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EXAMINATION OF A LAKE-EFFECT SNOW EVENT WITH THE FOCUS ON NEW TECHNOLOGY

Kevin Barjenbruch, Rick Hiltbrand,
James Kosarik, and Robert LaPlante
NOAA/National Weather Service Forecast Office
Cleveland, Ohio

1. INTRODUCTION

The Lake-Effect Snow (LES) study was initiated to evaluate the capability of the modernized National Weather Service to detect and predict LES events with the goal of improving the public warning and forecast services associated with these events. The main objectives of this study are to assess the ability of the Weather Surveillance Radar - 1988 Doppler (WSR-88D) and the Geostationary Operational Environmental Satellite - 8 (GOES-8) to detect the development and evolution of the lake-induced snow squalls, and to document the impact of the new observing systems and forecast methods on the resulting LES forecasts. This paper will examine the LES event that occurred on 1 and 2 January 1995, over northeast Ohio and northwest Pennsylvania. The event will be examined by first reviewing the analysis of the event. The extensive display capabilities of PC based Gridded Information Display and Diagnostic System (PCGRIDDS) will then be used to present an evaluation of the model data and a discussion of the performance of the Nested Grid Model (NGM) and the Early Eta Model (ETA) for this LES event. Next, an assessment of the ability of the NEXRAD Weather Service Forecast Office (NWSFO) Cleveland, Ohio, (CLE) WSR-88D (KCLE) to detect the development and evolution of LES bands will be given. The effectiveness of the GOES-8 digital data in remotely monitoring LES bands by using the RAMM Advanced Meteorological Satellite Demonstration and Interpretation System (RAMSDIS) workstation will be discussed. Finally, a technique for integrating GOES-8 and WSR-88D data to predict snowfall intensity beyond the effective range of the radar will be presented.

2. EVENT SYNOPSIS

A cold front moved across the eastern Great Lakes during the afternoon of 1 January 1995 and was followed by a modified Arctic airmass, which advected into the region on a westerly flow. At 0000 UTC 2 January 1995, a 20 to 30 knot westerly flow below 700 mb developed with 850 mb temperatures around -7 °C. Very little directional wind shear was indicated by the KCLE velocity azimuth display wind profile (VWP) through the night (not shown). The Lake Erie water temperature was about 6 °C, which contributed to a very unstable lapse rate in the lower atmosphere. LES bands began to develop around 0200 UTC on 2 January 1995 and intensified around 0600 UTC as the coldest air began to advect over Lake Erie. The heaviest snowfall was confined to within 10 miles of the lakeshore from Mentor, Ohio, located 20 miles northeast of Cleveland, to Erie, Pennsylvania, see Fig. 1. The LES ended during the afternoon of 2 January 1995 as low level winds backed to the southwest, shifting the LES bands over Lake Erie.

3. MODEL DIAGNOSIS OF THE EVENT

Output from the ETA and the NGM from 0000 UTC 1 January both indicated that a strong cold front would move across the eastern Great Lakes region during 1 January and reach the East Coast by 1200 UTC on 2 January. The greatest amount of low level cold advection would pass across Lake Erie between 0000 UTC and 1200 UTC 2 January. Forecasters at NWSFO CLE diagnosed the potential LES event by using PCGRIDDS to display the 0000 UTC 1 January ETA and NGM model runs. The Dockus LES scheme was also evaluated (Dockus 1985).

The Dockus scheme, used regularly by CLE forecasters, is a LES forecasting tool. It uses empirically derived data and a decision tree process to derive quantitative snowfall amounts for 6 hour periods, out to 48 hours. The main parameters used in the Dockus scheme are the 850 mb temperatures, the boundary layer winds from the ETA or NGM, and the water temperature of Lake Erie near Cleveland. The water temperature of Lake Erie is used so a temperature differential between the lake and 850 mb can be computed through the forecast period. A temperature difference of 13 °C or more between the lake and 850 mb indicates that LES is possible. The 13 °C difference corresponds to a dry adiabatic lapse rate through 850 mb, with the layer obtaining absolute instability (Dockus 1985). The boundary layer winds are used as the steering currents of the potential LES bands.

The Dockus scheme, based on the boundary layer winds and 850 mb temperature data from the ETA and NGM model runs from 0000 UTC on 1 January, showed that LES was likely over extreme northeast Ohio and northwest Pennsylvania between 0600 UTC 2 January through 0000 UTC 3 January. Output from the Dockus scheme indicated that up to 7 inches of snowfall was possible over extreme northeast Ohio with up to 15 inches over Erie County, Pennsylvania.

The gridded data from the 0000 UTC on 1 January ETA and NGM model runs were remarkably similar with respect to the wind direction and temperature fields through 48 hours over the Lake Erie area. The model runs indicated almost due westerly winds would develop from 1000 mb to 700 mb beginning 0000 UTC 2 January and last through 1800 UTC 2 January. The forecast for the directional wind shear between 1000 mb and 700 mb at CLE was no more than 20° at 1200 UTC on 2 January, as shown in Fig. 2. Niziol (1987) and Niziol et al. (1995) pointed out that LES bands begin to break down if the change in wind direction in this layer is greater than 30°.

Temperature forecasts from the two models indicated strong low level cold advection would occur over Lake Erie between 0000 UTC and 1200 UTC on 2 January. The temperature at 1000 mb was expected to decrease from 3 °C at 0000 UTC on 2 January to -6 °C by 1200 UTC making it cold enough for a snow event. The 850 mb temperature was expected to fall from -6 °C to -16 °C during this 12 h period, indicating cold advection of nearly 1 °C/h.

The lake to 850 mb temperature differential was expected to greatly exceed 13 °C by 1200 UTC 2 January. The expected differential was forecast to be 22 °C along with little low level directional wind shear. A local rule used at NWSFO CLE indicates that when the lake to 850 mb temperature differential is 20 °C or greater along with little low level directional wind shear, heavy LES is likely. Therefore, with continuity between the forecast models with respect to low-level wind and temperature fields, a snow squall warning was issued for Lake, Geauga, and Ashtabula Counties of Ohio as part of the early morning (4:00 a.m. EST) zone package Sunday morning, 1 January. The warning was valid for Sunday night and Monday. A snow squall warning was also issued for this same time period for Erie and Crawford Counties in northwest Pennsylvania by the NWSFO in Pittsburgh.

4. MODEL VERIFICATION

The low-level wind direction and temperature forecasts for 2 January from the ETA and NGM model runs from 0000 UTC on 1 January were very accurate. Subsequent model runs from 1200 UTC on 1 January and 0000 UTC on 2 January supported what was projected by the earlier ETA and NGM model runs. Verification of the NGM 36-h wind direction and temperature forecasts at CLE valid for 1200 UTC on 2 January showed only a 10° error in wind direction and a 1 °C error in temperatures at 1000 mb, 850 mb and 700 mb (Table 1). The analysis of the 1000 mb and 700 mb winds across Lake Erie, at 1200 UTC on 2 January, (see Fig. 3) revealed very little directional wind shear between these two levels.

An important feature in the gridded data was how the low level thermal fields changed in the vertical with time. At the start of the 0000 UTC on 1 January model runs, an 850 mb thermal trough extended from eastern North Dakota to northern Texas and was east of the 700 mb thermal trough which extended from North Dakota to northern Utah. The gridded data indicated that by 1200 UTC on 2 January, the 700 mb thermal trough would have moved slightly to the northeast of the 850 mb thermal trough and extend across Lake Erie, as shown in Fig. 4. Figure 5, the 700 mb and 850 mb temperature analysis at 1200 UTC 2 January, showed the 700 mb thermal trough was initialized a little to the east of the 850 mb thermal trough. The size of both thermal troughs were also a little larger than what was initially forecast from 0000 UTC 1 January.

The mechanism that seems to have accelerated the 700 mb thermal trough to the east of the 850 mb thermal trough was a strengthening upper level jet. An 80 kt jet streak was shown at 300 mb over Colorado and Kansas at 0000 UTC on 1 January. The gridded data indicated that the jet streak would increase to 110 kt by 0000 UTC on 2 January as it moved east across southern Missouri and Kentucky. The jet streak was then projected to remain at 110 kt and reach Virginia and New Jersey by 1200 UTC on 2 January.

In reality, the jet streak reached 115 kt over northern Arkansas and western Tennessee by

0000 UTC on 2 January and increased to 120 kt over eastern Tennessee and North Carolina by 1200 UTC 2 January (figures not shown). The strengthening jet streak increased winds down through 700 mb which helped to accelerate the 700 mb thermal trough to the east of the 850 mb thermal trough. The importance of having the colder air at 700 mb nearly vertically stacked over the 850 mb thermal trough over Lake Erie is quite significant for LES. A steeper lapse rate between the lake and 700 mb allows the clouds to develop through a greater depth in the atmosphere. This leads to a greater potential for significant LES (Niziol 1987 and Niziol et al. 1995).

5. GROUND TRUTH

Snow bands, as detected by the CLE WSR-88D radar, began to form over western Lake Erie around 0200 UTC on 2 January. This is soon after the lake to 850 mb differential temperature reached 13 °C, based on the 0000 UTC on 2 January 850 mb NGM analysis (not shown). The bands continued to develop eastward and reached extreme northeast Ohio around 0500 UTC. The bands persisted through the night, primarily across Lake County and northern Ashtabula County, Ohio, and Erie County, Pennsylvania. The snow began to diminish over extreme northeast Ohio after 1200 UTC 2 January and over extreme northwest Pennsylvania by 1800 UTC as winds below 850 mb began to back to the southwest. This shifted the snow bands offshore of northeast Ohio and northwest Pennsylvania and made them parallel to the south shoreline of Lake Erie. Figure 6 depicts the VWP from the CLE WSR-88D from 1352 to 1450 UTC, which clearly shows the wind above 2000 feet backing. The backing winds were not shown by any of the ETA or NGM model runs from 0000 UTC on 1 January through 1200 UTC on 2 January. This illustrates the importance of using the VWP in making short-term forecasts.

