristic of air at mid level moving down behind the thunderstorm, drying the precipitation while forming a downdraft.

The cross section (fig. 28) of the tornadic cell shows a slope in the reflectivities with a strong core of 56 dBZ but mostly under 6 km. And figure 29 is a map of the wind shear at very low altitude giving a shear of ∀ 6 to 8 m/s/km.

These cells, while severe, were marginally so. The main effect seems to have been the downing of the strong low level Jet behind them as suggested by their coma shape. This is characteristic of the type of tephigram that Albany was showing with dry cooler air in mid levels. These cells continued their way through an area north of Montreal but no further damages were recorded.

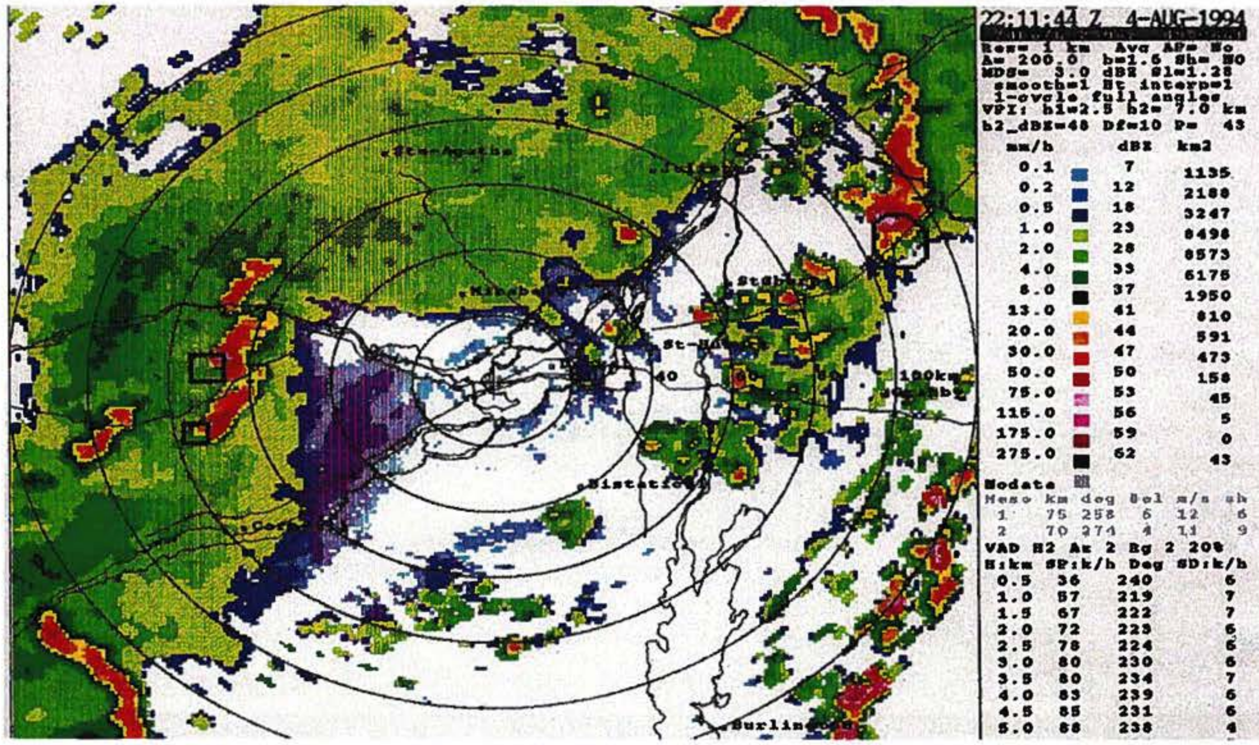


Figure 23: Refelctivities at 2.5 km above ground at 2211 GMT (August 4, 1994). Two thunderstorms have a meso-cyclonic rotation detected (black square boxes. The southern one will give an F! tornado in Alexandria, Ontario.

