*EASTERN REGION TECHNICAL ATTACHMENT*
*NO. 2000-05*
*DECEMBER, 2000*

# LAKE EFFECT AND LAKE ENHANCED SNOW IN THE CHAMPLAIN VALLEY OF VERMONT

*Alexander Tardy*
*NOAA/National Weather Service*
*Burlington, Vermont*

**Editor's Note:** The author's current affiliation is WFO Sacramento, California

## 1. INTRODUCTION

The weather phenomena known as lake effect snow has long been documented for the Great Lakes Region (Peace and Sykes 1966; Holroyd 1971; Lavoie 1972; Niziol et al. 1995). The snowfall associated with these large bodies of water usually has a significant impact on people and aviation several times each winter. Recent software such has the Buffalo Toolkit ,called BUFKIT (Mahoney and Niziol 1997) has enabled forecasters to predict the magnitude, areal coverage, and duration of these mesoscale events. Also, lake effect forecasting has improved with the development of high resolution models that recognize local terrain features and the existence of large lakes. Less literature exists about snow produced by smaller bodies of water (Carpenter 1993; Cosgrove et al. 1996), mainly because it does not fall at established observing sites, affects few people, and occurs infrequently. However, since the recent installation of a Weather Surveillance Radar-1988 Doppler (WSR-88D) near Burlington, Vermont, several events have occurred that exhibit similar characteristics and effects as those associated with Great Lakes snows.

The purpose of this study is to analyze snowfalls associated with Lake Champlain with the use of Doppler radar data, Geostationary Operational Environmental Satellite (GOES-8) data, and high resolution numerical output from the Meso-Eta (Black 1994) model. The impact of these snowfalls can be as great as synoptic scale storms. The most common result of arctic air crossing the relatively warmer Lake Champlain is low clouds and flurries. However, on rare occasions snow squalls with visibilities less than a 1/4-mile and up to 33-cm (13 inches) of pure lake effect snow in a 12-h period have been observed. This paper will explore events which fit the category of lake effect or lake enhanced, and develop criteria for forecasting them.

## 2. BACKGROUND

Lake Champlain straddles the border of Northern Vermont and Northern New York (Fig. 1). This narrow body of water is oriented north to south and is approximately 200-km long with a maximum width of 19-km. The great length of the lake makes it one of the largest bodies of fresh water in the United States covering 1127 $km^2$. Several large islands are located in the northern portion of the lake. The lake averages 20-m deep, but the greatest depth is 122-m. The lake level is normally between 29 and 30-m above mean sea level (MSL).

A gradual upward-sloping valley extends to the east of the lake with more rugged terrain along the western side in New York. The communities of Burlington and St. Albans, Vermont, and Plattsburgh, New York, have a combined population of more than 110,000. Their proximity to the water allows various lake influences on local weather with direct or indirect effects.

## 3. DATA and METHODOLOGY

Events were selected by using 1996-1998 archived Doppler radar data from the WSR-88D located in Colchester, Vermont (KCXX), which is 3 miles north of the Burlington International Airport (Fig. 1). The radar's proximity to the lake makes it ideal for studying lake effect snow since the radar beam will intersect the lowest levels of any precipitation and clouds. The elevation of KCXX is 131-m (431-ft) above MSL. To define an event, composite reflectivity data and velocity azimuth display (VAD) wind profiles (VWPs) were examined to identify echoes downwind of the lake. An event was classified as lake effect if it had an elongated band of precipitation downwind of the lake, and was not associated with any obvious surface boundary or wind shifts. A lake enhanced event was determined to be those cases when radar showed a convective cellular shaped area of precipitation that originated or enhanced over the open waters, while there was other convective activity upwind of the lake. The lake enhanced events were associated with moving or stationary surface boundaries. The events associated with an obvious synoptic scale system were not used (e.g., widespread snow on the western side of a low). The period of an event was based on heaviest snowfall estimated from composite reflectivity products.

Lake Champlain water temperatures were obtained from the Lake Champlain Transportation Company at the Kings Street Ferry Dock in Burlington. The instrument is 1.8 meters under the water. Lake Champlain usually freezes over by January or February, but the open waters did not freeze from 1996 to 1998. Surface wind speeds, wind directions and air temperatures over the lake were collected from instrument sites at the Sandbar State Park (SAN), operated by Vermont Electric Company, and the Colchester Reef (CRF), operated by Vermont Monitoring Cooperative. Data were not available for SAN after November 1996. Figure 1 shows that both locations, especially CRF, represent conditions over the open water. Land air temperatures and wind data were taken from the Automated Surface Observing System (ASOS) at the Burlington International Airport (KBTV). The average wind velocity during the period of heaviest snowfall, determined by radar data, was used in this study. Snowfall reports came from various weather spotters and from the WFO in Burlington.

Numerical model output from the Meso-Eta in the form of hourly soundings was evaluated using BUFKIT software. During the study, the Meso-Eta had a horizontal resolution of 29-km and vertical resolution of 50 levels, but it was not sufficient to resolve a 19-km wide Lake Champlain. Wind data for these model soundings were compared with those depicted on the VWP. Using BUFKIT, the wind and temperature from the Meso-Eta were taken from the nearest data level of the native grid for the specified height. BUFKIT allows the operator to enter the lake surface temperature which is used to calculate forecast instability over the open water. The instability is categorized as none, conditional, moderate, or extreme and is based on differences between surface to 850-mb and surface to 700-mb temperatures (Niziol 1987; Niziol et al. 1995). In addition, model sounding parameters such as mean layer wind shear and heights of inversion level were analyzed against the VWP during the event. The critical over-the-water fetch was determined by using the mean 1,000 to 5,000-ft level wind from the VWP.

Upper air, surface, and satellite data were examined with the use of the General Meteorological Package Analysis and Rendering Program (GARP; Jesuroga et al. 1997). Upper air analyses were restricted to observed data at 1200 and 0000 UTC, while the surface plots were available each hour. GARP was used to analyze the surface plots. Satellite data were obtained from GOES-8 infrared [10.7 microns (μm)] and visible (0.65 μm) imagery.

## 4. EVENTS

Eight events from 1996 through 1998 were selected to study. It was determined that certain synoptic scale patterns were responsible for producing lake effect versus lake enhanced snow events. All eight events are defined in Table 1. Five of the eight cases were considered the lake effect type.

### 4.1 Lake effect bands

In the five lake effect events, a strong area of high pressure (1028-mb to 1045-mb) extended from the Midwest states north across the Great Lakes and Ontario. The surface pressure gradient associated with this pattern produced a northerly wind over Lake Champlain. This wind direction allows for the greatest fetch.

To generate vertical velocities sufficient to develop clouds and precipitation, sufficient atmospheric instability must be present over the open water. The average surface to 700-mb lapse rate was found to be 24C° for the five cases. This magnitude would be categorized as bordering between "conditional" and "moderate" instability from the surface to 700-mb (Mahoney 2000). CRF and SAN observations showed that the air over the water warmed by 0.7°C to 2.5°C during each snow event. The average wind direction at KBTV was observed to back by 10 to 20 degrees compared with CRF winds in three cases. A recent study by Cosgrove et al. (1996) determined that the most important factors for lake effect snow from the similar sized Finger Lakes in New York (oriented north to south) were; fetch, wind direction, and 850-mb to water temperature differential.

A description of each of the five lake effect events follows.

#### *Lake effect case 1*

On 27 November 1996, an extraordinary and extended lake effect event unfolded. Two distinct and large bands of snow were depicted by Doppler radar with reflectivity intensities ranging from 20 to 34 dBZ at 0913 UTC (Fig. 2). These persistent bands channeled down the Champlain Valley and merged over the southern end of the lake for more than 12 hours. The heaviest snow occurred between 0600 and 1700 UTC 27 November. A total of 33-cm (13 inches) of snow fell in the town of Cornwall (see Fig. 1). Based on this report it was estimated that the snow was falling at a rate of 2.5 to 5.1-cm (1 to 2 inches) per hour within the nearly stationary band. The VWP data in Fig. 3 and Table 2 show unidirectional north winds from the surface to 11,000-ft. This resulted in winds parallel to the long axis of the lake, approximately an 85-km over-lake fetch. In addition, Table 1 shows surface winds at KBTV, SAN, and CRF were from the north at 13 to 26 knots. The Meso-Eta forecast sounding at 0900 UTC indicated minimal shear in a surface to 7,000-ft layer (Table 3 and Fig. 4) with relative humidities greater than 90 percent. Using the lake temperature of 7°C (Table 1) as the surface temperature, the Meso-Eta indicated conditional instability with a surface to 700-mb lapse rate of 22C°. Conditional instability is sufficient to produce lake effect snow if it is accompanied by cyclonic vorticity advection at 500-mb and the airmass trajectories are along the longest fetch of the lake (Niziol 1987). It is interesting to note that the surface to 850-mb lapse rate was 24C°, which is considerably more unstable than the surface to 700-mb. For this case, the instability below 850-mb was more crucial than the surface to 700-mb lapse rate. This more than satisfies previous studies by Niziol (1987) and Holroyd (1971) which stated that pure lake effect requires a lake surface to 850-mb temperature difference of at least 13C° (dry-adiabatic lapse rate).

The 1000 UTC 27 November 1996 surface analysis has a 1040-mb high pressure area building into the Great Lakes with a northeast geostrophic flow over Vermont (Fig. 5). Upper air data at 1200 UTC depicted an open 500-mb trough over eastern New England with a cold pool of air (-33°C) over southern Vermont (Fig. 6A). Figure 6B shows a northerly 850-mb flow with the -16°C isotherm advecting into the Champlain Valley. Visible satellite images during the morning hours showed two distinct bands of clouds merging over the southern end of the lake (not shown). The 27 November 1996 case met the important factors in the study by Cosgrove et al. (1996), as northerly winds set up over the longest fetch of Lake Champlain, and steep lapse rates existed from the lake through 850-mb.

***Lake effect case 2***

Another lake effect event occurred on 15 November 1996 from 0100 to 1000 UTC. The lake water temperature was 10°C and an arctic blast produced 850-mb temperatures of -16°C. The Meso-Eta run from 1500 UTC 14 November (Fig. 7) forecast “extreme” lake induced instability (Table 4). A 1045-mb high pressure area was centered over Ontario Canada allowing for a northeast pressure gradient over Lake Champlain (Fig. 8). The 500-mb trough heights were near 552-dm (Fig. 9). The Meso-Eta forecast of an 8,000-ft deep boundary layer was verified by the KCXX VWP (Tables 2 and 4). However, unlike the lake effect case 1, there was 30 to 40 degrees of wind shear (Fig. 10), but the mean 1,000-ft to 5,000-ft winds were 360 degrees at 20-kt providing a nearly ideal trajectory. But the degree of directional wind shear is detrimental to well-organized activity according to Niziol et al. (1995). The composite reflectivity at 0459 UTC 15 November showed a well-defined band of 15 to 25 dBZ snow extending from the southern end of Lake Champlain and the fetch appeared to be 37 to 46-km (Fig. 11). GOES-8 10.7 µm satellite images at 0915 UTC showed an enhanced (-18°C) area of cold cloud tops southeast of Lake Champlain (Fig. 12). The author during this event observed visibilities of 1 statue mile or less near Monkton at 0530 UTC (Fig. 1). In addition, orographic enhancement was evident as snowfall rates increased in the higher terrain away from the lake shore.

***Lake effect case 3***

The importance of the fetch length over a narrow lake was evident with the lake effect event on 24 March 1997. Composite reflectivity images showed very light precipitation from 0800 to 1100 UTC (not shown). The Meso-Eta forecasted a surface to 700-mb instability in the "moderate" category, with a surface to 850-mb lapse rate of 22C° (Table 4). Air temperature at KBTV dropped to -9°C which was colder compared with the lake surface temperature at 1°C. The mean wind observed and forecast for the 1,000-ft to 5,000-ft level was 320 degrees which allowed a short fetch of 19 to 24-km. This fetch is only 12 percent of the possible length of Lake Champlain, which is not sufficient for organized lake effect despite moderate instability, minimal directional shear and cyclonic vorticity advection (Niziol 1987). Another limiting factor, not seen in lake effect cases 1 and 2, was that the subsidence inversion lowered to 5,000-ft as an arctic 1032-mb high moved into western New York. This capping of the boundary layer has been found more significant to controlling lake effect than how much instability because in decreases the depth of the unstable layer (Byrd 1992). The inversion height was also found to be a significant limiting factor in a study of lake effect snow from the Great Salt Lake (Carpenter 1993). A light covering of snow was reported in Hinesburg (Fig. 1) on 24 March. KBTV reported a visibility of 6 statue miles with light snow and Marginal Visual Flight Rules (MVFR) from a low cloud ceiling.

***Lake effect case 4***

A weak north-south oriented band of lake effect snow developed on 21 December 1997 and lasted from 0900 to 1400 UTC. The synoptic scale pattern showed an area of high pressure building across Ontario producing a weak northerly flow over Lake Champlain and "conditional" instability (Table 4). Upper air analyses depicted a 500-mb trough axis over head with 534-dm heights (not shown). Meso-Eta forecasts indicated that an inversion would lower to 2,000-ft above the model terrain (Table 4). This strong inversion did develop as the KCXX radar observed very light winds in the shallow boundary layer (Table 2). The subsidence inversion and light winds were the primary limiting factor in this case. Note that the Meso-Eta hourly soundings from BUFKIT over-forecast the wind speed (Table 3). Radar showed only a weak return of reflectivity (0 to 16 dBZ) on 21 December extending southeast of the lower end of Lake Champlain (not shown). KBTV was affected by low stratocumulus clouds with MVFR conditions and flurries.

***Lake effect case 5***

A similar synoptic pattern to lake effect case 4 was seen on 14 February 1998. Figure 13 shows a band of -4 to 11 dBZ returns extending downwind from the southern end of the lake and extending inland at 0756 UTC 14 February 1998. The heaviest precipitation fell between 0400 and 0900 UTC. The VWP at 0845 UTC suggests that the winds were from a favorable northerly direction (Fig. 14). However, a strong subsidence inversion most likely limited the vertical development of clouds. Similar to lake effect case 4, Meso-Eta forecasts indicated that an inversion would lower to 2,000-ft above the model terrain (Table 4) suggesting that organized lake effect would not materialize. However, model wind direction and speed did not verify well with data obtained from the VWP (Table 2 and 3). The surface to 700-mb instability was forecast to be "conditional," while the lake surface to 850-mb temperature differential was noted to be 16C°. It was interesting that the reflectivity image in Fig. 13 appears to show a bend in the band of snow. This turning may be a topographic effect caused by precipitation banking into the higher terrain. However, it also could be a reflection of more northerly flow aloft as the precipitation is carried into higher levels of the atmosphere with time.