Snowfall totals (Fig. 1) over northeast Ohio for the event ranged from around an inch over eastern Cuyahoga County and northern Geauga County to between 6 and 7 inches over eastern Lake and northern Ashtabula Counties. Snowfall totals over northwest Pennsylvania ranged from 1 to 2 inches over northern Crawford County to between 6 and 8 inches over northern Erie County.

6. RADAR

LES development initially occurred over the western basin of Lake Erie near 0200 UTC 2 January. In Fig. 7, note the area of 0 to 4 dBZ returns from just north of the islands over the western basin of Lake Erie (north of Erie County, Ohio, see Fig. 1) to a position north of CLE as shown on the CLE WSR-88D 0202 UTC 0.5° base reflectivity product. The sensitivity of the radar, in clear air mode, during the first two winter seasons has proven very useful in early detection of developing snow bands over Lake Erie at NWSFO CLE.

Local geographical factors aided in this snow band development. During the overnight hours, a land breeze often develops over Lake Erie. This land breeze can aid in the development of LES (Passarelli and Braham 1981; Schoenberger 1986). Near CLE, the orientation of Lake Erie shoreline shifts from west-to-east abruptly to southwest-to-northeast. Since the land breeze develops roughly at a 90° angle to the lakeshore, west of CLE, the land breeze then intersects the west wind at a 90° angle. The resulting convergence is often detected by the CLE WSR-88D, operating in clear air mode, as an area of reflectivity returns, generally less than 0 dBZ. With a weak synoptic gradient, the land breeze may penetrate 20 miles out over the lake.

East of CLE, the northeast to southwest orientation of the lakeshore produces a land breeze, of which a component is opposed to a west wind and consequently, the land breeze usually does not penetrate far into the lake. Consequently, snow band development east of CLE usually occurs near the shore as with this event.

Another factor that aids in the development of snow along the south shore of Lake Erie east of CLE is the topography of the area. Rather abrupt hills rise some 500 to 600 ft higher than the lake within 20 miles of the lakeshore. The surface wind convergence and upward lift generated by this terrain, enhances snowfall intensity.

LES band development continued and by 0608 UTC, a band of 24 to 27 dBZ reflectivity returns extended inland across Lake and northern Ashtabula Counties in northeast Ohio. Figure 8, a 0.5° base reflectivity product at 0608 UTC, depicts this band location. Throughout this formation stage, a favorable wind profile (see Fig. 9), directional shear less than 30° from the planetary boundary layer to 10,000 feet (Niziol 1987 and Niziol et al. 1995), was indicated by the WSR-88D VWP product.

The LES band of 24 to 27 dBZ reflectivity returns persisted through 0900 UTC. Snowfall rates during this period were 0.5 to 0.75 inches per hour. NWSFO CLE forecasters throughout the first two winter seasons with the WSR-88D (1993-94 and 1994-95) have noted snowfall rates that correlate well with a certain range of reflectivities. Snowfall rates of about 0.5 inches an hour often occur with 25-29 dBZ reflectivity returns and snowfall rates of an inch or more an hour occur with 30-34 dBZ reflectivity returns. Just as with rainfall, a correlation of snowfall and radar reflectivity returns has been proven to exist (Wilson 1973) and studies are underway to produce an operationally accurate reflectivity-snowfall rate equation. A lack of precise snowfall measurements has precluded any attempt to make a formal correlation of radar estimated snowfall amounts from the CLE WSR-88D at this time.

By 1005 UTC, two well defined bands were evident on the KCLE 0.5° base reflectivity product (Fig. 10). The original band still extended across Lake County, but had weakened. A primary band now extended from the western portion of Lake Erie eastward to north of the Ohio-Pennsylvania border. This is what one would expect with a boundary layer wind blowing nearly parallel to the long axis of the lake (Niziol 1987 and Niziol et al. 1995). NWSFO CLE forecasters have noted this type of multiple banded structure with a west wind.

Between 1005 and 1100 UTC 2 January, the primary band over the lake shifted south, reaching northeast Ashtabula County and northern Erie County. This band moved little from 1100 through 1400 UTC. The secondary band continued across Lake and northwest Ashtabula Counties (figure not shown).

Until 1323 UTC, the WSR-88D was forced to remain in clear air mode, volume coverage pattern (VCP) 31, through maximizing the nominal clutter area. At this time, the nominal clutter area was reduced and the WSR-88D reverted to precipitation Mode, VCP 21.

It has become customary for forecasters at NWSFO CLE to operate the WSR-88D in clear air mode until well defined LES bands with reflectivity returns of 28 dBZ or greater are detected. During snow band formation, operation in clear air mode, VCP 31 or 32, is advantageous due to the improved sensitivity of the radar. Note that in clear air mode, displayed returns range from -28 to +28 dBZ. This sensitivity allows for early detection of band formation as well as for the detection of land breezes and resultant convergence zones. Even during the mature stage of this event, operation in VCP 31 yielded information not available in VCP 21. Note the LES band with reflectivity returns of 4 dBZ or less near the city of Erie on the 1321 UTC 0.5° base reflectivity product, VCP 31, (Fig. 11) as opposed to the reflectivity return pattern on the 1323 UTC 0.5° base reflectivity product, VCP 21, (Fig. 12).

When mature snow bands have developed, it is routine at NWSFO CLE to switch the radar to precipitation mode. Reflectivities in the snow bands have often been observed to reach 35 dBZ and in a few cases, even 40 dBZ. With a maximum displayable reflectivity of 28 dBZ in clear air mode (VCP 31 or 32), the true reflectivity maximum will be lost. Note in Fig. 12 the area of 30 to 34 dBZ reflectivity returns visible as opposed to the broad area of 28 dBZ displayed in Fig. 11. During periods of peak LES activity, as in this case, weak reflectivity returns of 5 dBZ or less, usually on the edge of the LES bands, are sacrificed to obtain better resolution of the higher reflectivity returns.

Throughout the snow event, there were very few radar reflectivity returns of 5 dBZ or more over Erie County, Pennsylvania, including the city of Erie. Figures 11 and 12, 0.5° base reflectivity products at 1321 UTC (VCP 31) and 1323 UTC (VCP 21), respectively, indicate this lack of reflectivity returns near the city of Erie.

This is not surprising; this limitation of the WSR-88D is simply due to the increase in height of the radar beam with distance from the radar and the low topped nature of LES bands. The city of Erie is 90 nm from the CLE WSR-88D. For Erie, a 0.5° elevation angle, the radar beam elevation is at about 10,770 ft, assuming standard atmosphere. Even during the mature stage of band formation, cloud tops of the snow bands are typically under 12,000 ft (Reinking et al. 1993).

Around 1400 UTC, winds at 4,000 ft and above started to back to the southwest and the LES band over Lake and Ashtabula Counties weakened and shifted offshore. The primary band, in response to the backing winds, shifted north of Ashtabula County, but continued into extreme northwest Pennsylvania. This backing flow was indicated on the 1450 UTC VWP product (Fig. 6). This real time monitoring of the flow is significant as a strong correlation has been proven to exist between the wind direction in the levels from 2000 to 7000 ft and snow band orientation (Niziol 1987 and Niziol et al. 1995). At this time in the city of Erie, heavy snow was falling at the rate of 1 to 2 inches an hour, but due to the radar limitations, reflectivity returns near the city of Erie remained less than 5 dBz.

At 1603 UTC, KCLE was again returned to clear air mode, VCP 31, in an attempt to better identify the location of the heavy snow band reaching the city of Erie. Additional lower reflectivities, less than 5 dBZ, were displayed in the Erie area, but the reflectivity returns provided little significant band intensity or location information over the precipitation mode (VCP 21). This is apparent from a comparison of Fig. 13, a VCP 21, 0.5° base reflectivity product at 1557 UTC, and Fig. 14, a VCP 31, 0.5° base reflectivity product at 1603 UTC.

7. SATELLITE DATA

a. Features of the RAMSDIS Workstation

The RAMSDIS workstation ingests digital GOES infrared and visible imagery every half hour. This rate is twice as frequent as the Satellite Weather Information System (SWIS). This permits the forecaster to monitor and predict the evolution of mesoscale phenomenon much more readily. RAMSDIS has several advanced features that allow the forecaster to extract more information from satellite imagery than was possible with analog data of the SWIS era. When displaying digital infrared data on RAMSDIS, one can select from a variety of color enhancement tables. One of the most useful features of RAMSDIS is the ability to shift or stretch the color enhancement table so that the feature of interest can be seen more clearly. Such features could be cloud top temperatures from LES bands, lake surface temperatures, or ground surface temperatures.

RAMSDIS is able to overlay county background maps on to the imagery and has an adjustable imagery zoom magnification. These two features will allow the forecaster to closely observe LES bands and note their precise location and cloud top temperature. In addition, these capabilities provide for comparison of satellite and radar data and help in formulating short-term forecasts.

b. Comparison of GOES-7 and GOES-8 Data

GOES-7 and GOES-8 digital visible and longwave infrared (10.7 μm) data were obtained for 2 January 1995. However, GOES-8 shortwave infrared (3.9 μm) data were unavailable. Overall, longwave infrared imagery was more useful in examining LES bands than was visible imagery. Infrared imagery can be used 24 hours a day and the cloud top temperatures indicate the extent of vertical development of the LES bands. Because of its higher resolution (2 km), visible imagery is better at indicating the location of the edges of the LES bands and small features of the snow band cloud tops.