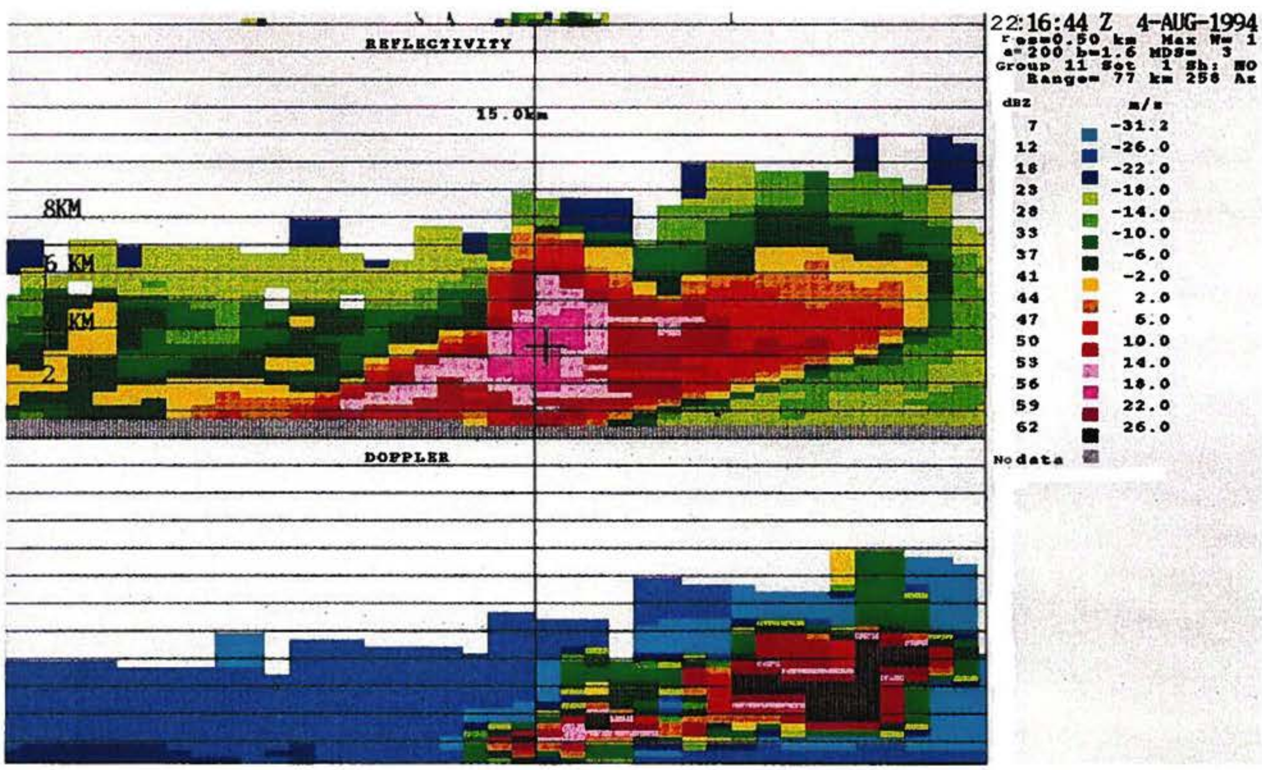


Figure 24: Vertical cross-sections of reflectivities and velocities for the Alexandria cell at 2215 GMT (time of the tornado)