### 4.2 Lake enhanced snow squalls

Mamrosh (1990) documented lake enhanced snow squall activity from Lake Champlain. This documentation stated that Lake Champlain contributes sufficient warmth and moisture to intensify the snow showers that accompany a cold front or trough. In the three lake enhanced cases included in this study a 500-mb long wave trough was present with heights ranging from 522 to 534 dm (not shown). A strong high pressure center of 1040-mb or greater was present over central Canada extending south into the Midwestern United States. The snow squalls occurred with the passage of a cold front and continued several hours afterwards. The events did show characteristics similar to lake effect, but based on the data could not be classified as this type. In two cases, 13 November 1996 and 12 March 1997, *east* winds at CRF did not shift to a northwest flow until several hours after the passage of the main surface cold front. In the 13 November 1996 case the wind at Burlington remained out of the east (Table 1). These events suggest a low level circulation or convergence zone interacted with lake moisture to produce intense snow squalls (30 dBZ or greater).

A description of each of the three lake enhanced cases follows.

#### *Lake enhanced case 1*

On 12 March 1997, an intense snow squall developed over Lake Champlain shortly after the passage of an arctic surface trough. Most of the snow shower activity occurred between 1600 and 1900 UTC and was not confined to downwind of the lake. At 1714 UTC a light south wind (8 knots or less) was observed at KBTV prior to the snow squalls. The surface wind and the 1,000-ft VAD wind veered to the northwest by 1739 UTC at similar speeds (Fig. 15). At this time heavy snow (30-39 dBZ) began at KBTV resulting in 2.5 to 5.1-cm (1 to 2 inches) in about 30 minutes. At 1809 UTC visibilities of less than a 1/4-mile were reported at KBTV.

Over the lake, the site at CRF showed an east wind shifting to the northwest during a 15-min interval from 1715 to 1730 UTC. It was interesting to note that simultaneously air temperatures at CRF rose a bit more than 2°C. The warming could be a result of sensible heating due to the advection of warmer air from the lake or latent heat release with the convective snow band. The Meso-Eta indicated “moderate” to “extreme” instability with a surface to 700-mb lapse rate of 31C° (Table 4). VWP data and Meso-Eta model forecast soundings showed unidirectional northwest winds (Table 2 and 3). The limiting factor here was the short fetch over water (25-km). However, as Fig. 16 indicates, at 1745 UTC a well-developed cell was identified by the WSR-88D Storm Cell Identification and Tracking algorithm (Operational Support Facility 1996) originating over the open lake. This intense low level squall was formed because three important factors for convection were met; additional moisture from the lake, extreme instability from the water surface to 850-mb temperature difference, and vertical lift from low level circulation and convergence associated with a secondary surface trough (not shown), plus frictional convergence with water-land interactions (Niziol et al. 1995).

#### *Lake enhanced case 2*

A similar event occurred on 13 November 1996, but the snow squalls that developed over Lake Champlain were more persistent (2100 to 0100 UTC). Surface observations at CRF showed an east wind abruptly shifting to the northwest at 2230 UTC. At 2300 UTC the wind at SAN also shifted from the east to the northwest at speeds around 10 knots. Air temperatures at both sites were observed to rise 1°C during the event. The VWP, in Fig. 17, shows northerly winds in the lowest 2,000-ft which is an ideal trajectory along the lake. Figure 18 depicts intense snow squalls containing a few pixels of 40 dBZ with much weaker reflectivity returns on the windward side of the lake. The heaviest snow occurring at this time was estimated at a rate of 2.5 to 5.1-cm (1 to 2 inches) per hour. The Doppler radar image at 2230 UTC (Fig. 18) corresponds closely with a 2245 UTC 10.7 µm satellite image (Fig. 19) indicating a southwest to northeast enhanced area of cold cloud tops (-21°C). The low level convergence zone over the lake combined with "extreme" lake-induced airmass instability (surface to 850-mb lapse rate of 26C°) resulted in boundary layer convection (Table 2). Despite severe directional wind shear seen on the VWP (Fig. 17), the 1,000-ft to 2,000-ft wind trajectories allowed for a long over-water fetch (Table 2). Above this altitude the winds were backing with increasing height associated with cold air advection.

Surface observations at KBTV did not suggest the passage of any surface trough considering that east winds prevailed with an air temperature increase of 0.6C°. The 2300 UTC surface analysis shows a 1036-mb high pressure center in the St. Lawrence Valley providing the gradient for north winds across Lake Champlain (not shown), but there was no indication of a surface trough. Considering the proximity of the high pressure allowing for a weak geostrophic flow, Burlington may have been experiencing a land breeze. In addition, Meso-Eta soundings indicated "extreme" instability with a subsidence inversion at 7,000-ft (Table 3). The limiting factor in this case was the severe wind shear in the lowest 5,000-ft observed on the VWP (Fig. 17) and simulated in the Meso-Eta forecast (Table 2 and 3). The Meso-Eta soundings forecast for the height of the inversion and the wind directions within this layer were near those observed (Table 2 and 4). This convective event was accompanied by extreme instability (26C° surface to 850-mb differential), convective latent heat release, and a persistent land breeze boundary providing the focusing mechanism (convergence zone) for lift (Byrd and Penc 1992; Peace and Sykes 1966). Peace and Sykes (1966) also found that there are often thermally and frictionally induced convergence zones over the lake when bands of snow are aligned along the long fetch of narrow lakes. Furthermore, winds backing from 1,000 to 5,000-ft (Fig. 17) oriented this band of convection so it was orographically enhanced over terrain as high as 1400-ft above MSL. Orographic lift combined with local flux of heat and moisture from the lake can raise the cap promoting further convective growth (Niziol et al. 1995; Lavoie 1972). Niziol et al. (1995) also wrote that the height and strength of the inversion determine the vertical extent of convective cloud growth on the lee side of the Great Lakes.

***Lake enhanced case 3***

On 12 November 1996, numerous snow squalls produced 8.6-cm (3.4 inches) in Burlington with occasional visibilities at 1/4-mile creating aviation and travel difficulties. Radar showed the intensity of the snow at 1939 UTC on the east side of the lake (Fig. 20). The precipitation occurred between 1400 and 2200 UTC. The snow squalls occurred several hours after the passage of the main surface trough at 1100 UTC 12 November 1996 (not shown). At this time surface winds at KBTV shifted to the north and prevailed throughout the event. Average wind directions at SAN and CRF were between 320 and 340 degrees at speeds of 10 knots (Table 1). VWP data shows a persistent northerly wind at 1,000-ft (Fig. 21) allowing for the maximum fetch over Lake Champlain. Above this layer directional shear was observed. Table 3 shows that the Meso-Eta did not forecast this wind profile, but instead predicted unidirectional winds at 300 degrees throughout the 5,000-ft layer. The Meso-Eta indicated “extreme” instability at 2000 UTC with surface to 700-mb lapse rates of 33C°. The GOES-8 10.7µm images (Fig. 22) show an enhanced area of cold cloud tops (-20°C to -25°C) that regenerated on the lee side of Lake Champlain during the event. The VWP depicted backing winds with height suggesting strong cold air advection (Table 2). A 1200 UTC analysis at 850-mb supported this, showing cold air (-12°C to -16°C) advecting with the northwest flow while a broad 500-mb trough lay over the region (not shown). The depth of the boundary layer was adequate to promote convective cloud growth, but the directional wind shear might have been the main limiting factor. This case was similar to the squalls that occurred on 13 November (lake enhanced case 2). However, this time the land breeze or convergence zone was not evident. Radar confirmed that this was a lake enhanced event since the more intense convective cells were over the open waters and downwind, while weaker activity was seen upwind (Fig. 20). Local reports from various NWS spotters showed 2.5-cm (1 inch) or less of accumulation outside the Champlain Valley of Vermont.

## 5. RESULTS AND FORECASTING APPLICATIONS

In five of the eight cases WSR-88D reflectivity products indicated a band of snow downwind from the lake, and it originated over the open water with no other snow showers in the Champlain Valley. The other three cases depicted intense snow squalls (cells with 30 dBZ or greater) on the lee side of the lake with much weaker activity upwind. In every event, the mean 1,000-ft to 5,000-ft VAD winds were between 300 to 030 degrees, and the wind fetch across the open water was 25-km or greater.

The eight cases presented in this paper clearly demonstrate that Lake Champlain can affect the local weather downwind of the lake, several hours after the arrival of arctic air. Cases similar to the 14 February 1998 event, lake effect case 5, (Fig. 13) have been witnessed to occur a few times during a typical winter. The installation of the WSR-88D has enabled these phenomena to be identified and the data used to enhance short term weather forecasting. These situations often have a significant influence on public and aviation forecasting. At times, skies will be clear in much of the Champlain Valley while stubborn low clouds and flurries linger near the lake in Burlington. In other situations several inches of snow will accumulate.

This study indicates that the temperature differential between the lake surface and 850-mb needs to be at least 15C° for the generation of lake effect snow. The 700-mb air temperature does not appear significantly to affect the production of lake effect or lake enhanced snow from Lake Champlain. In fact, the most significant lake event in this study (lake effect case 1) had 700-mb temperatures that were warmer than those at 850-mb (Table 4). Wind direction for determining fetch length, surface to 850-mb instability, depth of the mixed layer or height of the subsidence inversion, and the wind directions within this defined boundary layer were considered the most important forecast parameters. A numerical mesoscale model run for the Finger Lakes also found this to be the case (Cosgrove et al. 1996). The heaviest snow from lake effect will occur with sufficient instability, and a mean 1,000-ft to 5,000-ft layer wind direction from the north with speeds of 10 to 25 knots with minimal shear. This allows for the longest trajectory over the open waters of Lake Champlain (Fig. 1). Lake effect case 1, on 27 November 1996 (Fig. 2), suggests that the ideal lake effect situation would be to have a unidirectional north wind with little wind shear within a deep boundary layer. However, this is a rare atmospheric occurrence and most cases have several variables that limit the lake's effect and present the forecaster with a challenge. A critical limiting factor to the formation of lake effect snow may be subsidence (downward vertical velocities) from the approaching area of high pressure. The presence of a strong arctic high pressure system of at least 1025-mb is necessary to establish a northerly wind. However, this high pressure center will often result in subsidence that lowers the boundary layer with time (Pettersen 1956). Therefore, the window of opportunity is often limited to a few hours. For lake enhanced snow squalls, only a short time may be needed to rapidly intensify the snow showers if it is accompanied by other synoptic or mesoscale forces.

The upper air synoptic scale pattern observed for all the cases examined included a 500-mb long wave trough that provided neutral or cold air advection at this height. Once the trough axis passes, cyclonic vorticity advection becomes negative or neutral and the snowfall began to decrease. However, sufficient instability and north winds will promote weak lake effect that could be enhanced by additional short waves within the northwest flow. At 850-mb, cold air advection is required in order to maintain adequate instability for convective processes. Most important, at least one surface boundary or an arctic cold front was depicted to move across the lake during or preceding each lake enhanced event. Table 1 shows two dramatic wind shifts that occurred over the open waters. These wind shifts were observed by equipment at SAN and CRF. The change in wind direction that occurred in lake enhanced case 2 on 13 November 1996 (Table 1) would have gone undetected if it were not for these lake sites. The ASOS at KBTV did not detect any appreciable change in the wind direction or speed.

Forecasting these lake events will continue to be a challenge as with any mesoscale convective phenomenon. In addition, the apparent infrequent nature of Lake Champlain effect and enhanced snow does not allow the forecaster to attain sufficient experience. The resolution of the operational numerical models is not sufficient to resolve an extremely narrow valley.

This paper has examined radar data and mesoscale model forecasts that can be used to help forecast lake effect and lake enhanced snow from a narrow north to south oriented body of water. The first approach to forecasting these events is to examine the overall synoptic pattern looking for a west to east pressure gradient from the approaching arctic high pressure center. Additional dynamic, thermodynamic, and kinematic atmospheric structures that require investigation include a long wave 500-mb trough, cold air advection at 850-mb providing at least a 15C° water surface to 850-mb temperature differential, and mean boundary layer winds 300-010 degrees. To support heavy lake effect snow, the vertical wind shear below the inversion needs to be minimal (less than 40 degrees), and the mean wind direction should be 340-010 degrees. Identification of a surface trough, which could further enhance and focus the snow squalls, may be achieved by reviewing model forecasted surface winds and convergence.

Many of these model forecast hourly soundings and thermodynamic parameters can be viewed with BUFKIT (Mahoney and

Niziol 1997). Using the forecast soundings near Burlington, important parameters such as instability, inversion height (boundary layer depth), and wind profiles can quickly be analyzed for diagnosing possible lake events. Upper level support, such as positive vorticity advection and/or short waves, could help enhance any convective activity. Finally, the WSR-88D can be used for real-time short term forecasting of lake effect snow squalls and bands (Carter et al. 1996). The local KCXX radar's close proximity to Lake Champlain allows for superior VWP representation and reflectivity depictions. The recent availability of 15-minute digital GOES satellite images allow additional support to identifying lake effect situations and tracking intensity trends. Furthermore, Burlington's mesonet, specifically hourly CRF data, can be combined with the VWP to get a complete depiction of the boundary layer conditions.

## 6. CONCLUSIONS

Lake effect and lake enhanced snow events do occur in the Champlain Valley. On rare occasions the impact on the local weather can be as significant as the traditional Great Lakes snows. The availability of high resolution models, application software like BUFKIT, 15-minute digital satellite data, WSR-88D data, and local mesonets make it possible to issue short and long term forecasts for such localized weather events.

The events discussed were mesoscale, therefore investigation of thermodynamic and kinematic profiles is crucial to narrow down the potential window for theses events. Arctic cold air passing over a warmer lake alone is not enough to produce clouds and precipitation. This study showed that the limiting influence of short fetches, directional wind shear, and strong subsidence inversions can prevent or weaken organized lake effect snow. Once the potential for a lake influenced event has been identified, the use of real-time WSR-88D products can be used to track developing snow bands and squalls. This information can be incorporated into terminal aerodrome forecasts and public products such as the short term forecast. Persistence and trends would be the main factor in determining actual snowfall totals for a particular event. This study did not describe how reflectivity can approximately be correlated with snowfall amounts. However, on going studies, such as those being done at the WFO in Albany, toward developing a relationship between reflectivity and snowfall will further improve our ability to forecast specific snowfall rates in the future.

## ACKNOWLEDGMENTS

The author would like to thank Paul Sisson of WFO BTV, for his help in gathering data and for time spent reviewing several drafts. He would also like to thank Tom Niziol from the WFO in Buffalo for additional input and suggestions.

## REFERENCES


Black, T. L., 1994: The new NMC mesoscale Eta model: Description and forecast examples. *Wea. Forecasting*, **9**, 265-278.

Byrd, G. P., and R. S. Penc, 1992: The Lake Ontario Snow Event of 11-14 January 1990, Preprints, *5th Conference on Mesoscale Processes*, Atlanta, GA, Amer. Meteor. Soc., J59-66.