Note, on 2 January 1995 there were gridding problems with the GOES-8 satellite data. The problems caused the geography to be 12 nm too far north. All grid points should be shifted 12 nm to the south. The correction was determined since the western edge of Lake Erie was discernable in the infrared image, see Fig. 15.

<u>Longwave Infrared Imagery (10.7 μm)</u>

GOES-8 longwave infrared imagery has a horizontal resolution of 4 km while GOES-7 horizontal resolution is 6.9 km (Menzel and Purdom 1994). The application of color enhancement to the RAMSDIS GOES-8 infrared image at 1345 UTC 2 January makes the LES band clearly visible, as shown in Fig.

15, when looking at the coldest cloud tops. The coldest cloud tops are shown in purple-red and extend along the south shore of Lake Erie. Figure 16 shows the GOES-7 image at 1401 UTC 2 January using the same enhancement table. The two images are centered differently. GOES-7 was located near 135° west longitude while GOES-8 was near 90° west, thus creating different viewing angles. Examining Figs. 15 and 16, one can see that the increased resolution of the GOES-8 imagery allowed the finer scale structure of the LES band to be seen. On the GOES-8 imagery of the LES band, sharper temperature gradients are seen. A comparison of this sharp temperature gradient and snowfall reports indeed verified that this was the area of maximum snowfall.

Visible Imagery

Both GOES-7 and GOES-8 visible data have a horizontal resolution of about 1 km. The GOES-7 data are 6-bit imagery with 64 brightness levels while GOES-8 data are 10-bit imagery with 1024 brightness levels. The increase in brightness levels of the GOES-8 imagery allow for slightly easier identification of cloud-edge and cloud-top features of LES bands. However, for this case, the GOES-8 visible imagery did not show as vast an improvement over the GOES-7 imagery (images not shown).

c. Composite Imagery

Another useful feature of RAMSDIS is the ability to digitally average imagery to produce a composite image. One application of composite infrared imagery is to show where the coldest cloud tops persisted during a precipitation episode, and most likely where the heaviest precipitation fell. Hence, in an implicit way, composite imagery can be useful in determining storm total precipitation amounts. Figure 17 is a composite image of GOES-8 longwave infrared imagery from 1315 UTC to 1745 UTC 2 January 1995. The coldest cloud top temperatures are shown in red and are associated with the LES band that persisted from southwest New York through northwest Pennsylvania to extreme northeast Ohio. The LES band produced heavy snow in Erie, Pennsylvania, which accumulated 6 inches from 1200 UTC to 1800 UTC. The coldest cloud tops persisted over the city of Erie with an average cloud top temperature near -25 °C. Since cloud top temperatures have some correlation to snowfall rates, total snowfall estimates during the composite period could be made by using the composite cloud top temperatures.

8. INTEGRATING SATELLITE AND RADAR FOR SHORT-TERM FORECASTING

As mentioned previously, the WSR-88D has a limited range with the 0.5° elevation angle overshooting most of the snow bands before reaching the city of Erie. However, LES bands are well depicted close to the radar. In contrast, GOES-8 longwave infrared imagery has uniform, detailed horizontal resolution over most of the United States, but the data are updated only every half hour. By combining these datasets, and taking advantage of the strengths of each remote sensing system, much more information about the areal extent and intensity of snowfall can be inferred than if these datasets are used separately.

One informal method of integrating GOES-8 digital and WSR-88D data to predict snowfall intensity beyond the effective range of the radar is outlined here. First, the forecaster would correlate the LES band cloud top temperature with the intensity of radar reflectivity echoes near the radar. Ideally with ground truth snowfall observers, the cloud top temperature near the observer could be associated with the observed snowfall rate. Once an association between the cloud top temperatures and either radar reflectivity intensity or observed snowfall rate has been determined, it could be used to infer snowfall intensity beyond the effective range of the radar by using the enhanced GOES-8 cloud top temperatures. Adjustments to this association are required to account for wind drift of snowflakes before they reach the ground, orographic effects, and for liquid water content. The WSR-88D VWP, surface observations and forecast model data could be used to help determine the extent of wind drift of snowflakes.

Estimated snowfall rates based on our informal method of integrating satellite and radar data was used to infer snowfall intensity beyond the effective range of the radar for 2 January at 1345 UTC. Figure 18, 0.5° base reflectivity at 1346 UTC from the CLE WSR-88D, shows an intense LES band oriented west to east which intersects the south shore of Lake Erie in Ashtabula County. Maximum base reflectivity was in the 25 to 29 dBZ range. Another slightly weaker snow band was nearly parallel to the south shore of Lake Erie from just offshore of Cleveland to Ashtabula County. Referring to Fig. 15, one will notice that the coldest cloud top temperatures of -23 to -27 °C were aligned with the most intense reflectivity echoes; if the geography were shifted southward about 12 nm. For this situation, the cloud top temperatures near -25 °C were associated with moderate to heavy snow. These cold cloud tops extended along the south shore of Lake Erie through Erie, Pennsylvania, into southwest New York as shown in Fig. 15. Erie had heavy snow with a surface visibility of 1/4 mile at 1350 UTC on 2 January, while the CLE WSR-88D showed no reflectivity returns over that region (see Fig 18). Referring to Fig. 13 and examining Fig. 19, GOES-8 longwave infrared image at 1545 UTC on 2 January, one will notice--after shifting the geography southward about 12 nm--that the 20 to 24 dBZ reflectivity echoes were aligned with cloud top temperatures around -21 °C. Once again, the cold cloud tops extended along the south shore of Lake Erie beyond the effective range of the CLE WSR-88D. Erie reported heavy snow showers with a surface visibility of 1/4 mile at 1553 UTC.

A short coming of this estimation technique is that the low cloud tops of LES bands may become obscured by high clouds which would make the use of the above technique impossible. The correlation between the LES cloud top temperatures and the radar reflectivity intensity will likely vary during each episode and from event to event. For satellite data to be most useful, operational gridding problems must be kept to a minimum.

9. CONCLUSION

The introduction of gridded numerical model data to the forecast offices over the last few years has dramatically changed the way model data is displayed and interpreted. The use of gridded model data has allowed the forecaster to examine model data in a much more precise and thorough manner. Consequently, the forecaster can be more confident in the issuance of watches, warnings, and routine forecasts.

Better reflectivity resolution and display capabilities of the WSR-88D permits the forecaster to readily monitor the position, intensity and movement of the LES bands. The increased sensitivity of the radar in clear air mode permits earlier detection of LES bands. The VAD Wind Profile allows for monitoring and short term forecasting of LES band evolution and movement. Due to the low topped nature of LES, the effective range of the WSR-88D is limited.

The excellent display capabilities of the RAMSDIS workstation using GOES-8 digital data has allowed the forecaster to examine LES bands in high detail over Lake Erie and the surrounding terrain. GOES-8 digital data are received twice as frequent as the previous system, SWIS. When displaying digital infrared data on RAMSDIS, one can select from a variety of color enhancement tables and shift the color enhancement so that the feature of interest can be seen more clearly. RAMSDIS is able to overlay county background maps on to the imagery and has an adjustable imagery zoom magnification.

GOES-8 digital data can be successfully used to supplement the WSR-88D data beyond the effective range of the radar. An association can be made between the LES band cloud top temperature and the intensity of radar reflectivity echoes near the radar. In addition cloud top temperatures near ground truth snowfall observers could be associated with observed snowfall rate. Once an association between the cloud top temperatures and either radar reflectivity intensity or observed snowfall rate has been determined, it can be used to predict snowfall intensity beyond the effective range of the radar. This technique will not work if high clouds obscure the LES bands.

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TABLE 1. Observed and 36-h forecast projections from the 0000 UTC NGM 1 January 1995 cycle of wind direction and temperature (°C) at CLE valid 1200 UTC 2 January 1995.