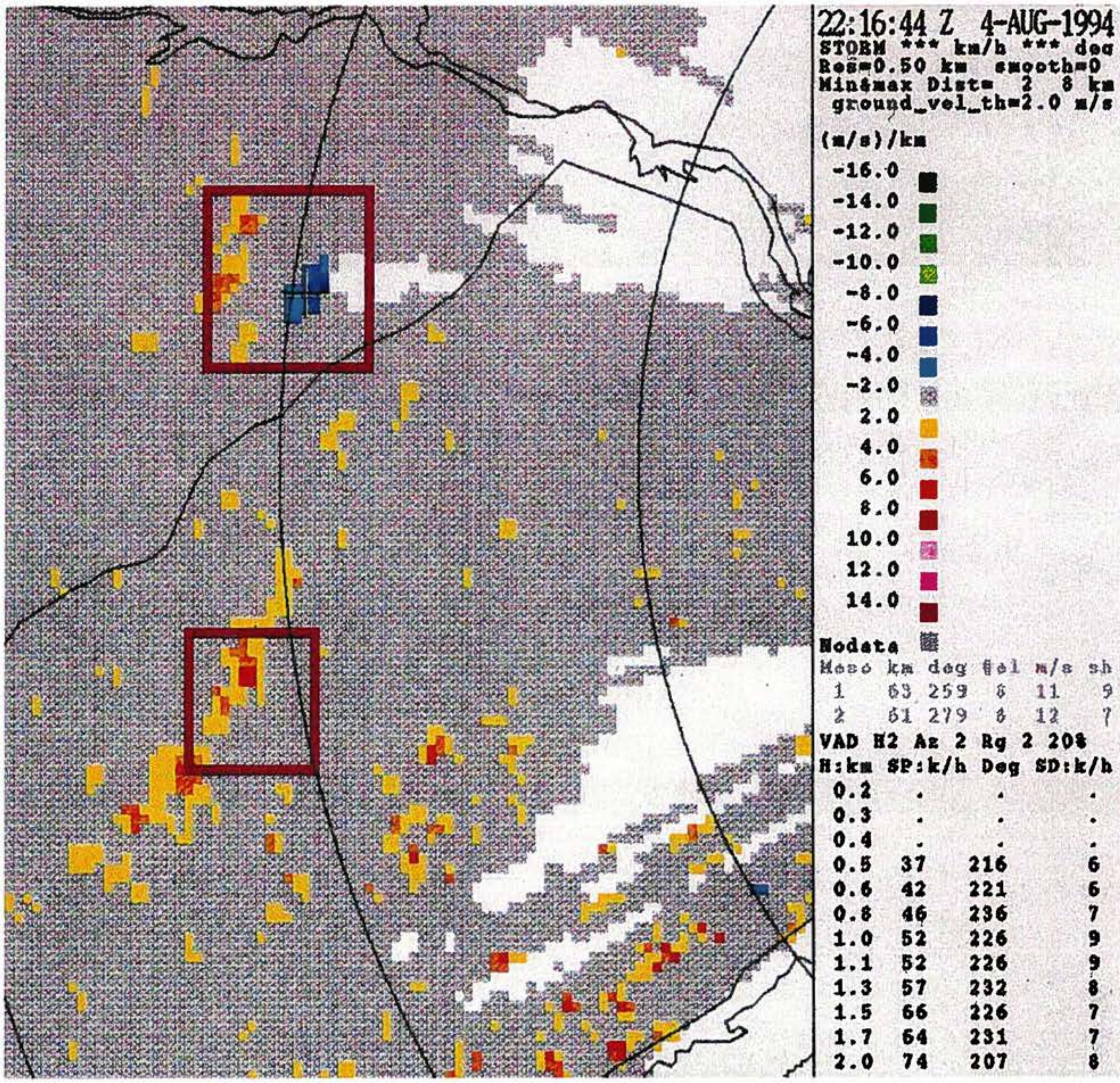


Figure 25: Shear near ground at 2216 GMT. Stronger shear around the two meso-cyclones (read squares) of 6 to 8 (m/s)/km.

5- Further Analysis

All the previous figures are in operational use to predict and follow severe weather events. Further analysis can be made after the fact to understand the behavior of these supercells. I chose to analyze the momentum and shear in the meso-cyclonic circulations associated with those cells.

5.1- Definitions

A meso-cyclonic circulation is associated with a transfer of an horizontal vortex into a vertical one by an updraft. It is seen as a doublet of radial velocities on a Doppler radar. The air on one side of the circulation is seen as going away from the radar while it is coming toward the radar on the other side. Once you have spotted this circulation, you can calculate its momentum by multiplying the speed by the distance to the center of rotation. The same way, one can calculate the shear between the plus and the minus side.

These rotation are not between two single points but form a continuum over a certain area and over a certain thickness of the atmosphere. Therefore a maximum value at each altitude where exist such a circulation can be noted and plotted on a graph. We can try to associate some characteristic to the behavior of that maximum in the case of tornadoes.