Carpenter, D. M., 1993: The lake effect of the Great Salt Lake: Overview and forecast problems. *Wea. Forecasting*, **8**, 181-193.

Carter G. M., T. L. Salem Jr., M. A. Wool,1996: The use of new technology for enhanced snow forecasts in the vicinity of Lake Erie and Ontario, Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, VA, Amer. Meteor. Soc., 567-572.

Cosgrove, B. A., S. J. Colucci, R. J. Ballentine, J. S. Waldstreicher, 1996: Lake Effect Snow in the Finger Lakes Region. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, VA, Amer. Meteor. Soc., 573-576.

Holroyd, E. W., III, 1971: Lake effect cloud bands as seen from weather satellites. *J. Atmos. Sci*., **28**, 1165-1170

Jesuroga, S., J. Cowie, S. Drake, D. Himes, 1997: GARP: A software tool to display and manipulate meteorological data, Preprints, *13th Intl. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, Long Beach ,CA, Amer. Meteor. Soc., 359-361.

Lavoie, R. L., 1972: A mesoscale model of lake effect snowstorms. *J Atmos. Sci*, **29**, 1025-1040.

Mahoney, E. A., cited 2000: BUFKIT Documentation. [Available on-line from http://www.nws.noaa.gov/er/buf/bufkit/bufkitdocs.html.]

Mahoney, E. A., and T. A. Niziol, 1997: BUFKIT: A software application toolkit for predicting lake-effect snow. Preprints *13th Intl. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, Long Beach, CA, Amer. Meteor. Soc., 388-391.

Mamrosh, R. D., 1990, The prediction of lake enhanced snow squalls in the Champlain Valley of Vermont, *Eastern Region Technical Attachment*, No. 90-8c, 5 pp.

Niziol, T. A., 1987: Operational forecasting of lake effect snow in western and central New York *Wea. Forecasting*, **2**, 310-321.

Niziol, T. A., W. R. Snyder, J. S. Waldstreicher, 1995: Winter weather forecasting throughout the Eastern United States. Part IV: Lake effect snow. *Wea. Forecasting*, **10**, 61-76.

Operational Support Facility, 1996: *WSR-88D Build 9.0 Precursor Training*, 1-7.

Peace, R. L. Jr., and R. B. Sykes, Jr., 1966: Mesoscale study of a lake effect snow storm, *Mon. Wea. Rev*., **94**, 495-507.

Petterssen, S., 1956: *Weather Analysis and Forecasting, Vol. II.* McGraw Hill, New York, 266 pp.

**Table 1.** Summary of wind and temperature reports from various sites in the vicinity of Lake Champlain for each lake effect snow case (LE) and each lake enhanced case (EN). The date and times indicate when the cases occurred. The winds (degrees/knots) and air temperature (°C) are an average during the cases for Burlington (KBTV), the Colchester Reef (CRF), and the Sandbar State Park (SAN). The lake water temperature (°C) were taken at the King Street Ferry Dock in Burlington. The table also includes the maximum snowfall reported to the NWSO in Burlington along with the location. (See Fig. 1 for locations.)

| Case | Date/ Time | Lake temp | KBTV temp | KBTV wind | SAN wind | SAN/ CRF | CRF wind | max snow report |
|---|---|---|---|---|---|---|---|---|
| LE1 | 11/27/96 06-17 UTC | 6.7 | -6.1 | 360/13 G 23 | 340/20 G 26 | -4.4/ -4.7 | 017/23 | 33.0 cm Cornwall |
| LE2 | 11/15/96 01-10 UTC | 10 | -7.0 | 010/09 | 005/14 G 22 | -4.4/ -3.8 | 024/16 | 7.6 cm Monkton |
| LE3 | 03/24/97 08-11 UTC | 1.1 | -8.8 | 330/08 | NA | NA/ -8.1 | 336/13 | 0.3 cm Hinesburg |
| LE4 | 12/21/97 09-14 UTC | 4.4 | -11.5 | 050/05 | NA | NA/ -9.6 | 037/09 | Trace Burlington |
| LE5 | 02/14/98 04-09 UTC | 2.2 | -10.8 | 005/08 | NA | NA/ -9.3 | 340/18 | Trace Burlington |
| EN1 | 03/12/97 16-19 UTC | 1.1 | -5.6 | 310/05 | NA | NA/ -4.0 | 117 to 332/08 | 5.1 cm Williston |
| EN2 | 11/13/96 21-01 UTC | 10 | -4.4 | 050/04 | 090-320/ 08 G14 | -3.3/ -2.8 | 074 to 336/10 | 14.0 cm Georgia Ctr |
| EN3 | 11/12/96 14-22 UTC | 10 | -1.1 | 010/03 | 325/11 G18 | 0.6/ 0.7 | 345/10 | 8.6 cm Burlington |

**Table 2.** Observed wind direction (degrees) and speed (knots) from KCXX VWP for specified heights and times during each lake effect case (LE) and lake enhanced case (EN). The VAD depth was the level of the highest wind available at the specified time. The mean fetch over open water was approximated using composite reflectivity data and the mean wind direction from the 1000-ft to 5000-ft height above mean sea level (MSL).

| Case | Date/ Time of VWP | 1000 ft | 2000 ft | 3000 ft | 4000 ft | 5000 ft | Mean wind 1-5 kft | VAD depth (ft) | Shear 1-5 kft (degrees) | Mean fetch (km) 1-5 kft |
|---|---|---|---|---|---|---|---|---|---|---|
| LE1 | 11/27/96 0907 UTC | 360/20 | 360/25 | 360/25 | 010/25 | 360/20 | 360/23 | 11,000 | 0 to +10 | 85 |
| LE2 | 11/15/96 0424 UTC | 010/20 | 020/20 | 360/20 | 340/15 | 340/20 | 358/19 | 8,000 | -30 to -40 | 37 to 45 |
| LE3 | 03/24/97 0938 UTC | 320/10 | 320/10 | 320/20 | 320/20 | 320/25 | 320/17 | 5,000 | 0 | 20 to 25 |
| LE4 | 12/21/97 1112 UTC | 050/05 | 360/05 | 350/05 | 050/05 | NA | 030/05 | 4,000 | -10 to -50 | 37 to 45 |
| LE5 | 02/14/98 0806 UTC | 020/05 | 290/10 | 360/15 | 350/15 | NA | 345/11 | 4,000 | -10 to -70 | 37 |
| EN1 | 03/12/97 1739 UTC | 300/05 | 290/20 | 300/20 | 300/20 | 300/25 | 298/18 | 11,000 | 0 to -10 | 25 |
| EN2 | 11/13/96 0015 UTC | 020/10 | 360/20 | 330/10 | 280/10 | 270/15 | 324/13 | 7,000 | -110 | 30 to 37 |
| EN3 | 11/12/96 2002 UTC | 360/10 | 340/15 | 310/10 | 320/15 | 310/15 | 328/13 | 9,000 | -50 | 30 to 37 |

**Table 3.** Meso-Eta forecast of wind direction (degrees) and speed (knots) from the KBTV hourly sounding for specified heights and time during each lake effect case (LE) and lake enhanced case (EN). Also the mean wind directions and mean wind speeds are computed from the 5 heights listed in the table.

| Case | Time/ Date run | Sounding Hour/Date | 1000 ft | 2000 ft | 3000 ft | 4000 ft | 5000 ft | Mean wind (1-5 kft) |
|---|---|---|---|---|---|---|---|---|
| LE1 | 1500 Nov 26 | 0900 Nov 27 | 350/25 | 355/28 | 005/30 | 010/30 | 010/30 | 362/29 |
| LE2 | 1500 Nov 14 | 0400 Nov 15 | 355/11 | 360/12 | 360/10 | 340/11 | 325/13 | 348/11 |
| LE3 | 1500 Mar 23 | 1000 Mar 24 | 315/17 | 310/20 | 310/23 | 315/25 | 320/26 | 314/22 |
| LE4 | 0300 Dec 21 | 1100 Dec 21 | 340/10 | 355/15 | 350/17 | 350/21 | 355/24 | 350/17 |
| LE5 | 0300 Feb 14 | 0800 Feb 14 | 325/17 | 325/19 | 330/23 | 325/25 | 320/28 | 325/22 |
| EN1 | 0300 Mar 12 | 1900 Mar 12 | 300/17 | 300/18 | 300/21 | 300/25 | 300/27 | 300/22 |
| EN2 | 0300 Nov 13 | 0000 Nov 14 | 340/07 | 322/08 | 305/11 | 300/12 | 290/15 | 311/11 |
| EN3 | 1500 Nov 12 | 2000 Dec 12 | 305/11 | 300/12 | 300/15 | 300/16 | 300/16 | 301/14 |

**Table 4.** Meso-Eta model forecast of temperatures at 850-mb and 700-mb from specified times during each lake effect case (LE) and each lake enhanced case (EN). Also included in the table are the observed lake water temperatures (see Table 1), the temperature differentials between the lake and the respective level, the BUFKIT instability category (Mahoney 2000), and the base of the inversion layer.

| Case | Time/Date UTC | Lake temp °C | 850 mb temp °C | differ-ential C° | 700 mb temp °C | differ-ential C° | Instability Category | Inversion Base (ft) |
|---|---|---|---|---|---|---|---|---|
| LE1 | 0900 Nov 27 | 6.7 | -17 | 24 | -15 | 22 | Conditional | 7,000 |
| LE2 | 0400 Nov 15 | 10.0 | -16 | 26 | -25 | 35 | Extreme | 8,000 |
| LE3 | 1000 Mar 24 | 1.1 | -21 | 22 | -23 | 24 | Moderate | 7,000 |
| LE4 | 1100 Dec 21 | 4.4 | -12 | 16 | -17 | 21 | Conditional | 2,000 |
| LE5 | 0800 Feb 14 | 2.2 | -16 | 18 | -16 | 18 | Conditional | 2,000 |
| EN1 | 1900 Mar 12 | 1.1 | -17 | 18 | -29 | 30 | Moderate | 10,000 |
| EN2 | 0000 Nov 14 | 10.0 | -16 | 26 | -21 | 31 | Extreme | 7,000 |
| EN3 | 2000 Nov 12 | 10.0 | -11 | 21 | -23 | 33 | Extreme | 16,000 |

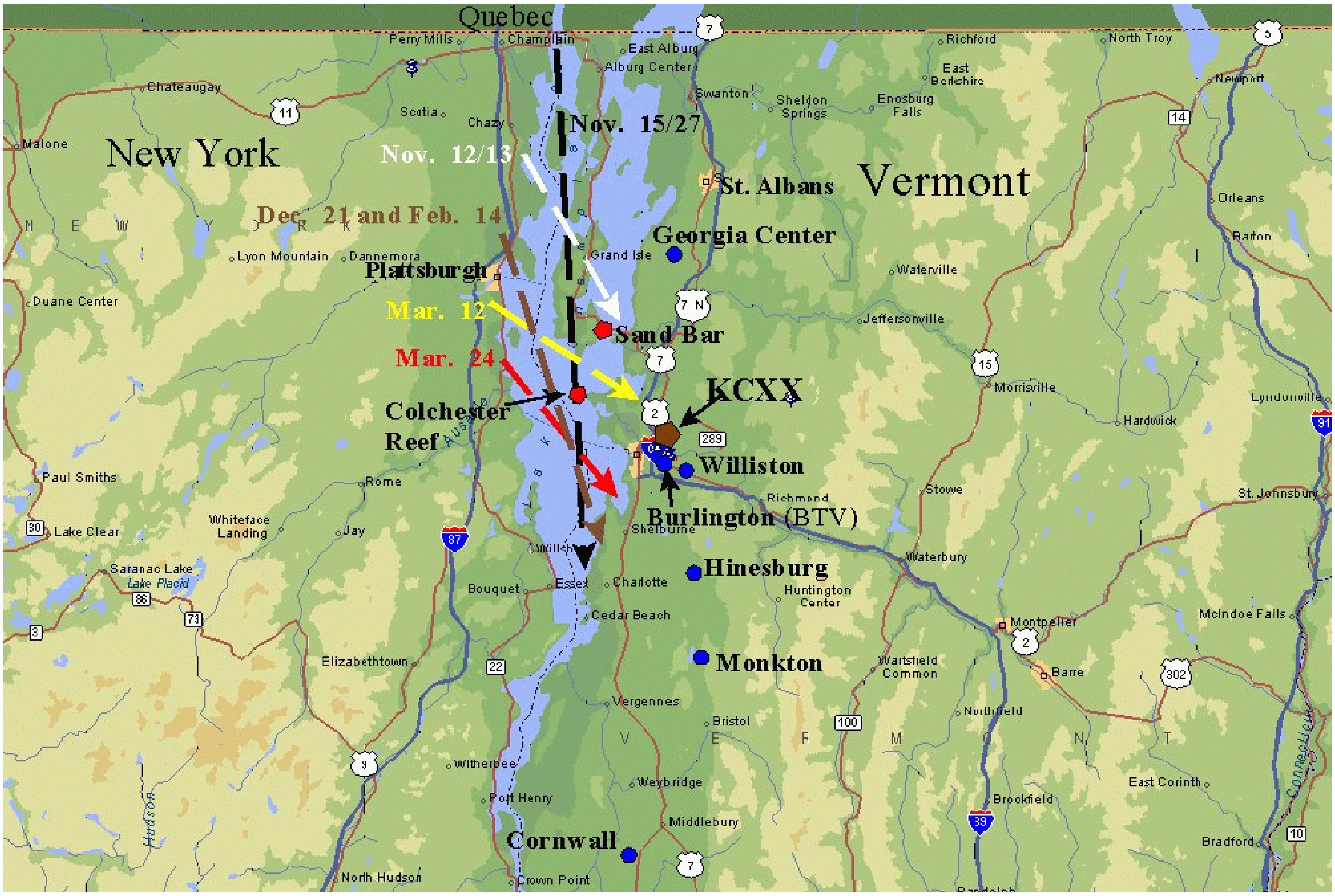


**Figure 1**. Map of the Lake Champlain region with broken arrows showing mean wind trajectory (determined by KCXX VWP and reflectivity products) during eight lake effect and lake enhanced events. Blue circles indicate the location of snowfall observers. Red polygons mark the location of Colchester Reef and Sandbar State Park.