	36-H Forecast		**Observed**	
	Direction (°)	Temp (°C)	Direction (°)	Temp. (°C)
700 mb	290	-19	280	-20
850 mb	290	-16	280	-17
1000 mb	270	-6	270	-7

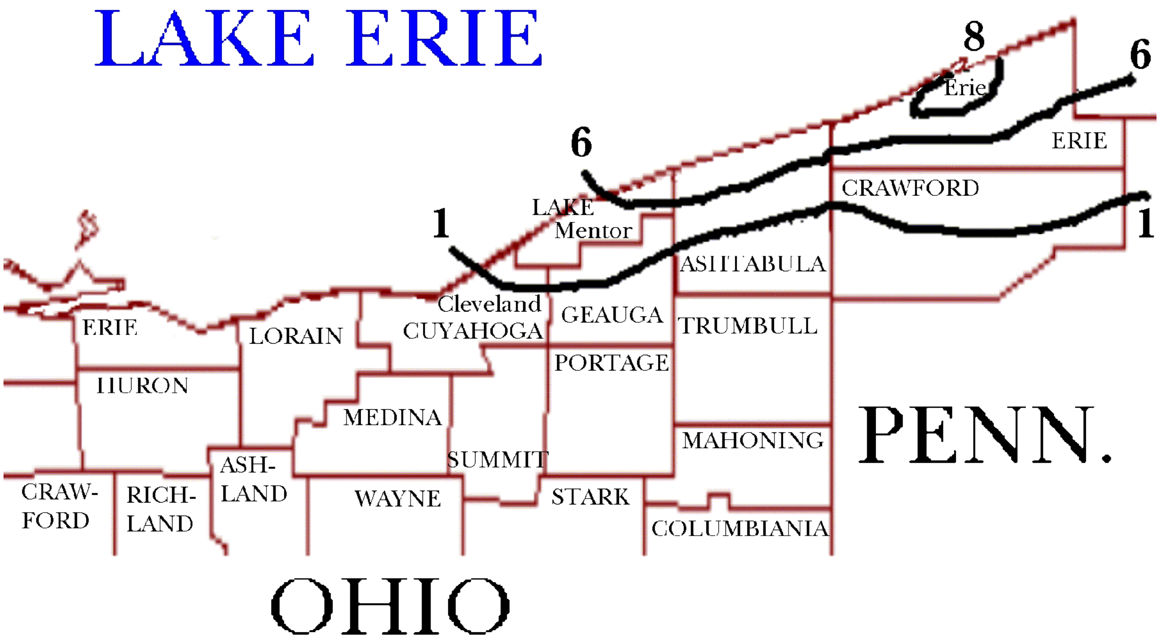

Figure 1. Storm total snowfall (inches) from 0200 UTC 2 January through 1800 UTC 2 January 1995.

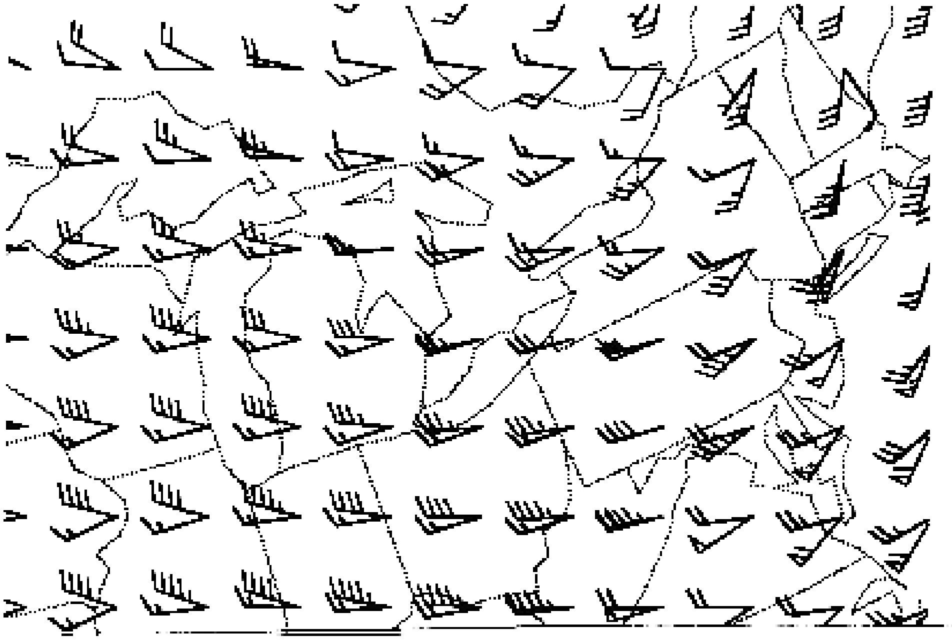

Figure 2. NGM 36-h forecast of 1000 and 700 mb wind direction and speed (kt) valid 1200 UTC 2 January 1995. Stronger speeds are those at 700 mb. A full barb is 10 kts, half barb 5 kts, and a pennant or flag is 50 knots.

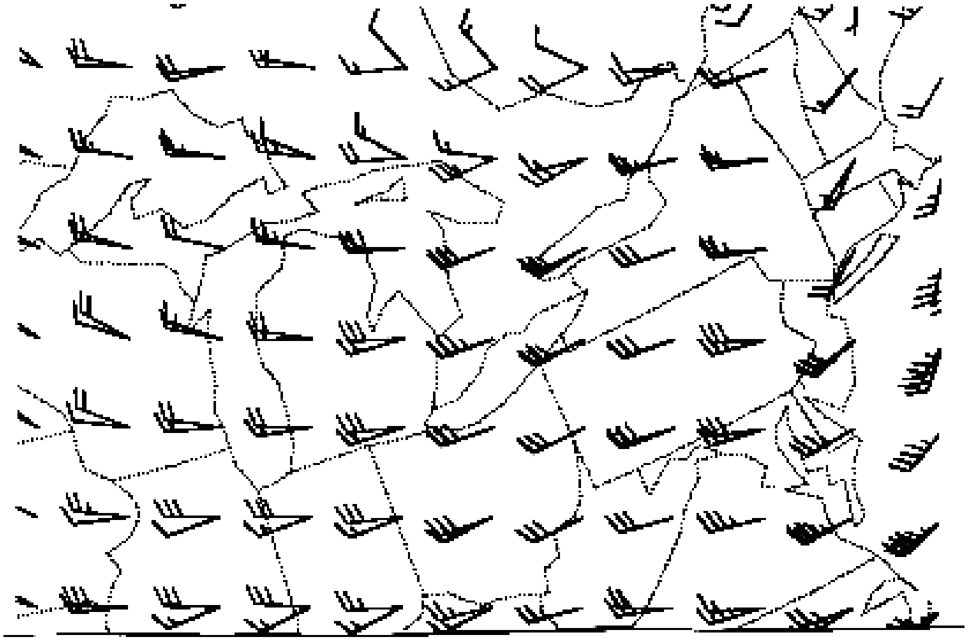

Figure 3. NGM analysis of 1000 and 700 mb wind direction and speed (kt) for 1200 UTC 2 January 1995. Stronger speeds are those at 700 mb. Wind barbs as in Fig. 2.

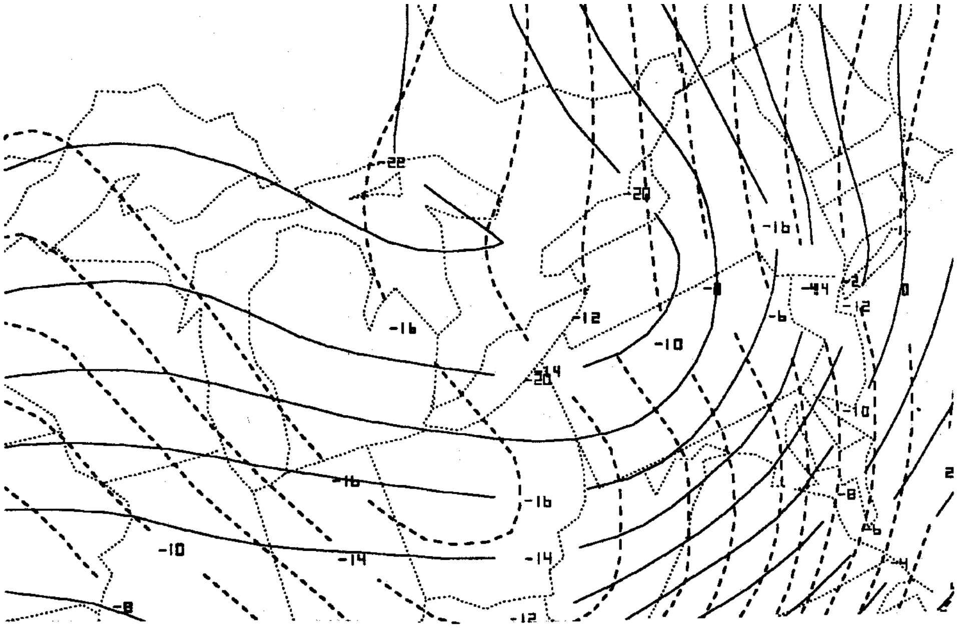

Figure 4. NGM 36-h forecast of 850 mb (dashed) and 700 mb (solid) temperatures (°C) valid 1200 UTC 2 January 1995. The contour interval for both temperatures is 2°C.

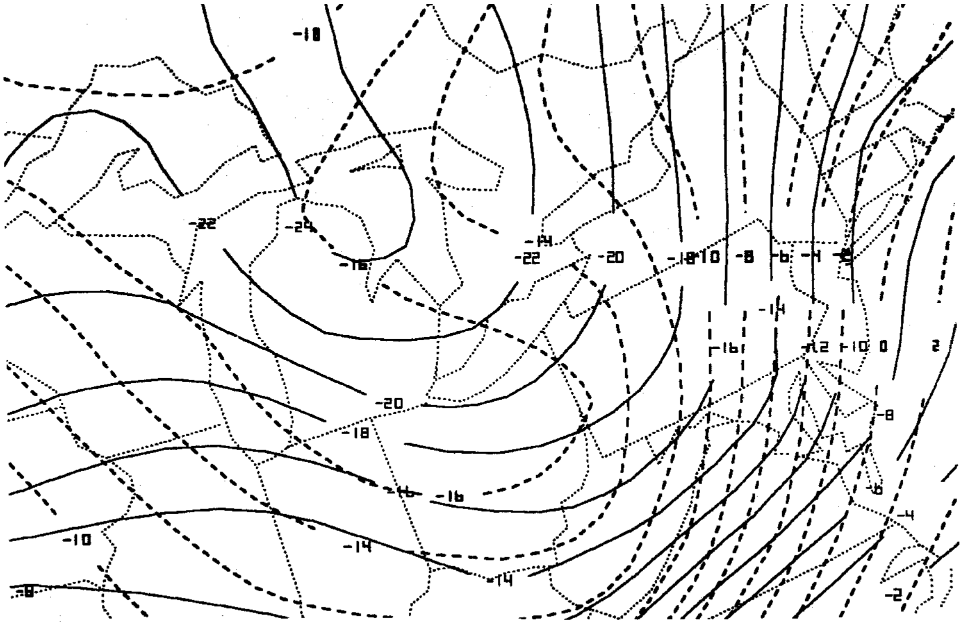

Figure 5. NGM analysis of 850 mb (dashed) and 700 mb (solid) temperatures for 1200 UTC 2 January 1995. The contour interval for both temperatures is 2°C.