5.2- Laurel and Rawdon tornadoes

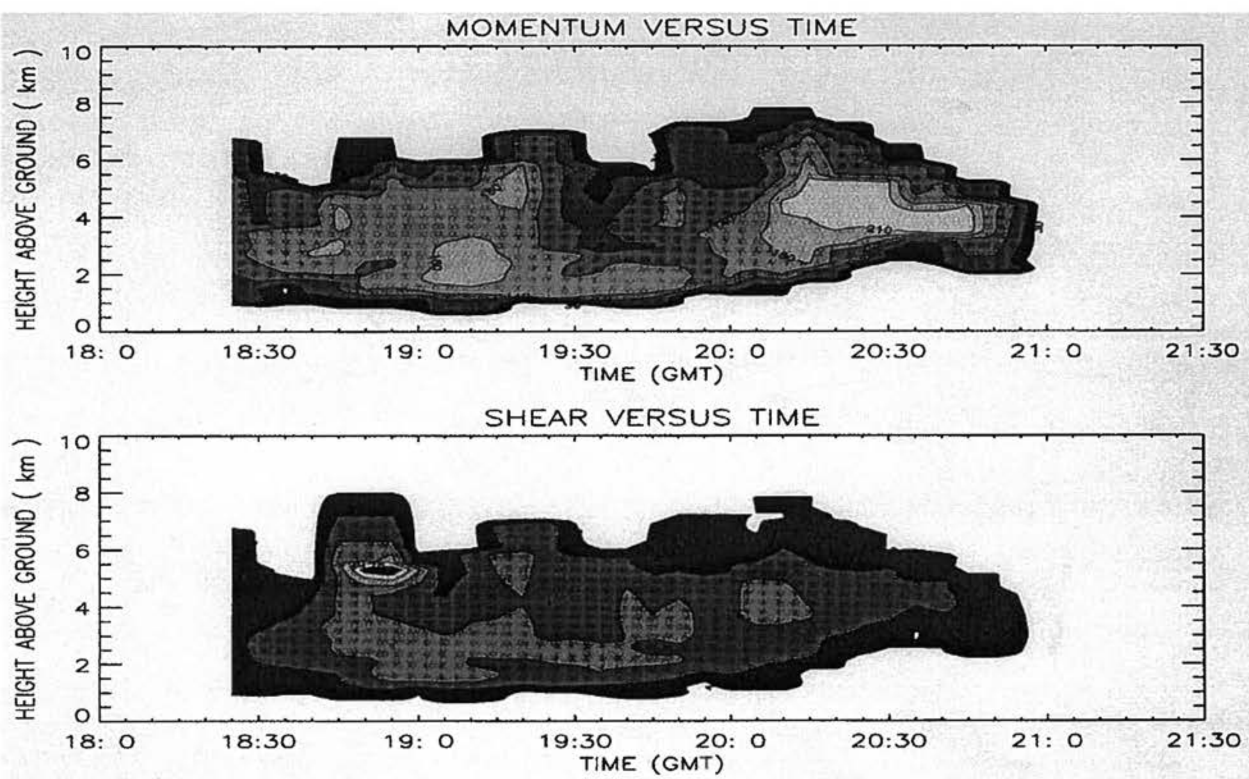


Figure 26 Shear and Momentum evolution of the Laurel and Rawdon tornadoes meso-cyclonic circulation

Figure 30 shows the values of the maximum of momentum and shear in the Papineauville supercells from 1825 GMT until 2100 GMT. We can see that a maximum shear exist at 6 km above ground (>26 m/s/km) at 1900 GMT but that it collapses by 1915 GMT, the time of the Laurel tornado. A weaker maximum of 14 m/s/km has built up at 4 km altitude and collapsed just prior to the Rawdon tornado at 2015 GMT.

On the other hand, the figure shows at the time of both tornadoes a strong development of momentum at low level (2-3 km) suggesting that the shear at upper levels as been transformed into momentum toward the ground. It seems an indication of a sudden rotating downdraft. This conforms to the analysis in a recent paper by NOAA researchers[5] and earlier ones by Burgess[6].

Figure 31 shows similar behavior of the supercell that passed just north of the first one with collapse of the shear at the same time of the increase of the momentum. In that case, it seems that everything was at low level however and possibly involving less mass of the cloud.