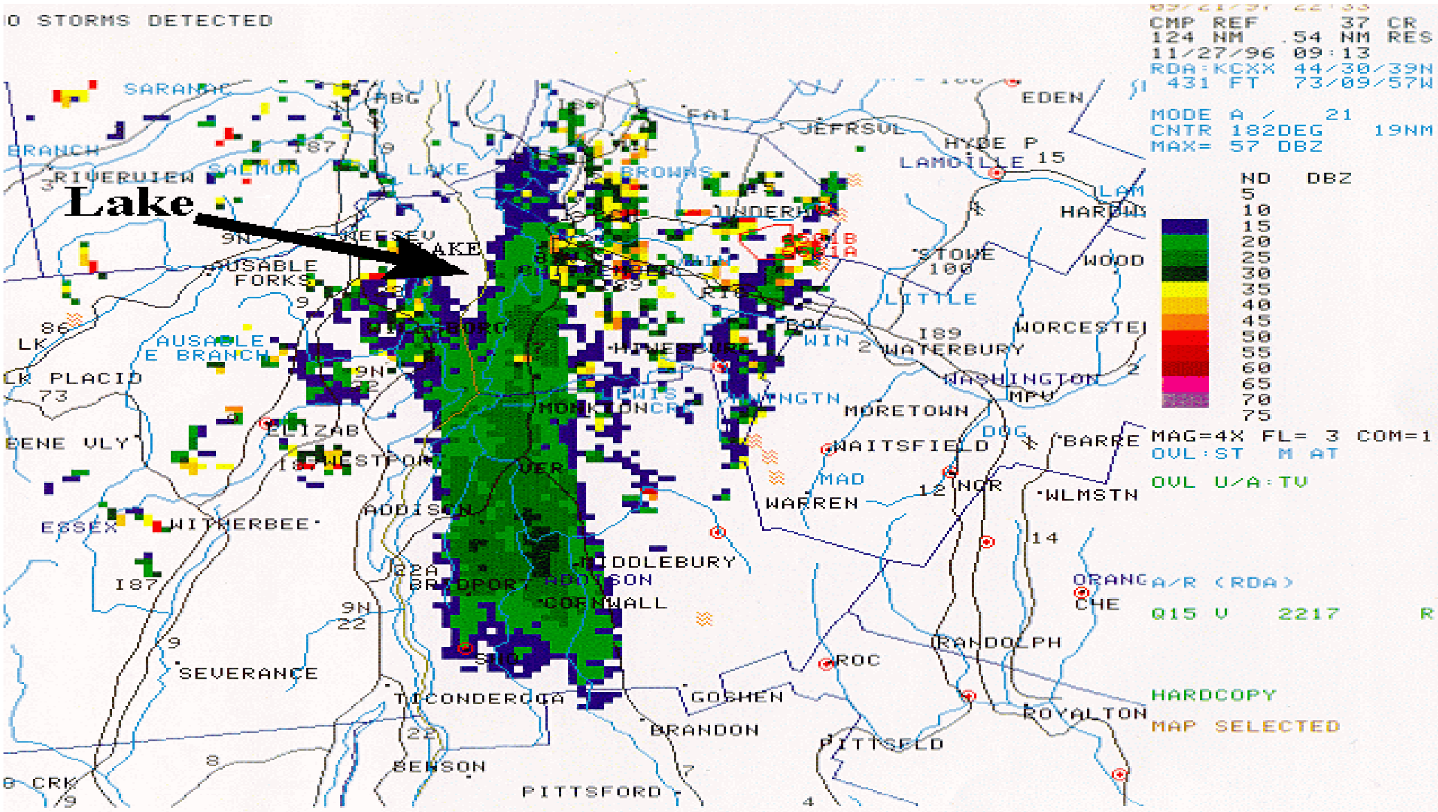


**Figure 2.** At 0913 UTC 27 November 1996 a large band of lake effect snow is depicted by a KCXX composite reflectivity image. Most notable is the area of 30 to 34 dBZ just north of Cornwall. The snow in this area may have been falling at a rate slightly over 2 inches per hour. The color table on the right depicts the intervals of maximum reflectivity in units of dBZ.

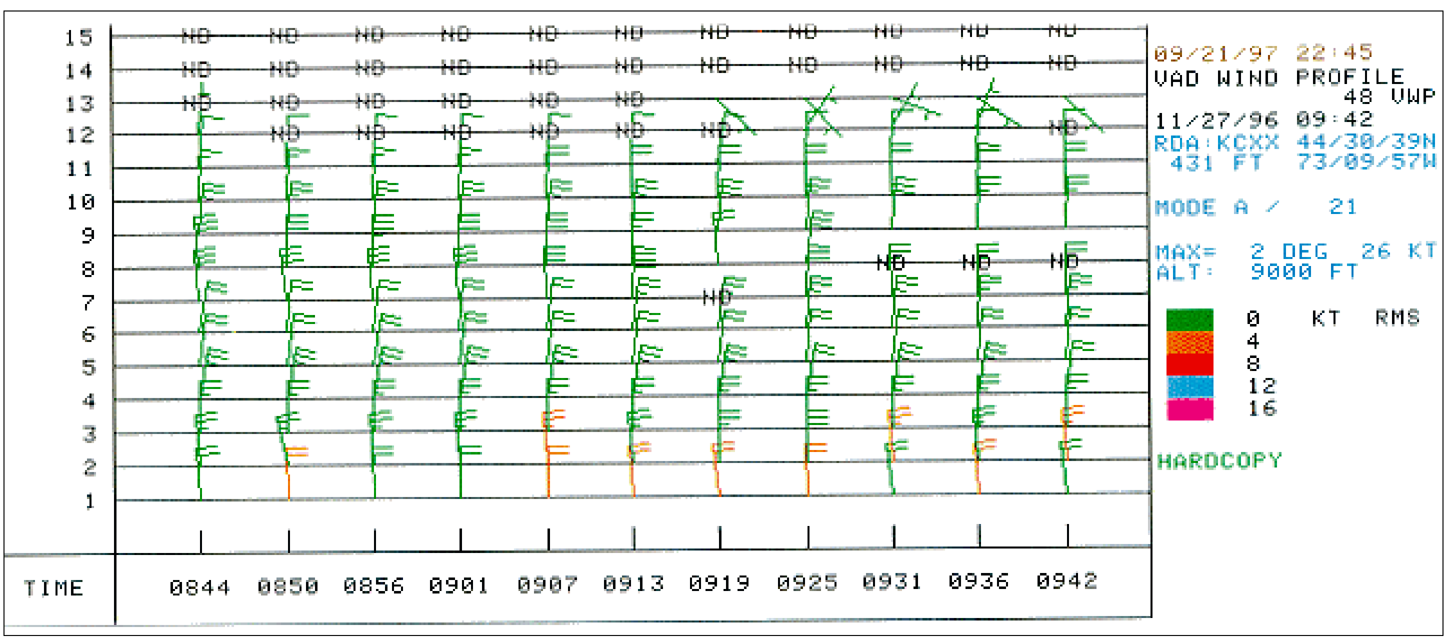


**Figure 3.** KCXX VWP from 0844 to 0942 UTC on 27 November 1996 depicting a deep layer of north winds at Burlington. Full wind barbs are 5 $ms^{-1}$ and half barbs are 2.5 $ms^{-1}$. Vertical axis is altitude in thousand feet. “ND” indicates no data. Color table at the right depicts the root-mean-square error (knots) for each wind estimate.

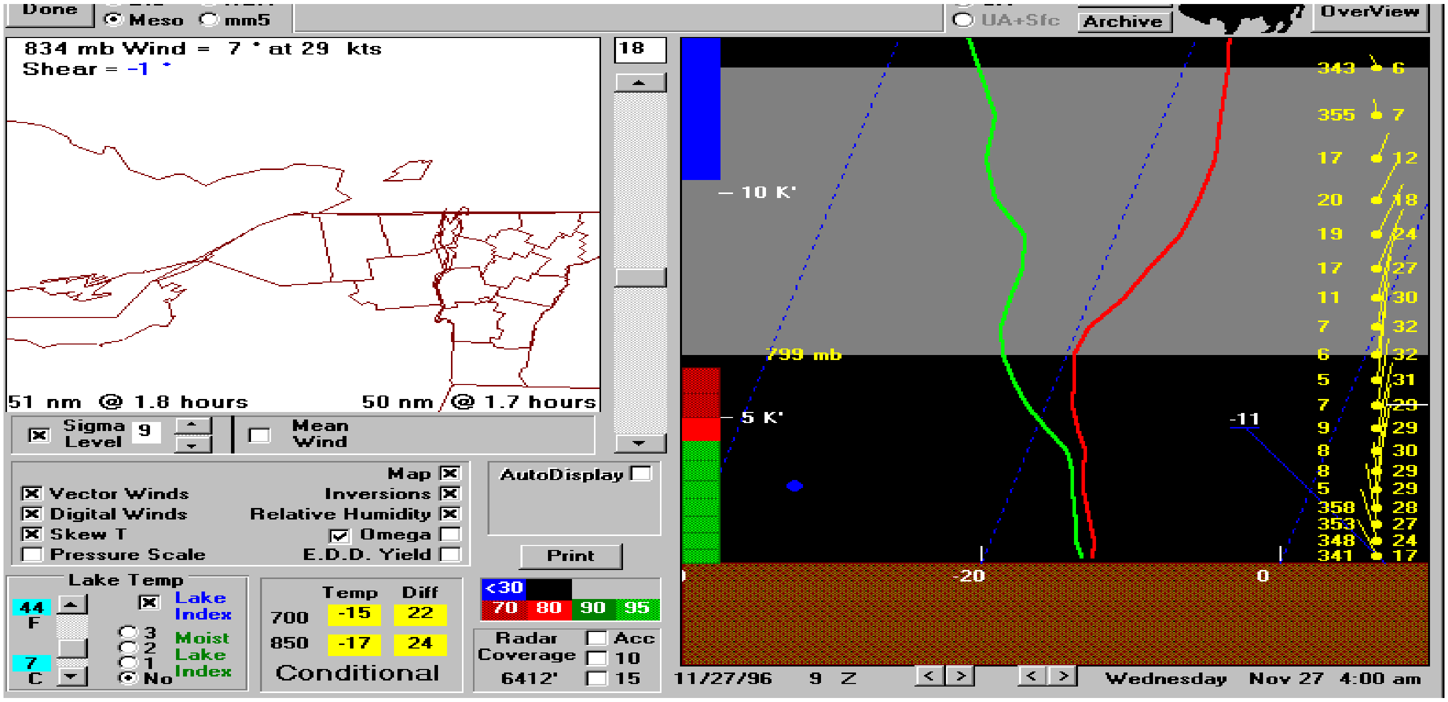


**Figure 4.** Meso-Eta forecast sounding at KBTV (Burlington) for 0900 UTC 27 November 1996 from the 1500 UTC 26 November run displayed with BUFKIT. The sounding depicts unidirectional north winds in a 7 kft layer. The gray shaded area on the sounding shows the depth of the inversion. The left side of the display shows were the lake temperature of 7°C was entered which resulted in "conditional" instability (Mahoney 2000).

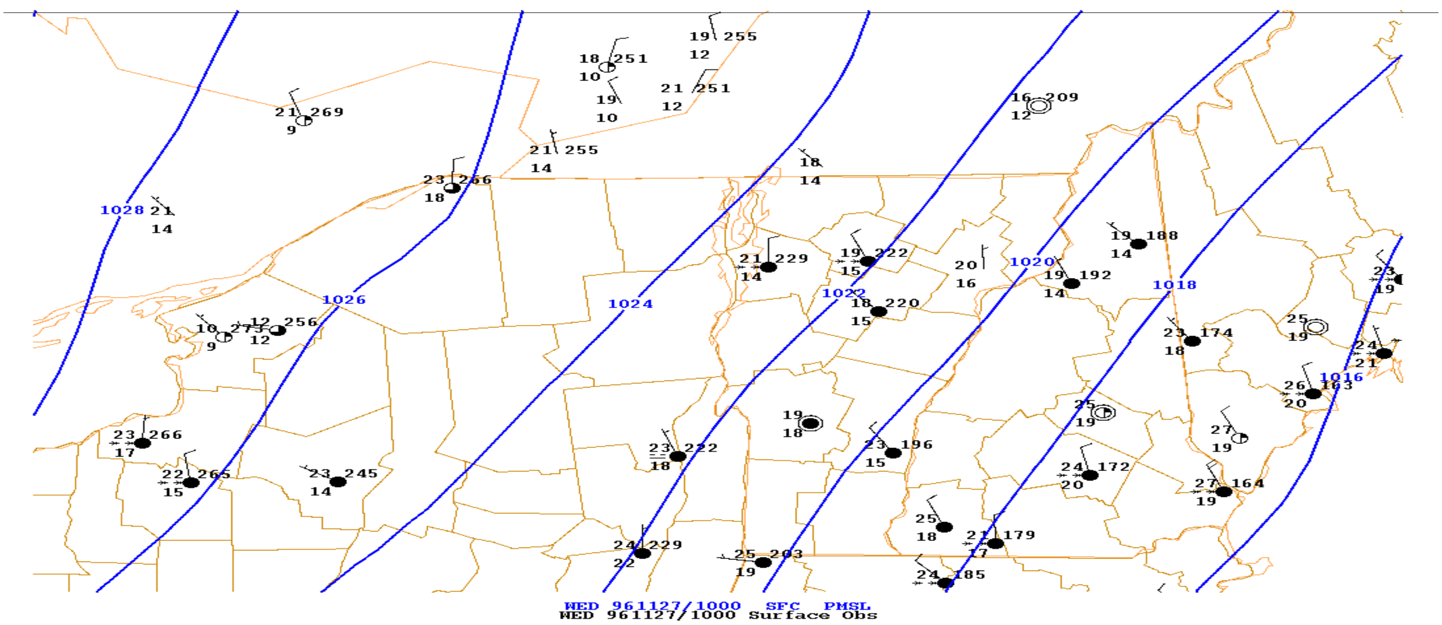


**Figure 5.** Surface analysis on 27 November 1996 at 1000 UTC. Solid lines are isobars contoured every 2-mb. Surface observations are shown on the map. Temperature and dew point temperature (°F) are on the left side of each observation. Present weather, if applicable, is located between the two temperatures. Full wind barbs ar 5 $ms^{-1}$ and half wind bards are 2.5 $ms^{-1}$. Mean sea level pressure is located on the upper right of the observations in units of tenths of a millibar. Sky condition, if available, is indicated by the shading of the circle.