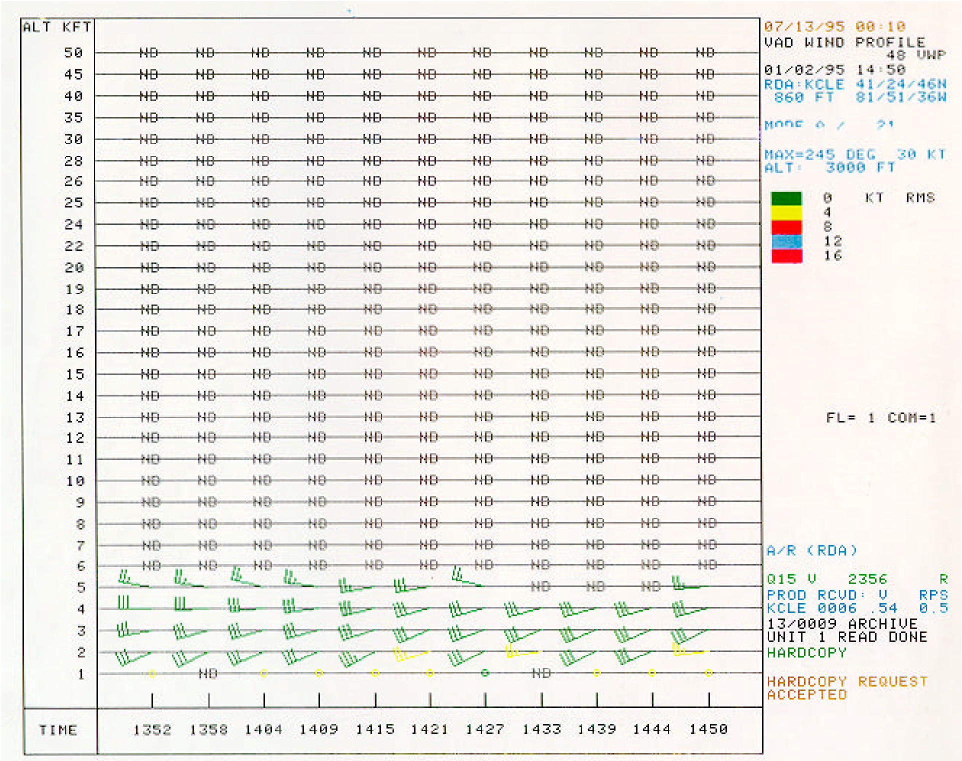

Figure 6. CLE WSR-88D VAD Wind Profile from 1352 to 1450 UTC 2 January 1995. Wind barbs as in Fig. 2.

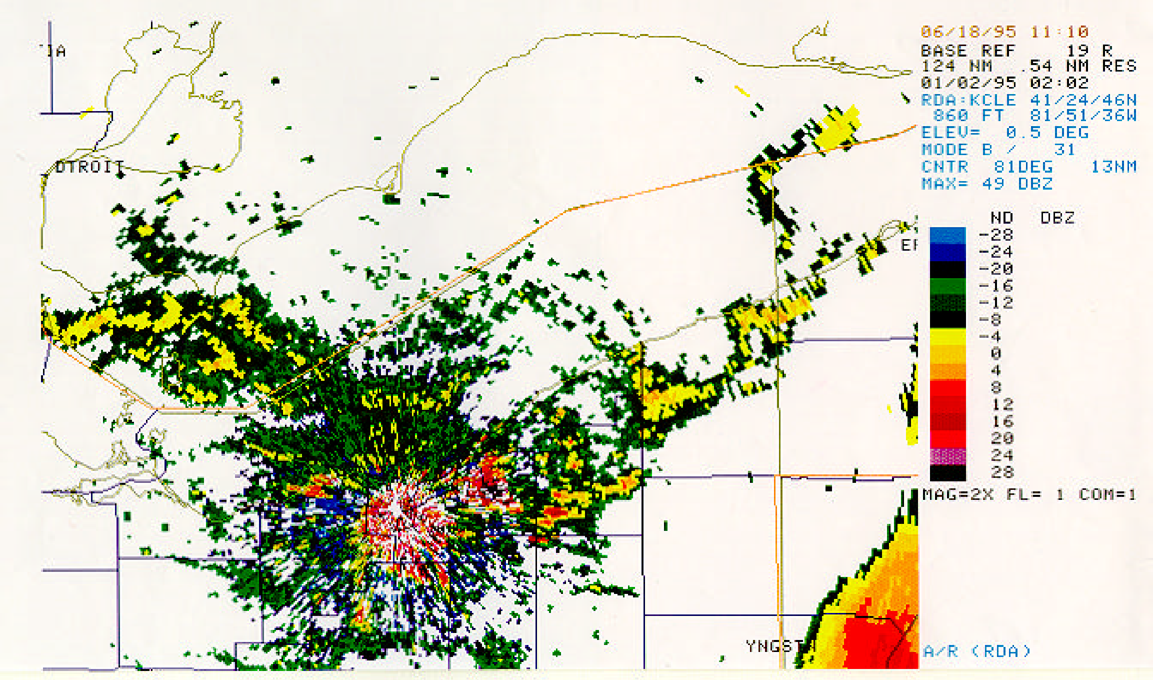

Figure 7. CLE WSR-88D 0.5 ° base reflectivity in clear air mode at 0202 UTC 2 January 1995.

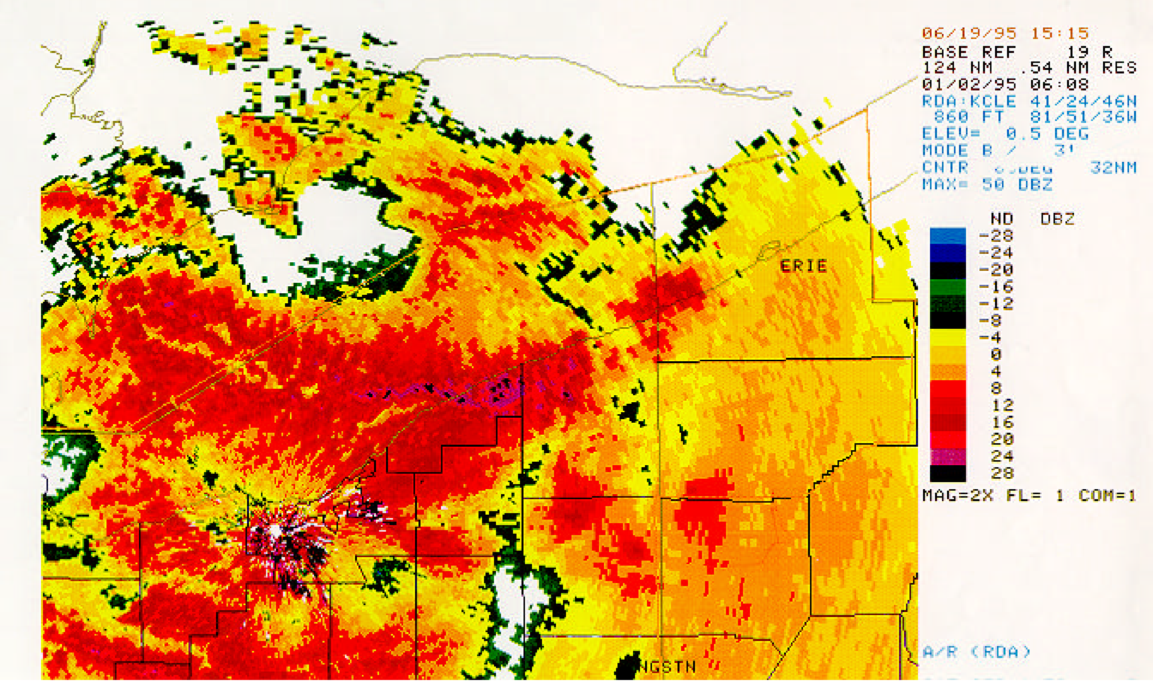

Figure 8. CLE WSR-88D 0.5 ° base reflectivity in clear air mode at 0608 UTC 2 January 1995.