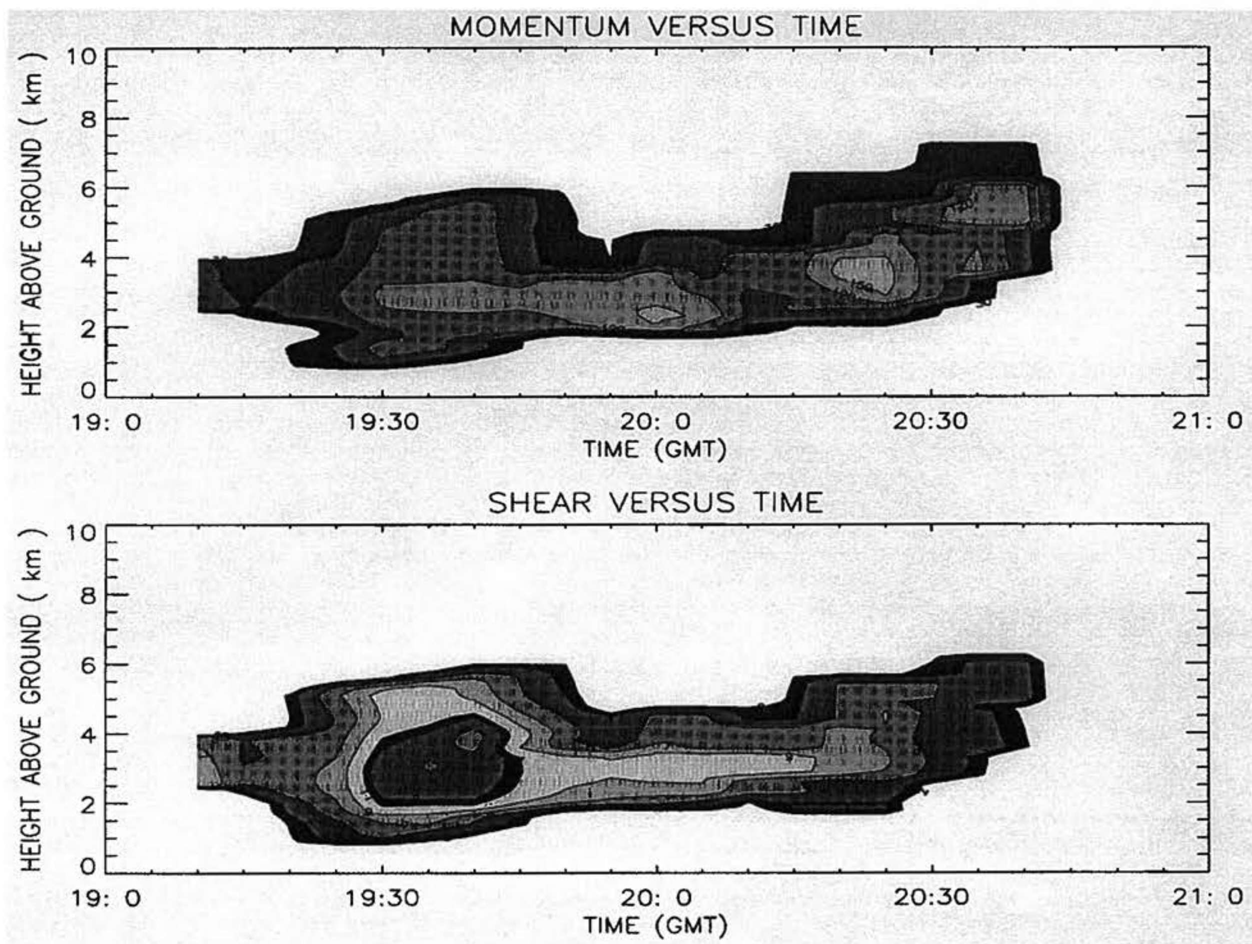


Figure 27 Shear and Momentum Evolution for a super-cell just north of the Rawdon tornado cell

[5] B. Grant and R. Prentice, 1996, "Mesocyclonic characteristics of mini supercell thunderstorms". NOAA home page paper //www.osf.noaa.gov/otb/papers

[6] D.W. Burgess et al. 1991, "Characteristics of mesocyclones detected during a NEXRAD test". Preprints, 25th Int'l Conference on Radar Meteorology, Norman Oklahoma, AMS p. 39-42

5.3- Alexandria

The figure 32 shows a similar but weaker story. This is the momentum and shear of the cell that gave a tornado to Alexandria at 2215 GMT. The first appearance of a meso-cyclone is very little time before the severe event. One can see a weak maximum of shear by 2210 GMT dissipating and a maximum of momentum going down toward surface by tornado time.

However everything is below 4 km and very weak. Another maximum is notice at 2300 GMT without damaging effects. As I said, this supercell was marginal and the analysis of the meso-cyclonic circulation is not as conclusive.