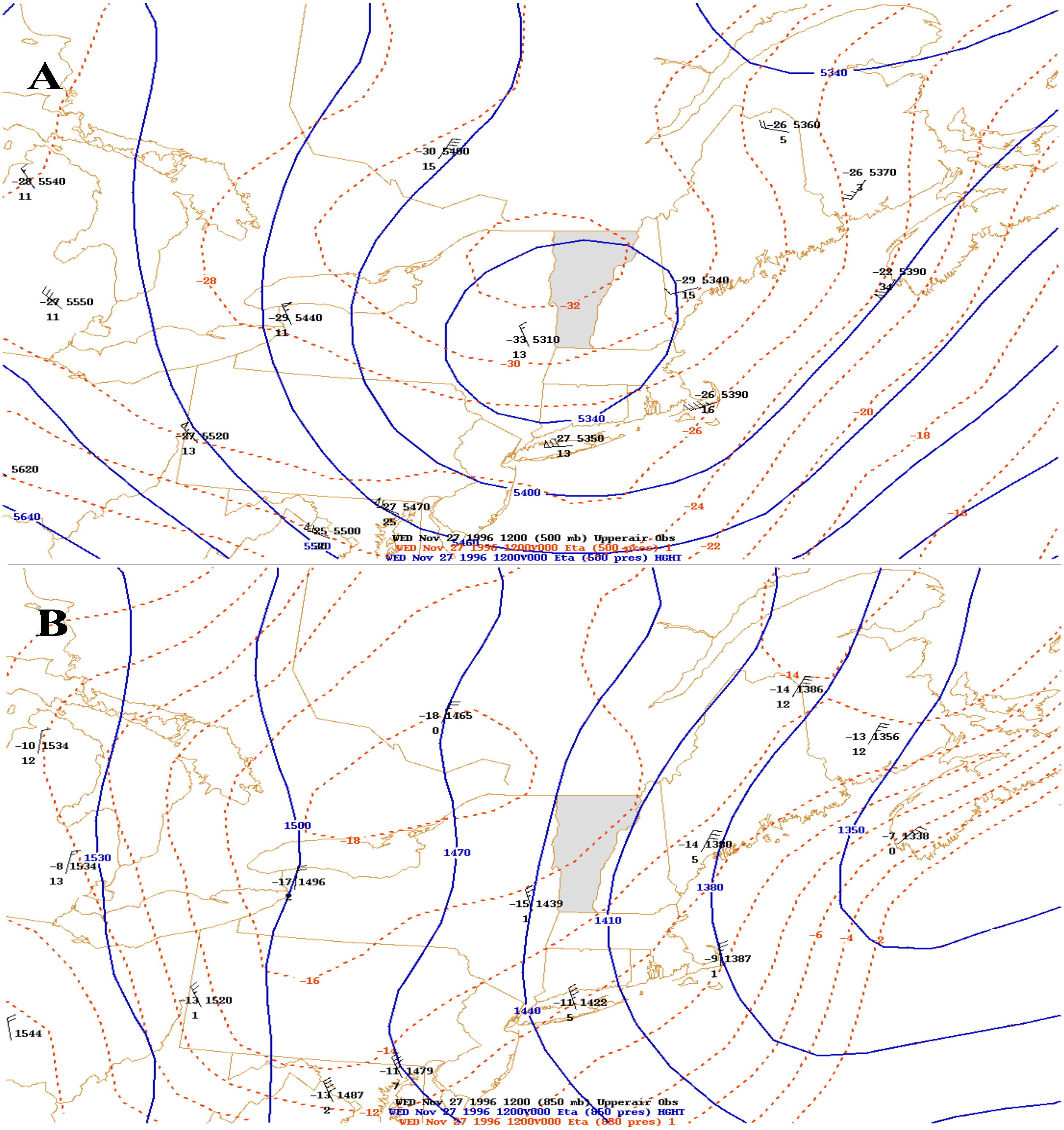


**Figure 6.** Upper air analyses from the Eta model on 27 November 1996 at 1200 UTC showing a 500-mb closed low (A) and 850-mb cold air advection (B). Solid lines are geopotential heights drawn every 60-m (A) and 30-m (B). Dashed lines are isotherms contoured every 2°C.

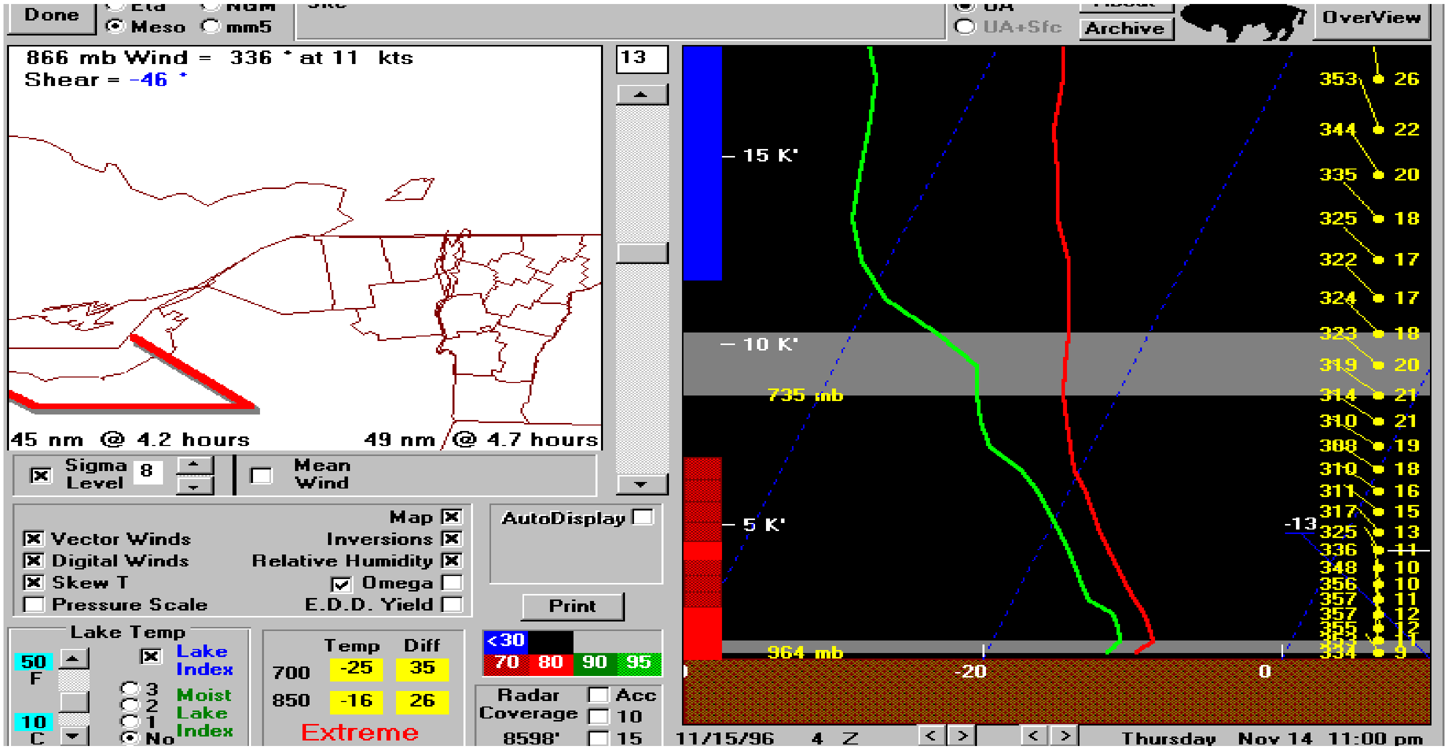


**Figure 7.** Meso-Eta forecast sounding for KBTV at 0400 UTC 15 November 1996 from the 1500 UTC 14 November run displayed with BUFKIT. The sounding shows extreme instability over Lake Champlain. Gray shaded areas on the sounding indicates an inversion layer. The left side of the display shows that a lake surface temperature of 10°C produced "extreme" instability.

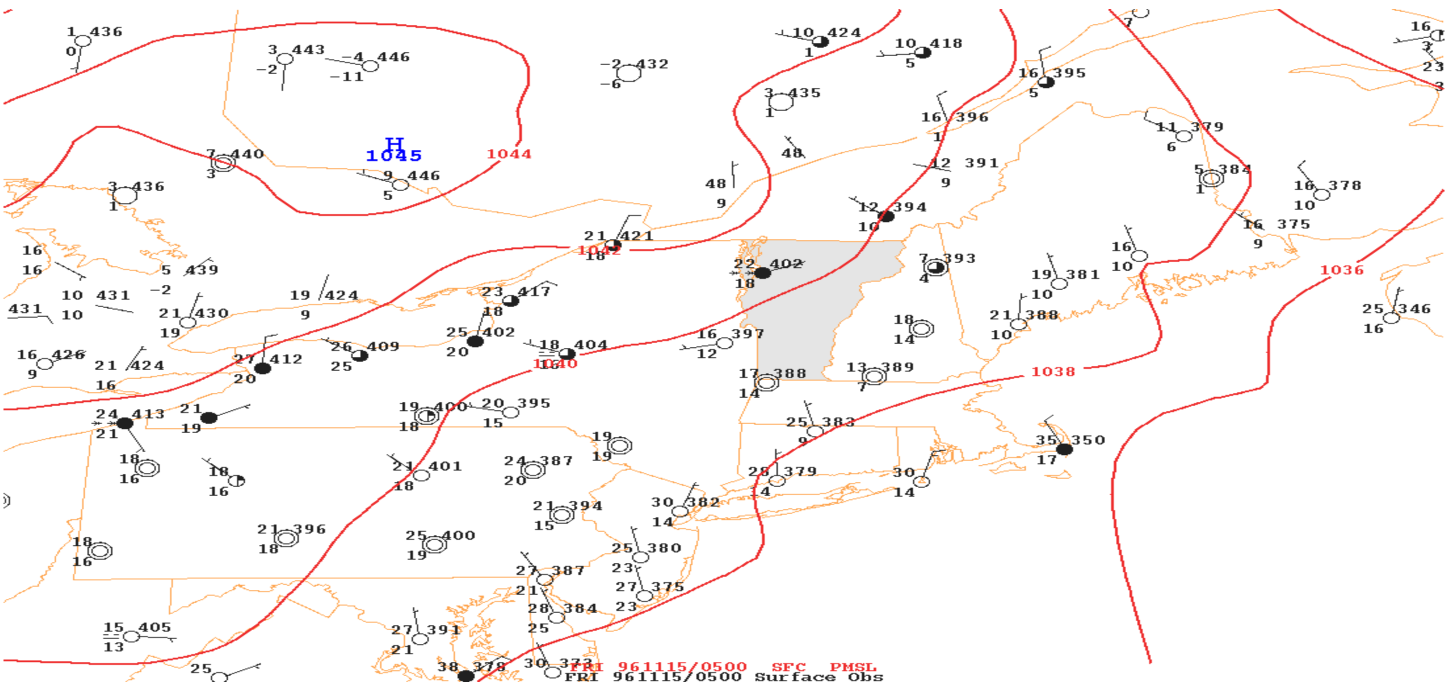


**Figure 8.** Same as Fig. 5, except it is from 0500 UTC on 15 November 1996.

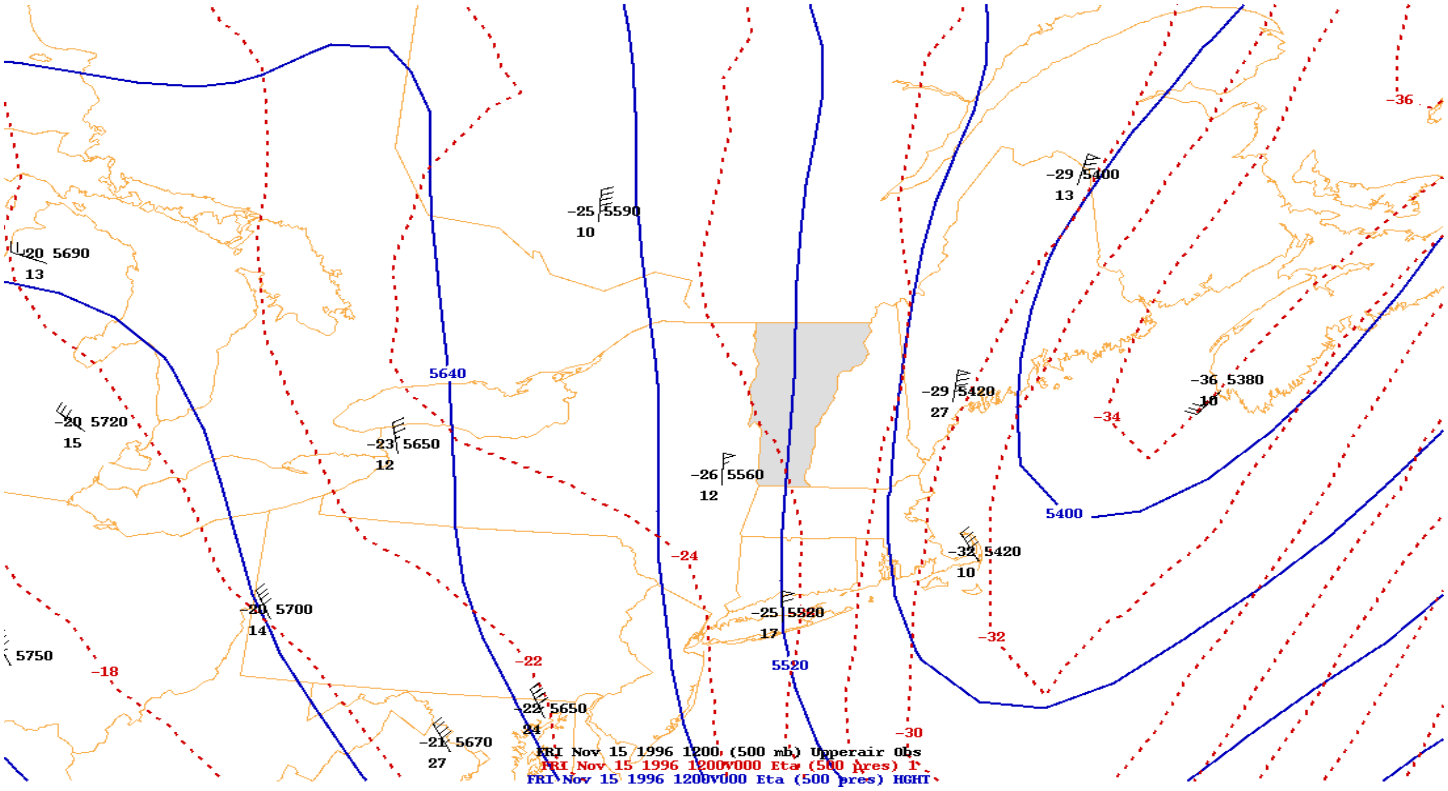


**Figure 9.** Eta model's 500-mb analysis at 1200 UTC 15 November 1996. Solid lines are geopotential heights (contoured every 60-m) and dash lines are isotherms (contoured every 2 °C). Upper air observations are shown.