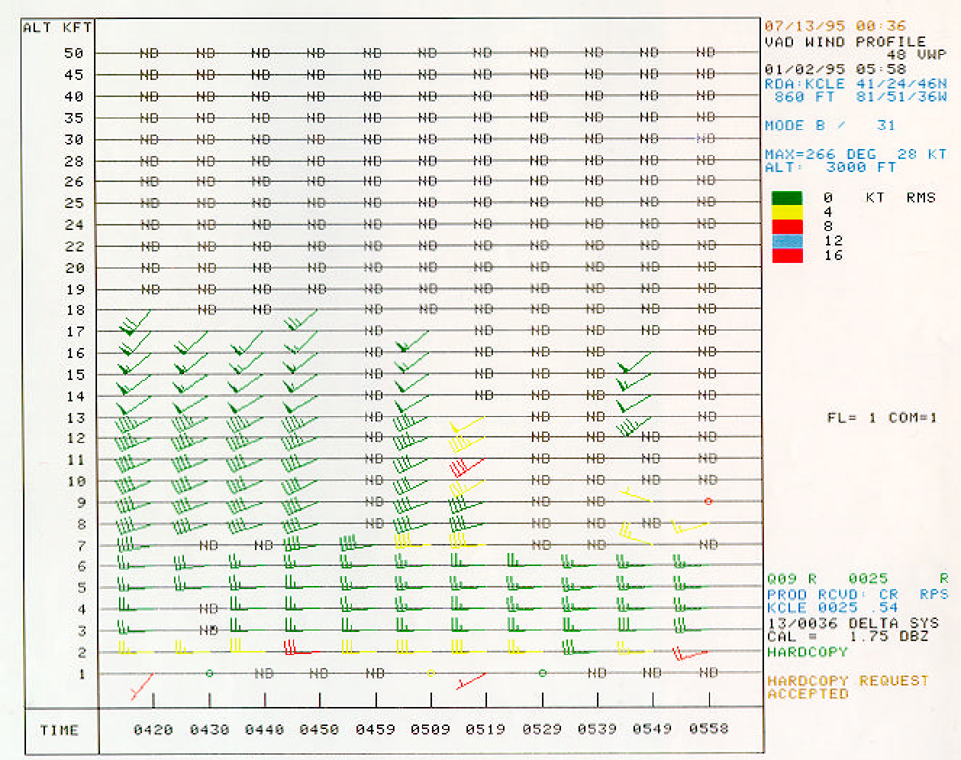

Figure 9. CLE WSR-88D VAD Wind Profile from 0420 to 0558 UTC 2 January 1995. Wind barbs as in Fig. 2.

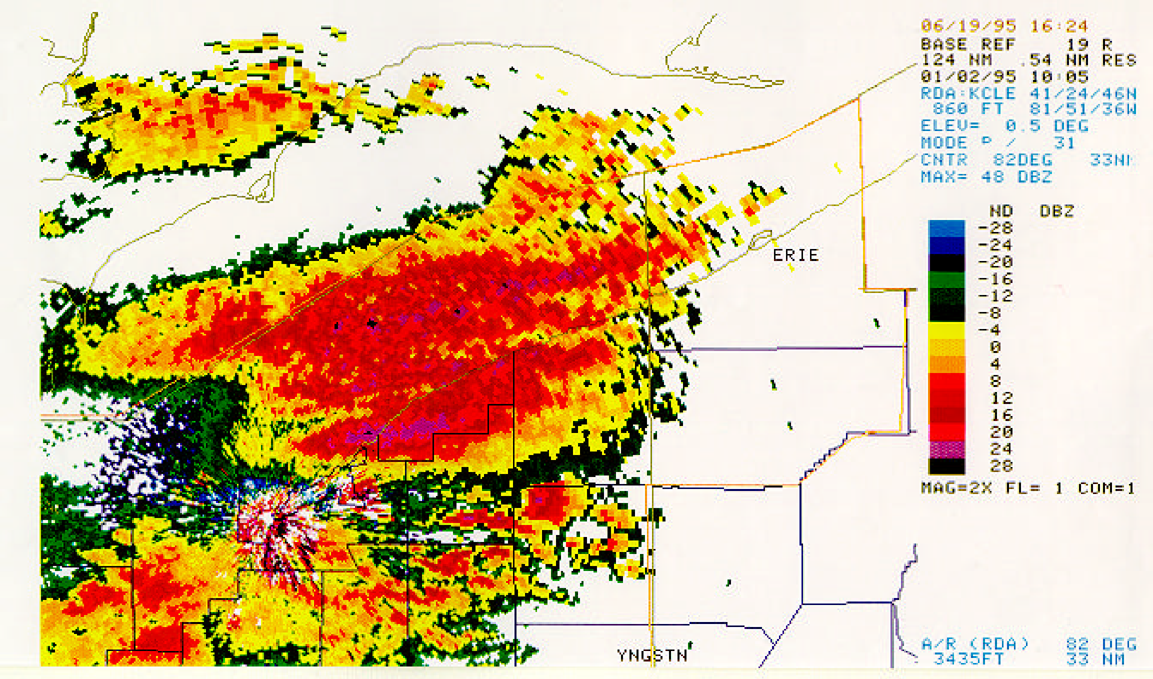

Figure 10. CLE WSR-88D 0.5 ° base reflectivity in clear air mode at 1005 UTC 2 January 1995.

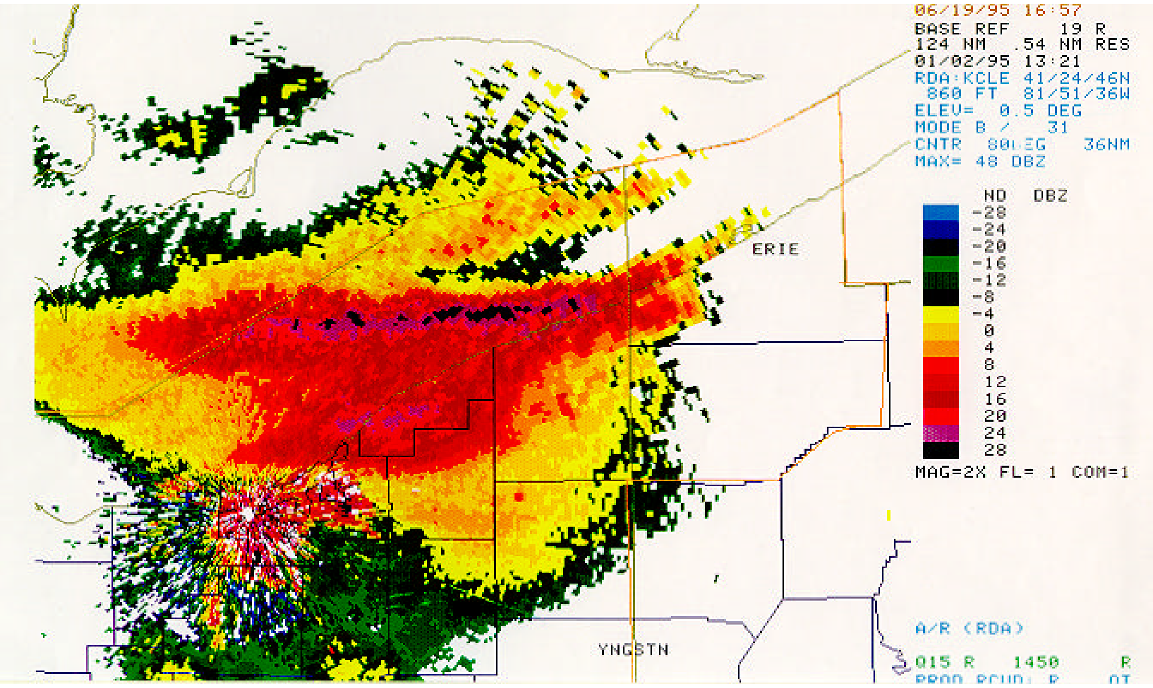

Figure 11. CLE WSR-88D 0.5 ° base reflectivity in clear air mode, VCP 31, at 1321 UTC 2 January 1995.

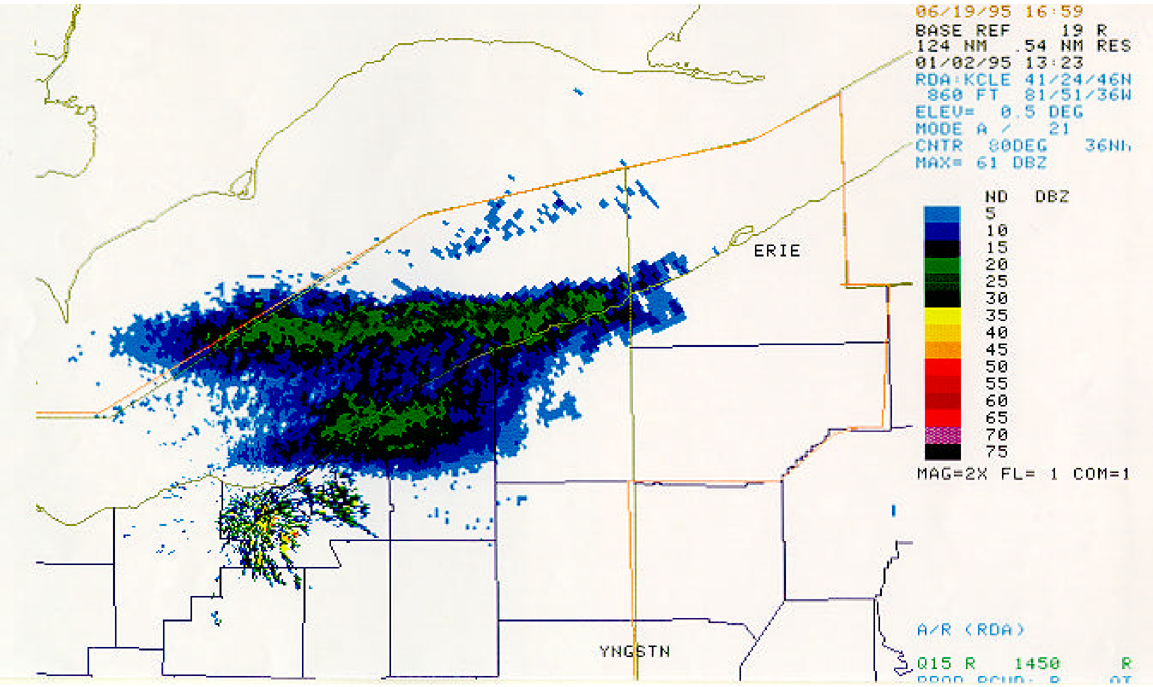

Figure 12. CLE WSR-88D 0.5 ° base reflectivity in precipitation mode, VCP 21, at 1323 UTC 2 January 1995.