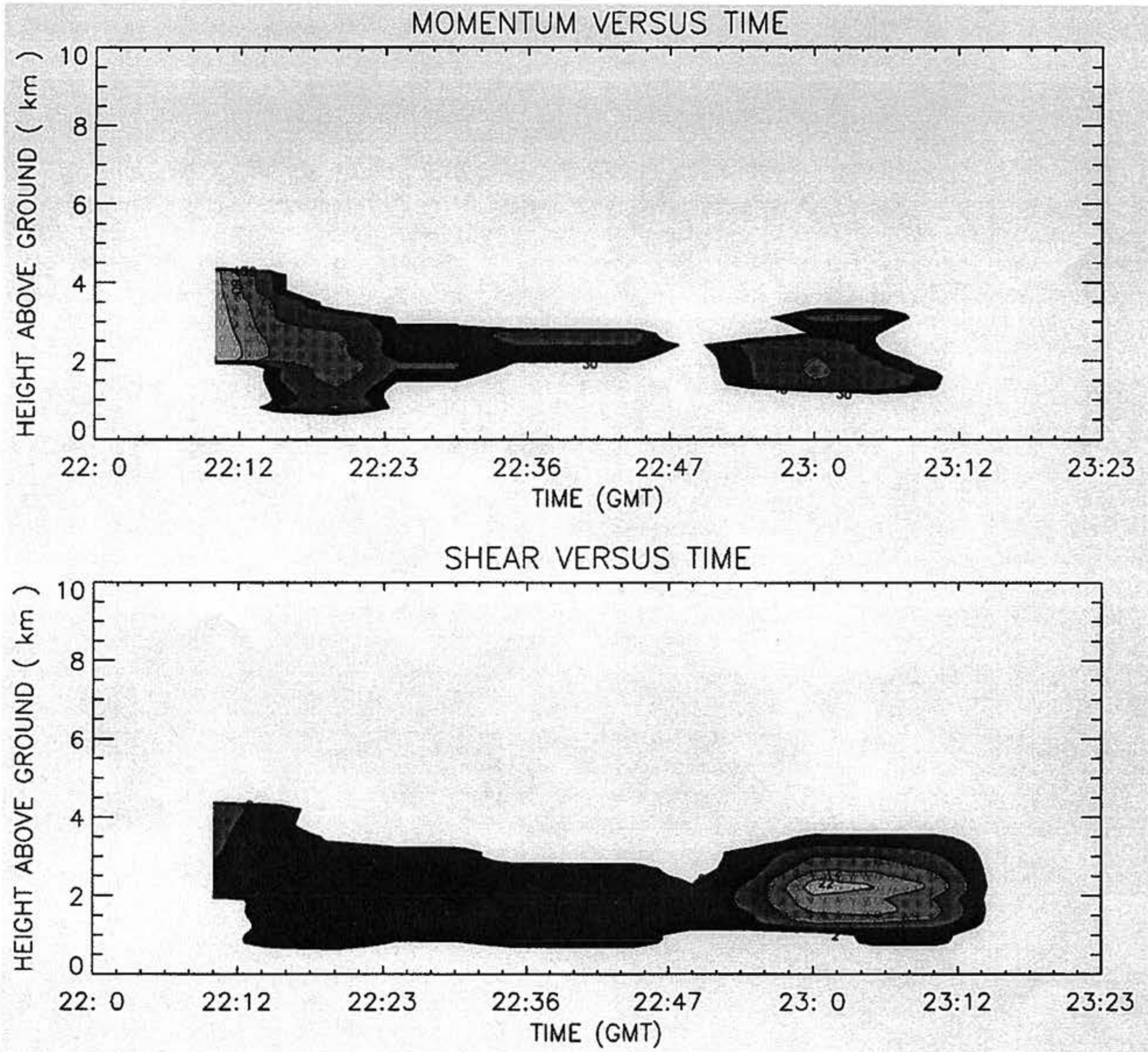


Figure 28 Shear and Momentum Evolution of Alexandria tornado meso-cyclonic circulation

6- Conclusions

The 4th of August was a very classic case of severe weather with strong dynamic and thermodynamic components. A study of the synoptic situation and of the tephigram of the previous evening pointed rapidly to the possible development of supercells giving heavy downpour and damaging winds with the possibility of tornadoes.

However, the morning analysis shows two different zones for that heavy weather: the first along the warm front with the strongest storms and the second along the southern edge of the clouds in the warm sector with more marginal and isolated cases.

After the onset of convection, the use of cross sections, meso-cyclonic circulation detection and other radar related algorithms made the detection of the dangerous thuderstorms possible. Following those cells made it possible to launch warnings to the threatened areas.

Finally, later analysis shows that supercells where the major severe weather generator even if some squall lines formed in the warm sector. The cells ahead of the warm front continued toward the East to give downpours and damaging winds in Trois-Rivières, Québec and Eastern Townships regions. The small supercells of the warm sector gave localized damages.

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