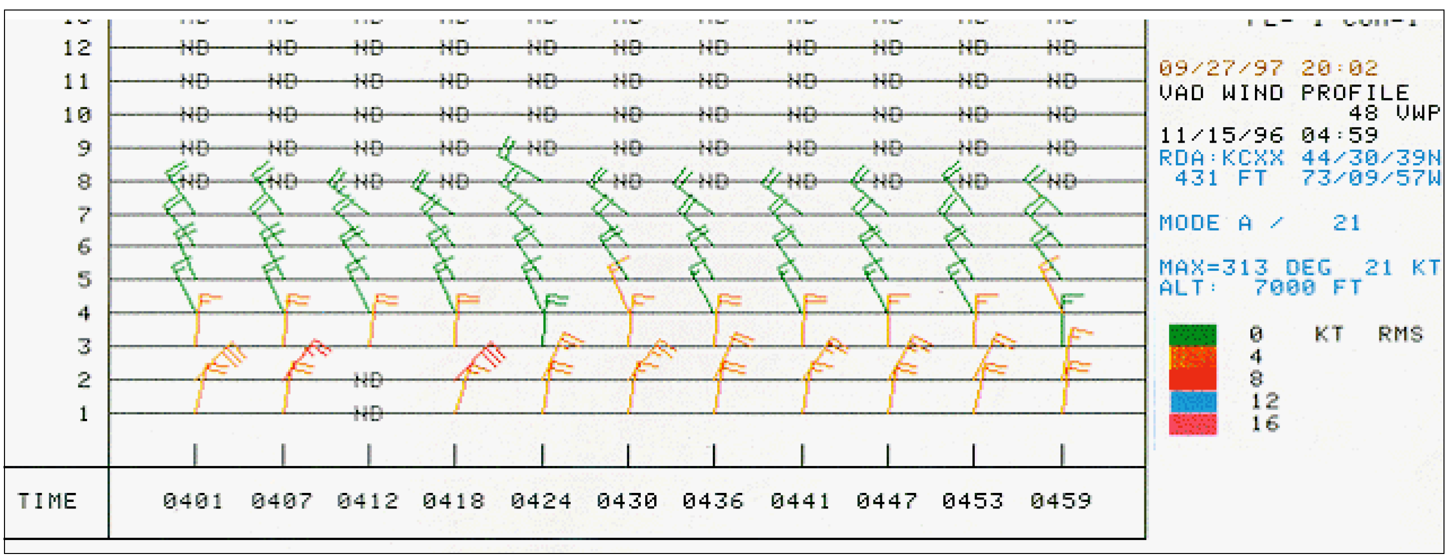


**Figure 10.** Same as Fig. 3, except it is from 5 November 1996 between 0401 and 0459 UTC. It depicts a trend towards north winds in the lowest 3,000-ft layer. This coincides with the development of a moderate band (20-29 dBZ) of lake effect snow.

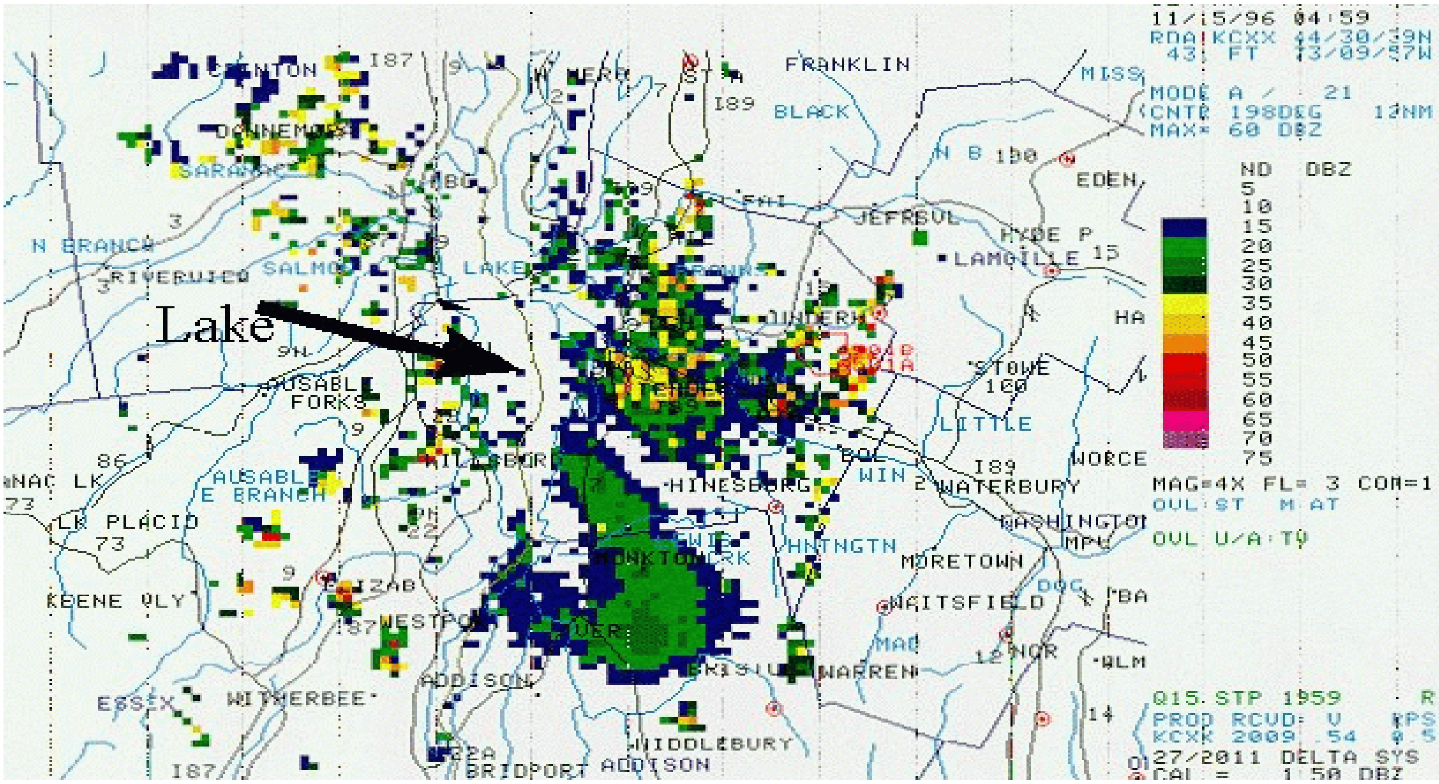


**Figure 11.** KCXX composite reflectivity image at 0459 UTC 15 November 1996. A band of lake effect snow extending from the southern end of Lake Champlain produced a steady snowfall from 0100 to 1000 UTC on 15 November 1996. The color table on the right depicts the intervals of maximum reflectivity in units of dBZ.

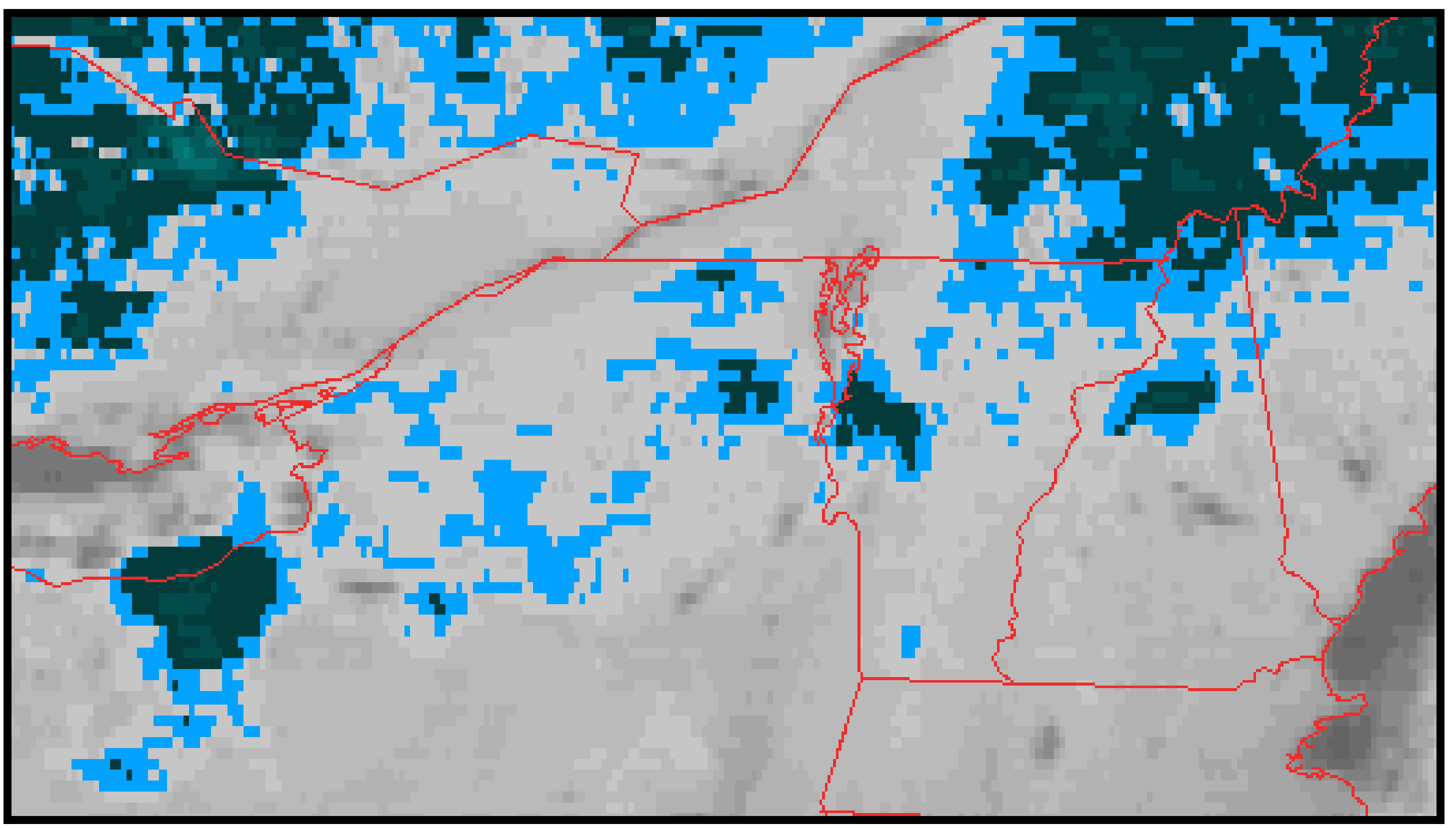

**Figure 12.** GOES-8 10.7 µm satellite image at 0915 UTC on 15 November 1996 showing a band of lake effect enhanced cold cloud tops (-18°C is the dark blue) extending southeast of Lake Champlain.

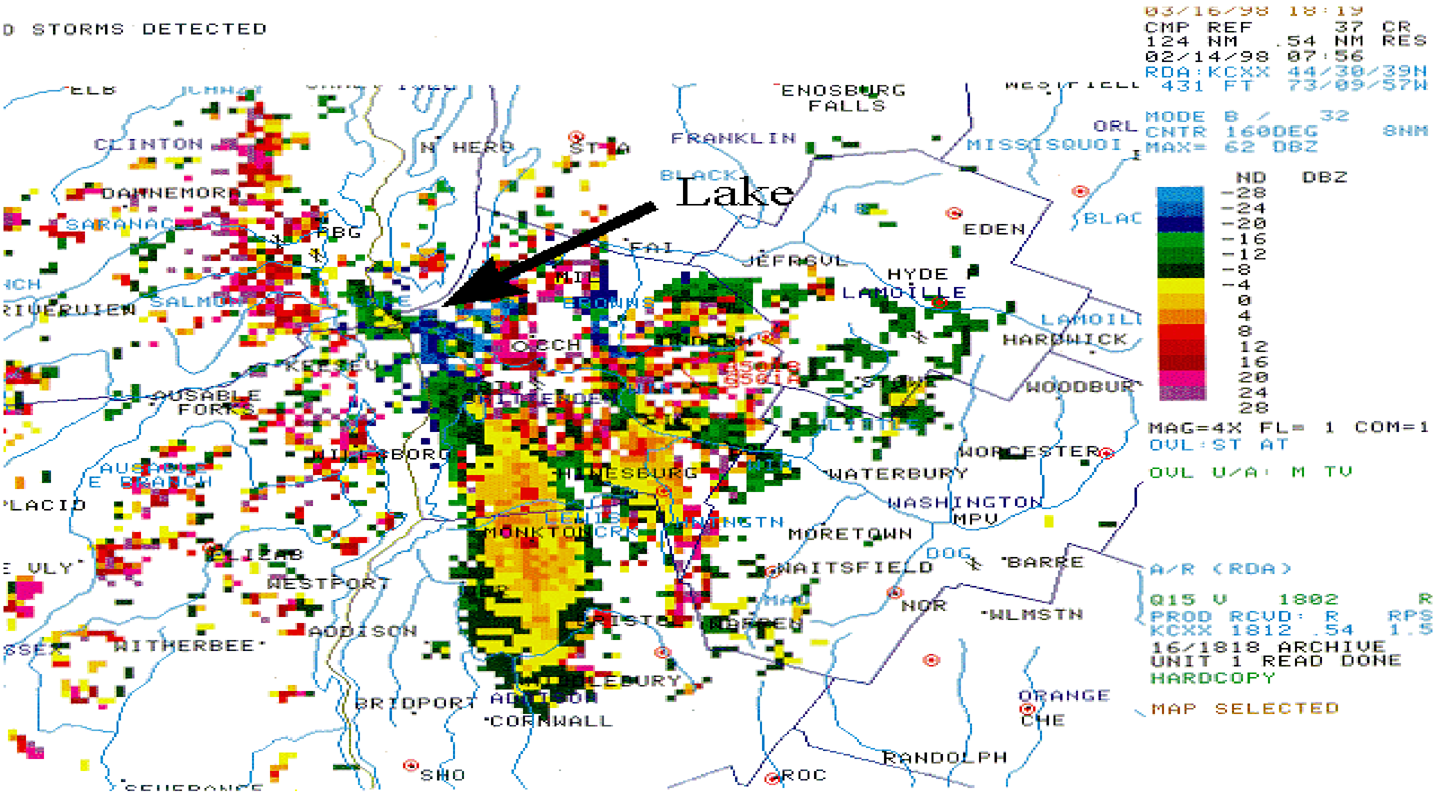

**Figure 13.** KCXX composite reflectivity image at 0756 UTC 14 February 1998. A weak band of snow is detected by radar on 14 February 1998. Reflectivity returns indicate that the band originates from the open waters just southeast of Plattsburgh (PBG) and then curves south with the northerly flow. The color table on the right depicts the intervals of maximum reflectivity in units of dBZ.