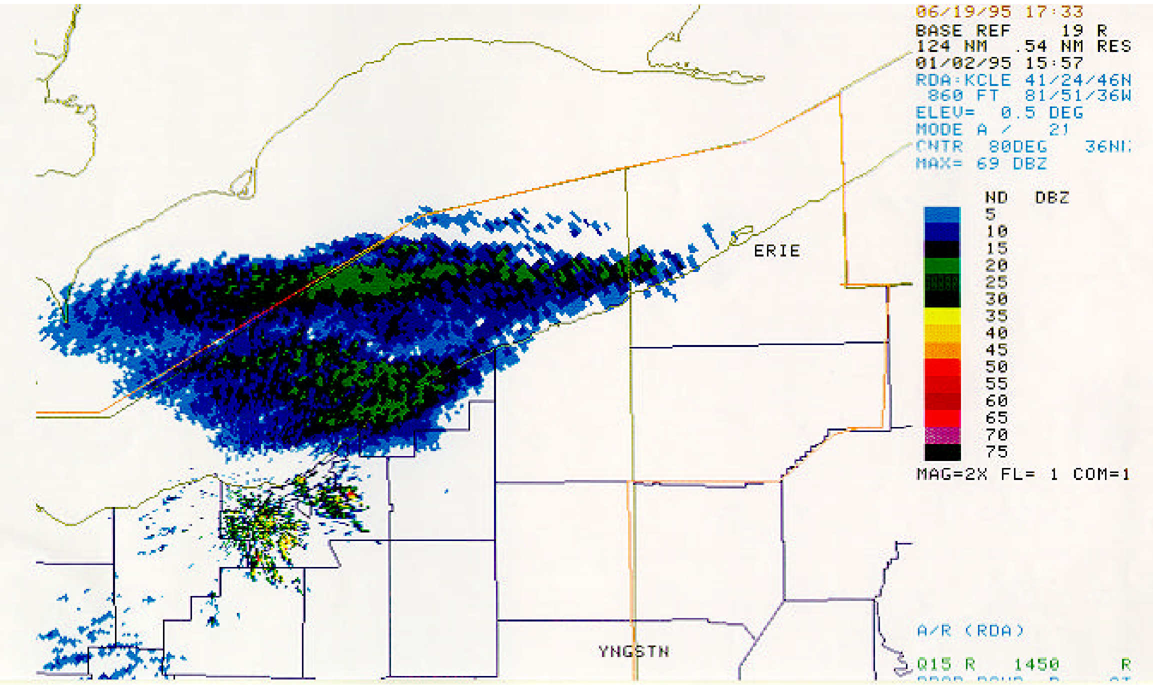

Figure 13. CLE WSR-88D 0.5 ° base reflectivity in precipitation mode at 1557 UTC 2 January 1995.

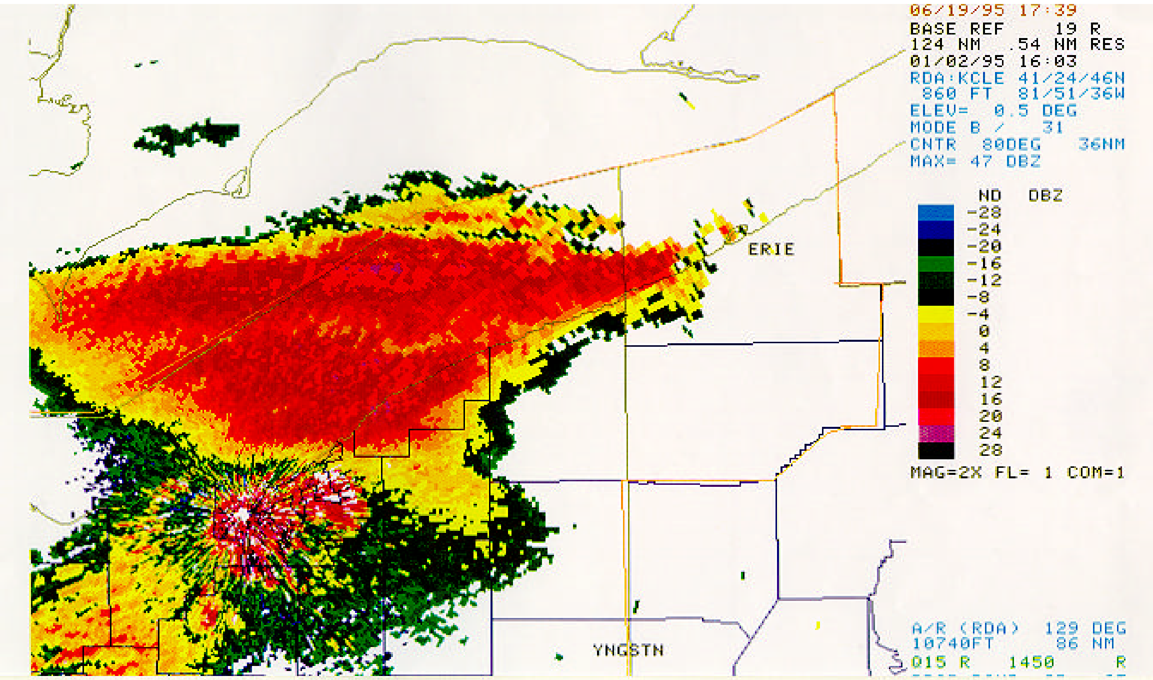

Figure 14. CLE WSR-88D 0.5 ° base reflectivity in clear air mode at 1603 UTC 2 January 1995.

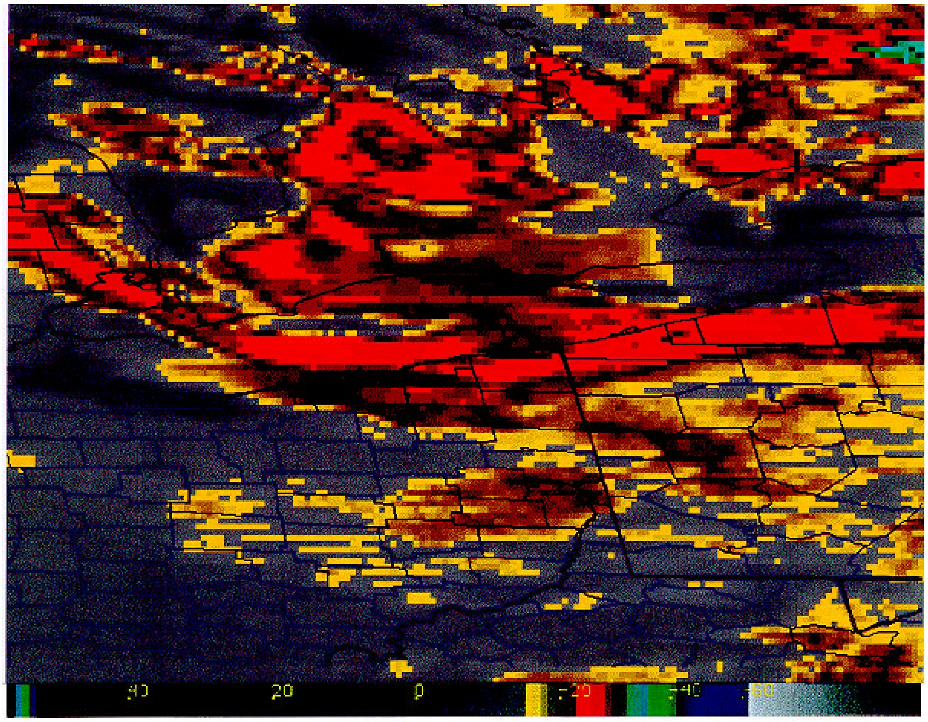

Figure 15. GOES-8 longwave Infrared (10.7 μm) image at 1345 UTC 2 January 1995.

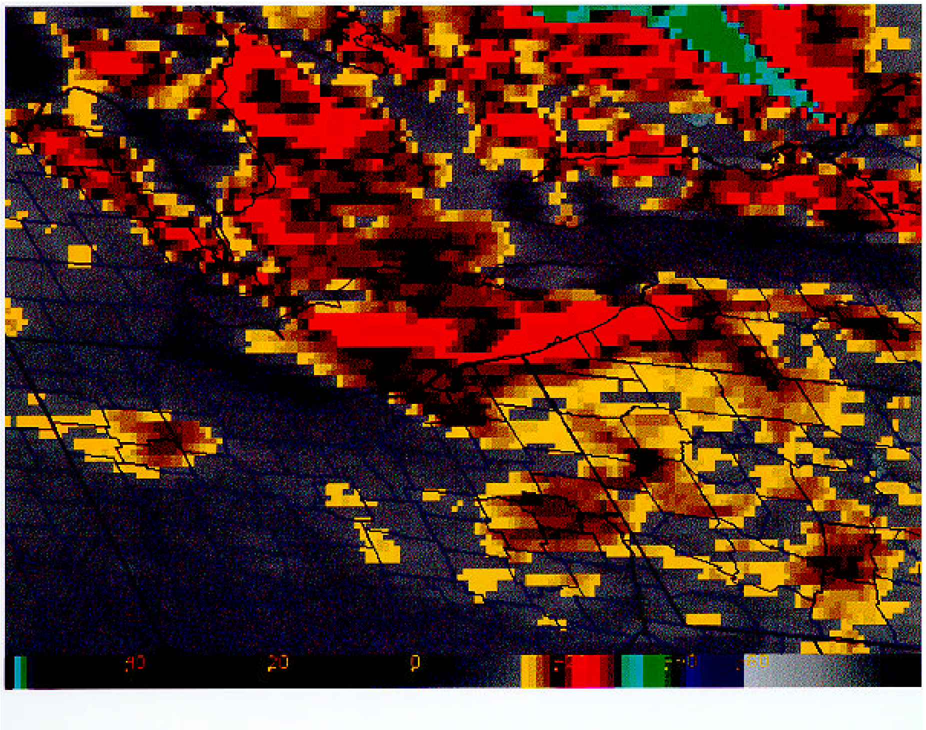

Figure 16. GOES-7 longwave Infrared (10.7 μm) image at 1401 UTC 2 January 1995.

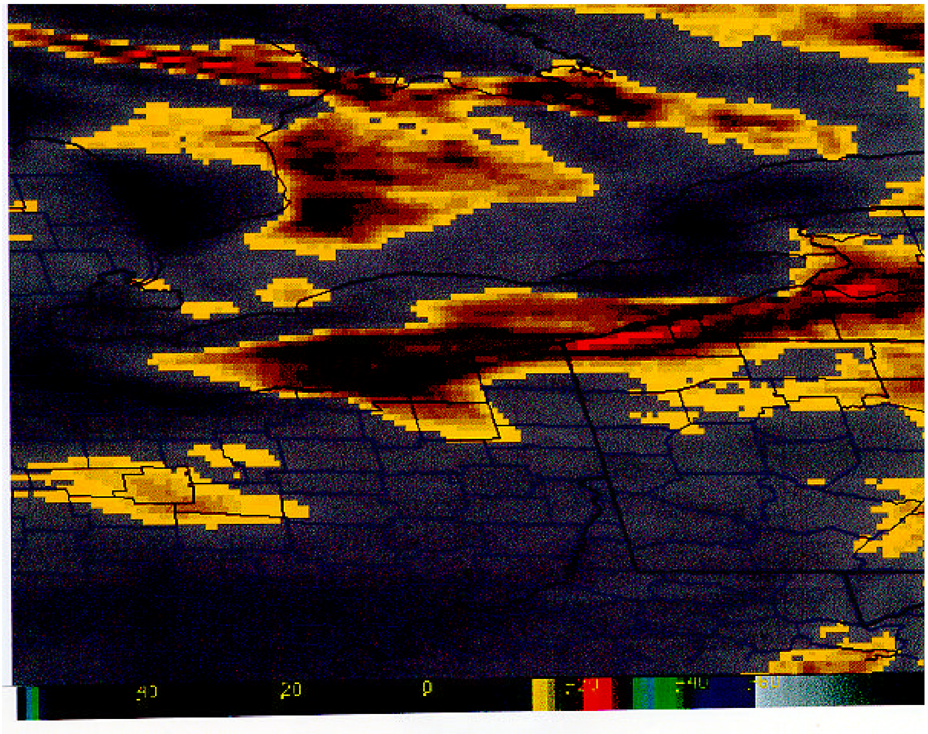

Figure 17. GOES-8 Composite longwave Infrared (10.7 μm) from 1315 UTC to 1745 UTC 2 January 1995.

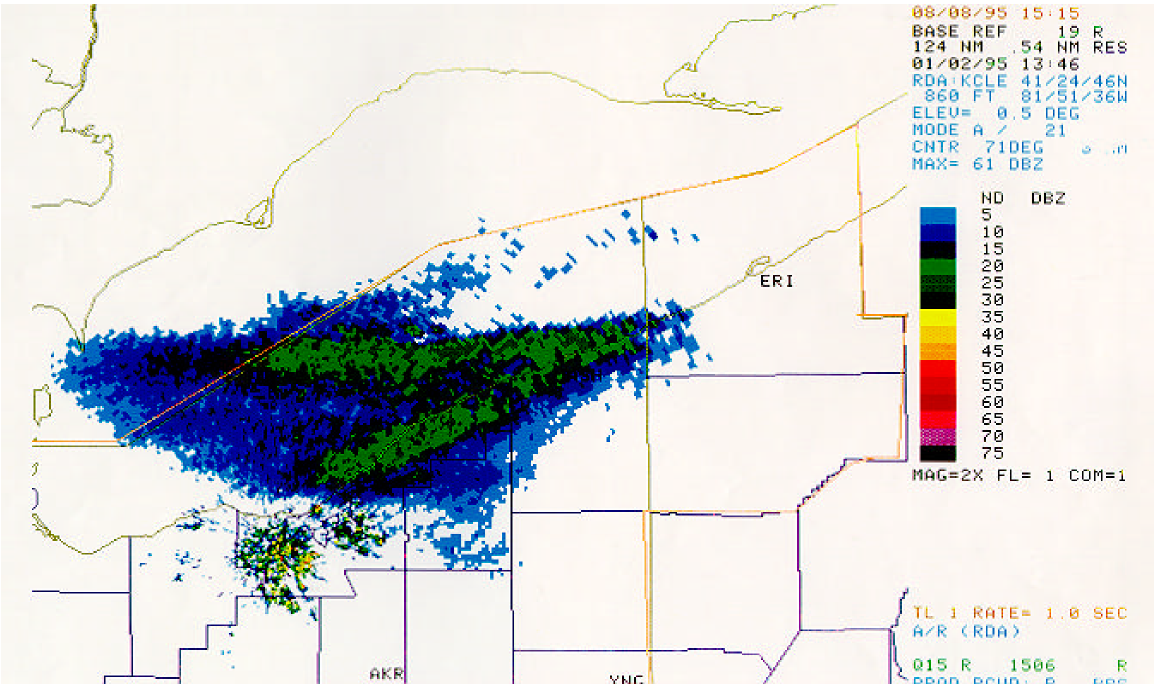

Figure 18. CLE WSR-88D 0.5 ° base reflectivity at 1346 UTC 2 January 1995.

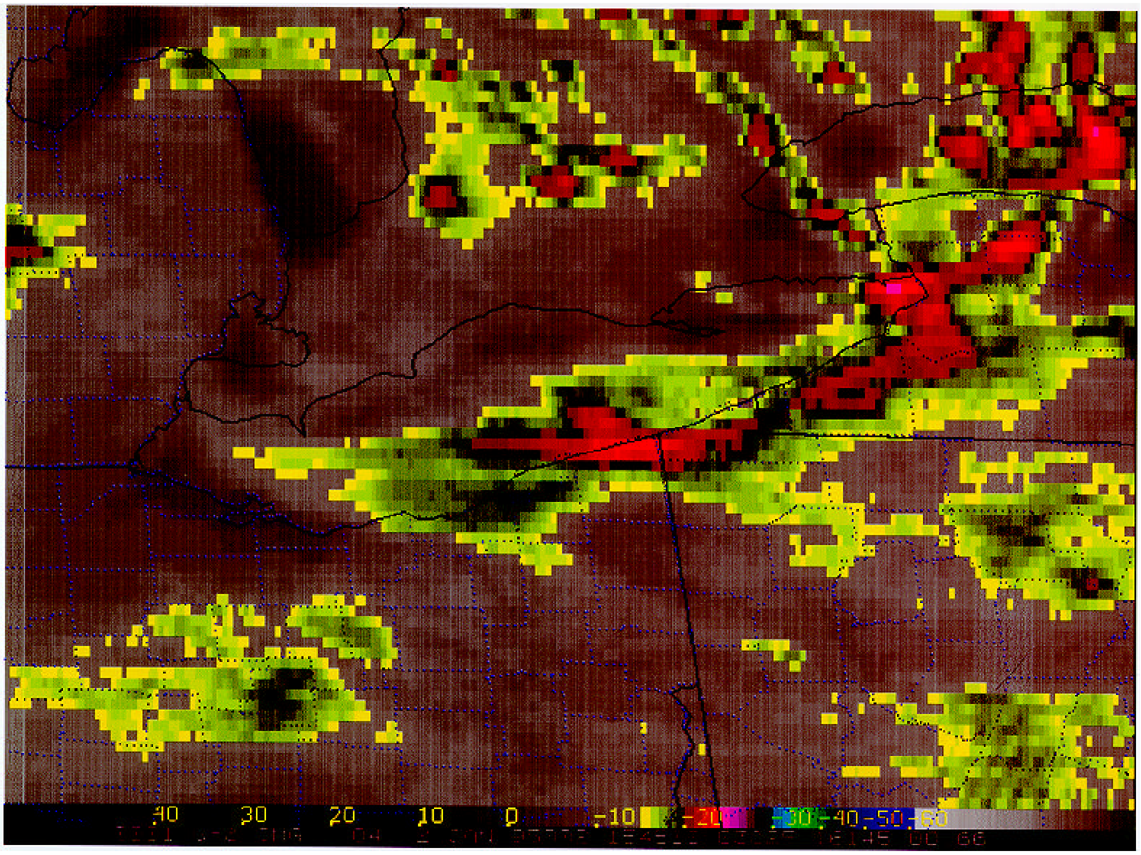

Figure 19. GOES-8 longwave Infrared (10.7 μm) image at 1545 UTC 2 January 1995.