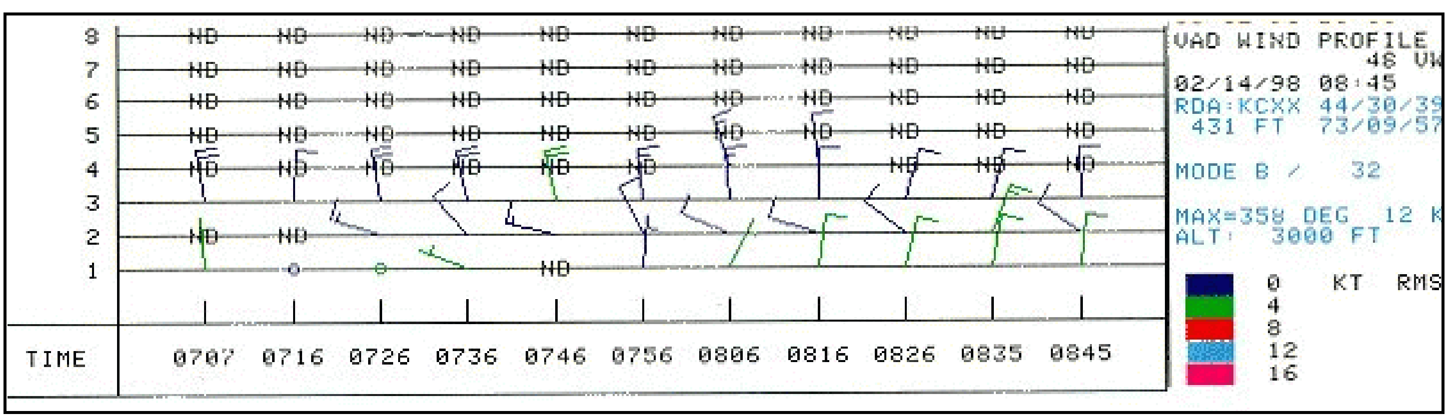

**Figure 14.** Same as Fig. 3, except it is for the period 0707 to 0845 UTC on 14 February 1998. It shows northerly winds in a 3,000-ft layer with an occasional westerly component at 2,000-ft.

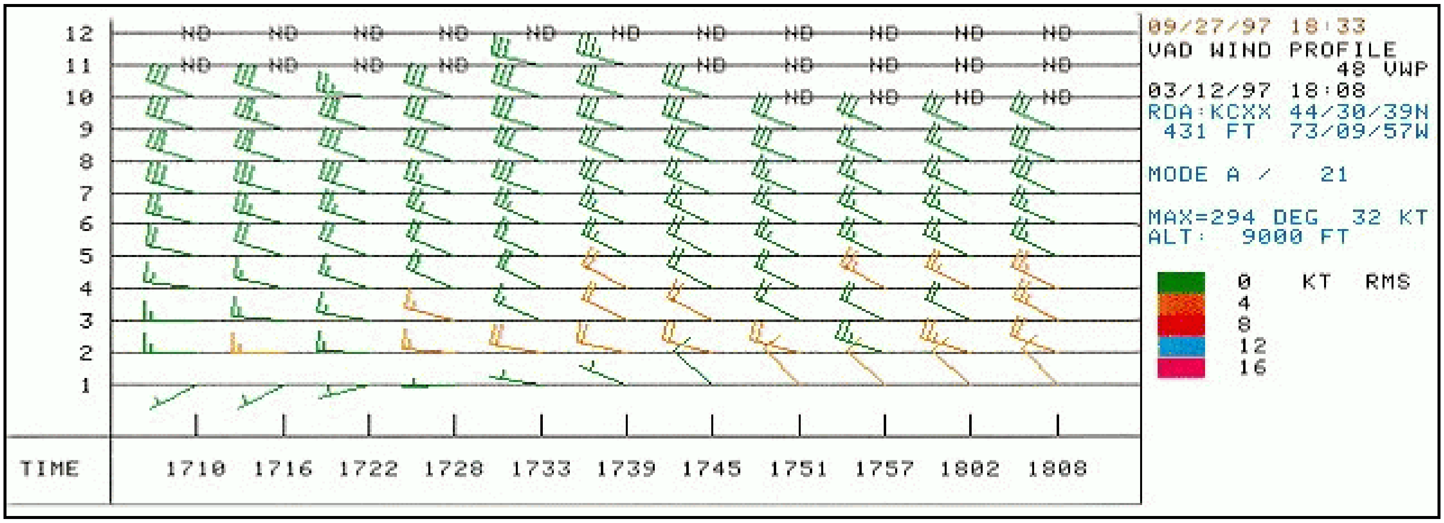


**Figure 15.** Same as Fig. 3, expect it is for 12 March 1997 between 1710 to 1808 UTC. It shows the passage of a surface trough around 1730 UTC.

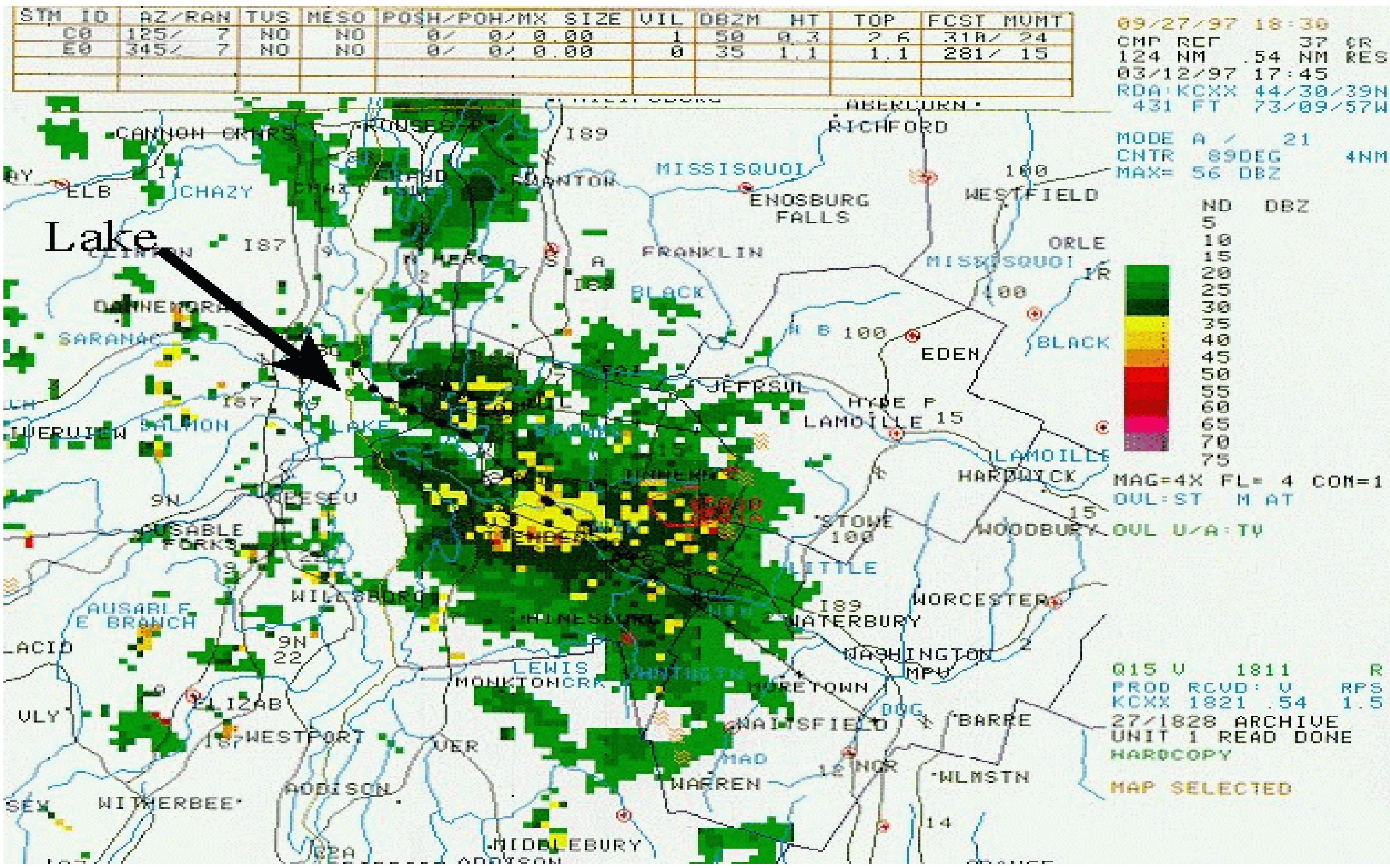


**Figure 16.** An example of lake enhanced snow squalls depicted by KCXX composite reflectivity at 1745 UTC on 12 March 1997. Burlington is located in the large area of 35-39 dBZ which was producing heavy snow. Other light snow showers are seen on the windward side of Lake Champlain. The WSR-88D SCIT algorithm identified this cell (black dots and line) and tracked it across the lake. The color table on the right depicts the intervals of maximum reflectivity in units of dBZ.

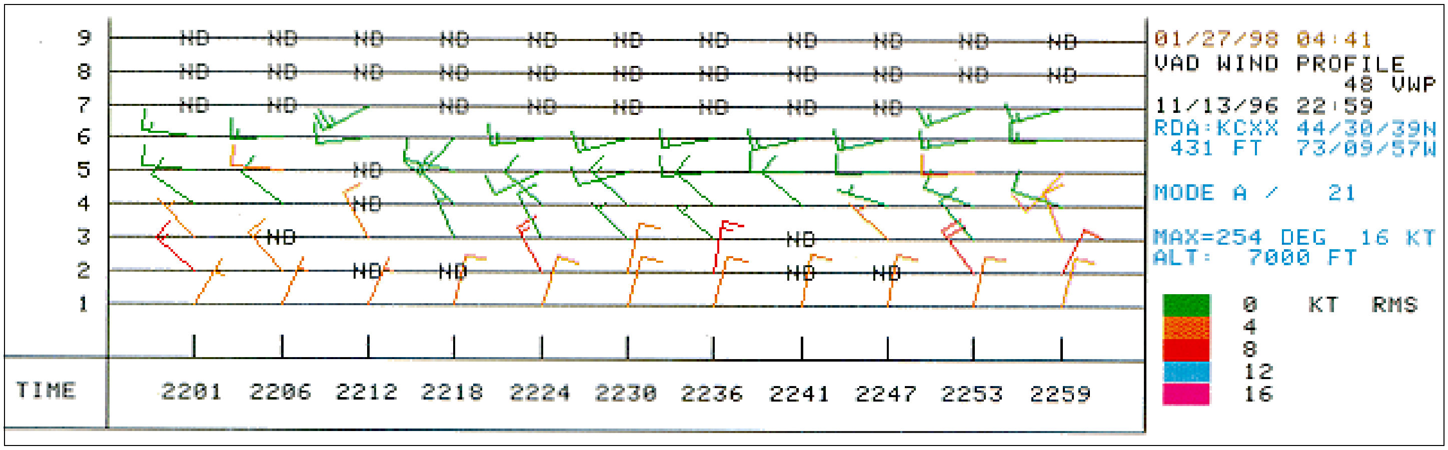


**Figure 17.** Same as Fig. 3, except it is for 13 November 1996 between 2201 and 2259 UTC. The north winds at 1,000-ft allowed for a long trajectory over Lake Champlain.

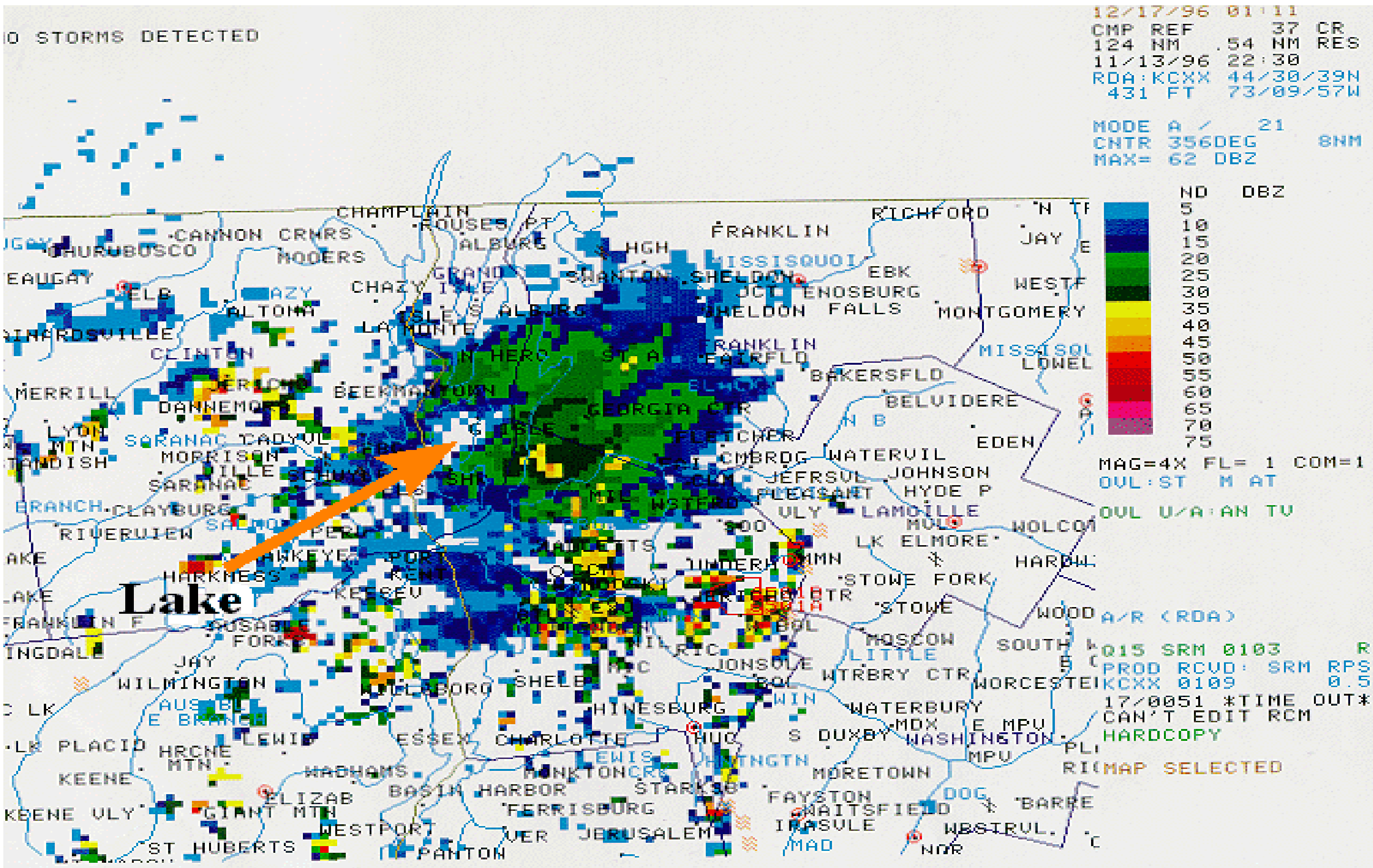


**Figure 18.** An intense lake enhanced snow squall depicted by the KCXX composite reflectivity image at 2230 UTC 13 November 1996. An impressive area of 30-40 dBZ is visible near the shore line of Lake Champlain. Lesser developed cells are seen north and south of this area over the open waters. A few light snow showers are seen on the windward side of the lake. The color table on the right depicts the intervals of maximum reflectivity in units of dBZ.

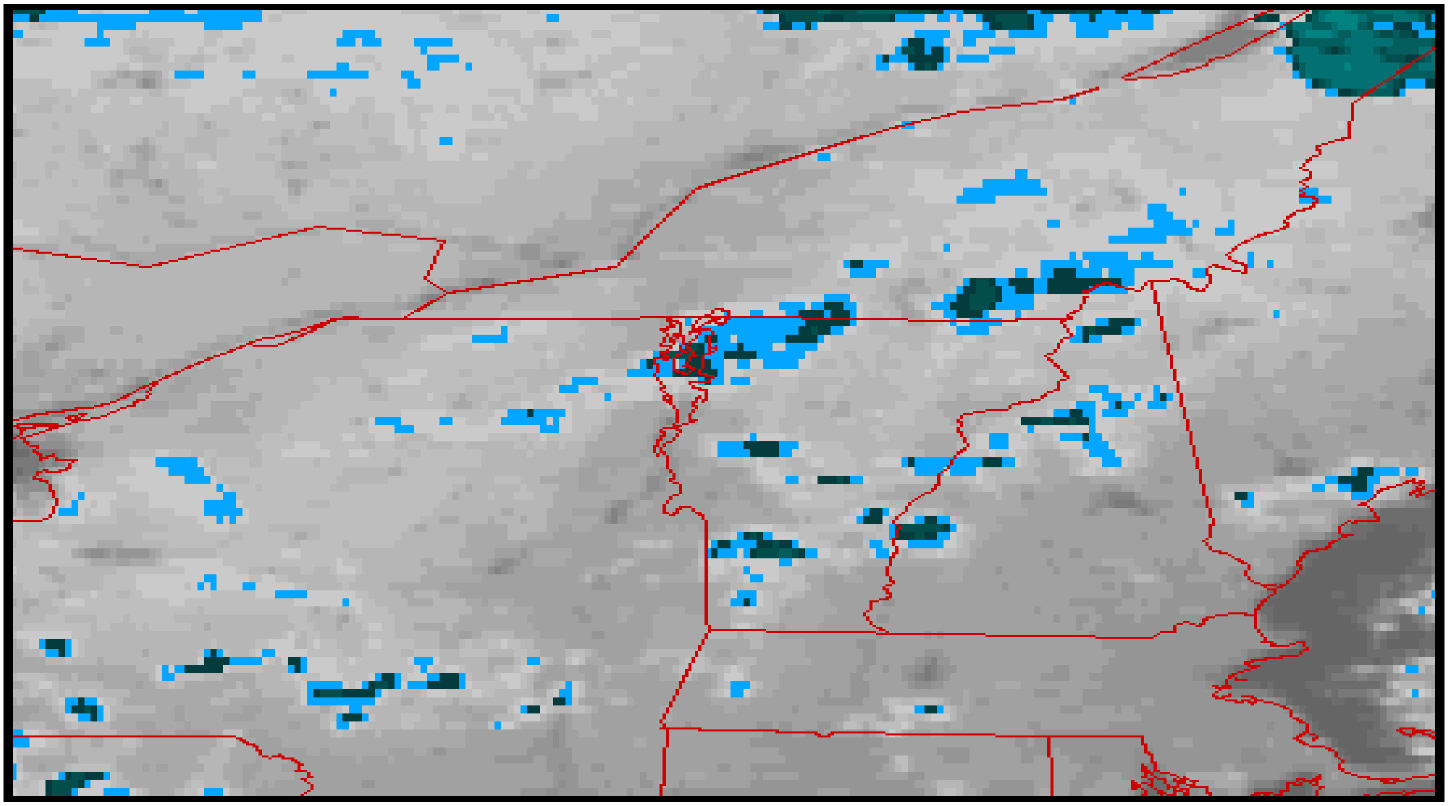

**Figure 19.** GOES-8 10.7 µm satellite image depicting enhanced clouds (dark blue is -21°C) over Lake Champlain at 2245 UTC on 13 November 1996. Other enhanced cold cloud tops indicate snow showers in the region.

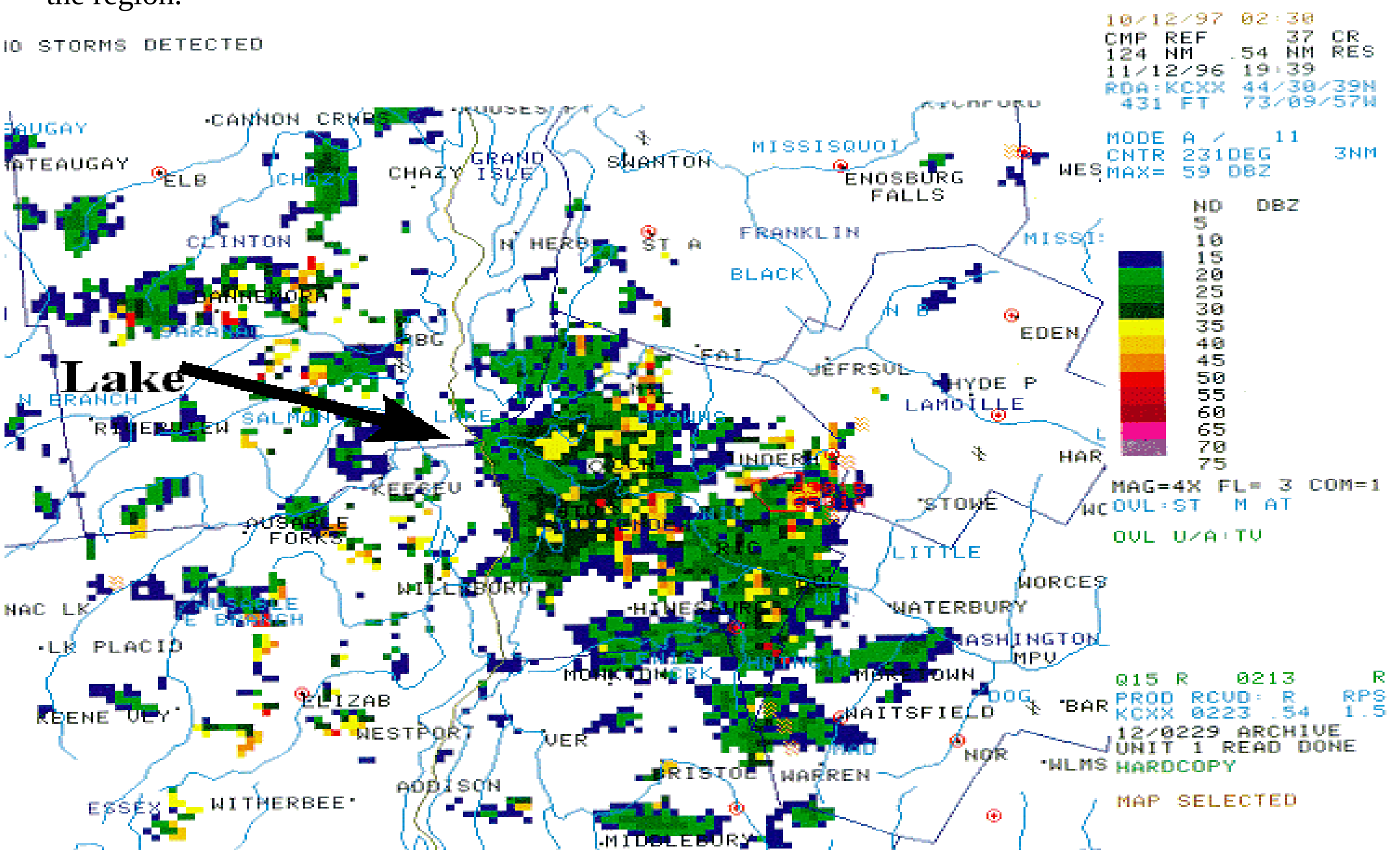


**Figure 20.** Composite reflectivity image at 1939 UTC from KCXX displays intense snow squalls (35-39 dBZ) that moved over Burlington on 12 November 1996. Numerous lighter snow showers are seen on the west side of Lake Champlain. The color table on the right depicts the intervals of maximum reflectivity in units of dBZ.

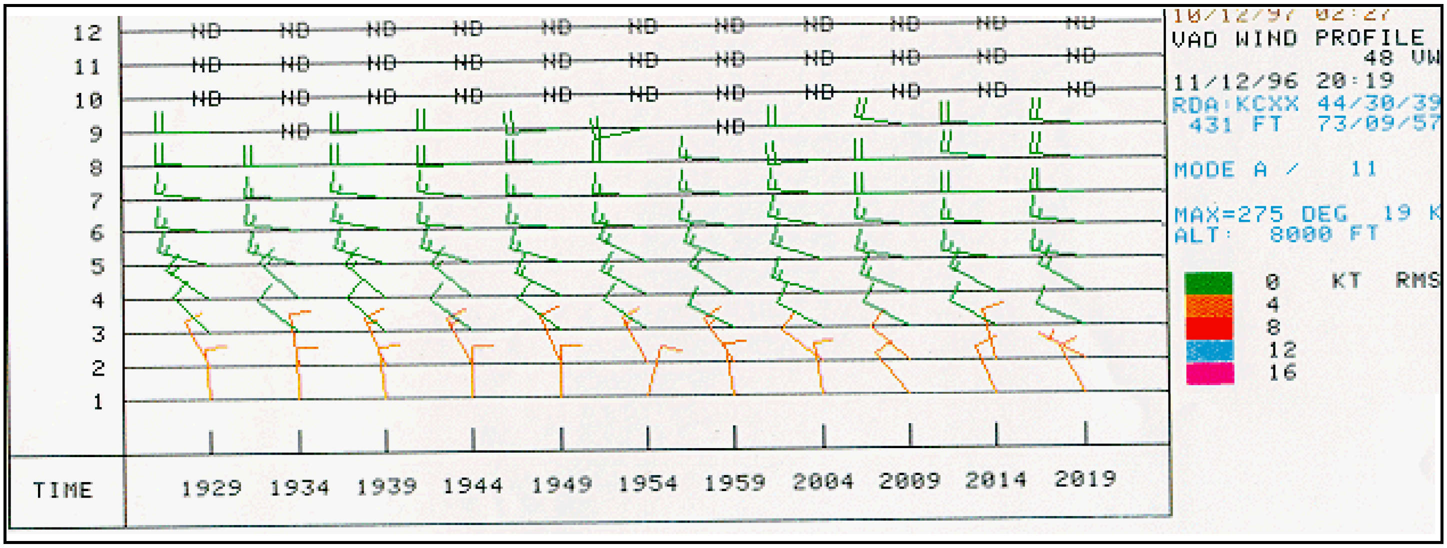


**Figure 21**. Same as Fig. 3, except from 2 November 1996 between 1929 and 2019 UTC. It shows strong directional shear in a 9,000-ft layer. A north wind was observed at 1,000-ft, which provided a long over-water fetch.

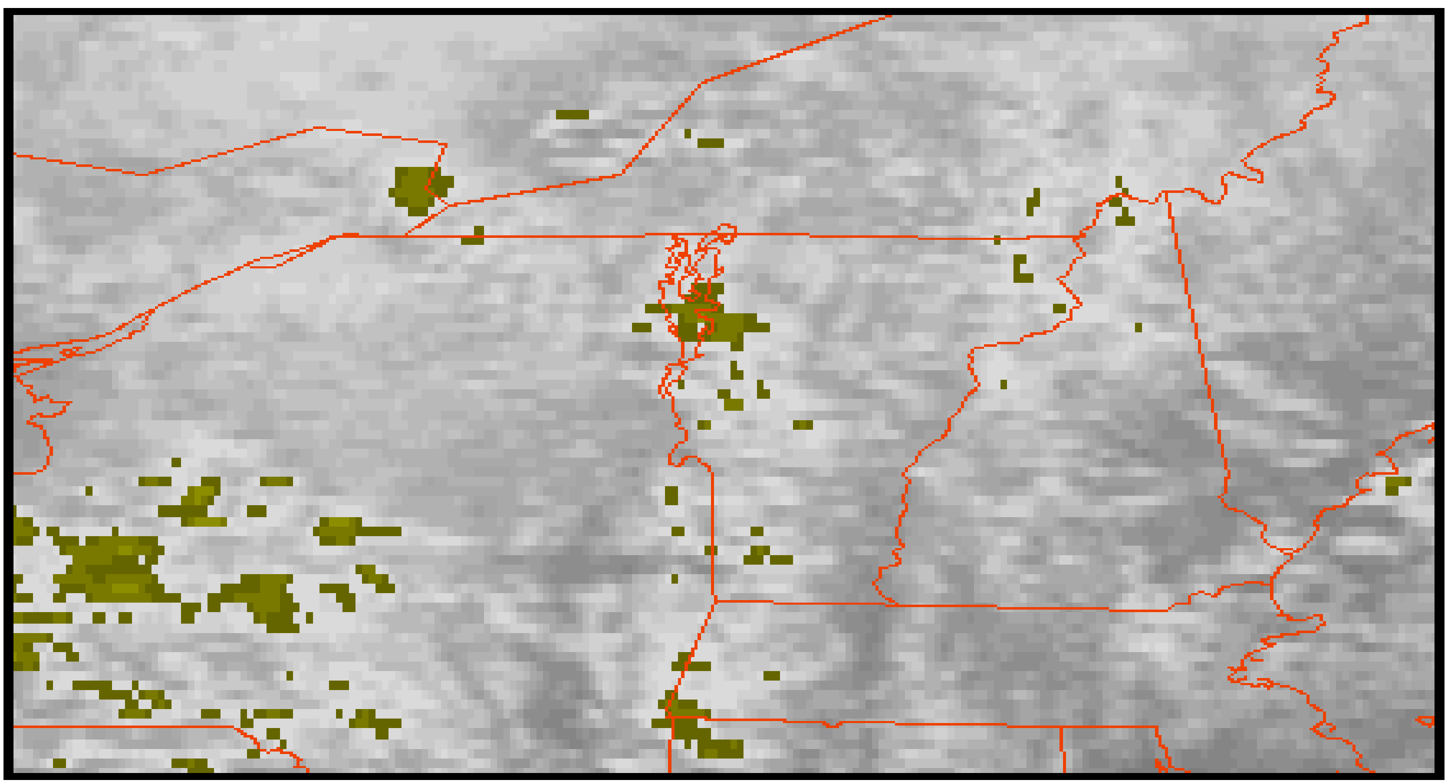

**Figure 22.** GOES-8 10.7 µm satellite image taken at 1745 UTC on 12 November 1996 depicting one of the heavy snow squalls that affected Burlington. Cloud top temperatures over Lake Champlain were between -20 and -25 °C indicated by the greenish-yellow enhancement.