The Lake Ontario Winter Storms (LOWS) Project

T. NIZIOL[1], R.F. REINKLING[2], R.A. KROPFLI[2], G. BYRD[3], R. BALLENTINE[4], A. STAMM[4], R. PENC[5], R. CAIAZZA[6], AND C. BEDFORD[7]

[1]National Weather Service Forecast Office, Buffalo, New York 14425, U.S.A.
[2]National Oceanic and Atmospheric Administration, Wave Propagation Laboratory Boulder, Colorado 80303, U.S.A.
[3]State University of New York, Brockport, New York 14420, U.S.A.
[4]State University of New York, Oswego, New York 13126, U.S.A.
[5]Pennsylvania State University, University Park, Pennsylvania 16802, U.S.A.
[6]Niagara Mohawk Power Corporation, Environmental Affairs Department, Syracuse, New York 13202, U.S.A.
[7]Galson Technical Services, Inc., East Syracuse, New York 13057, U.S.A.

ABSTRACT

In January and February 1990, the Lake Ontario Winter Storms project applied advanced remote-sensing techniques to lake effect snow storms to determine if that technology could be used to provide more accurate forecasts and nowcasts of the location and intensity of snow bands. This paper describes the project and plans for analyzing results.

The sampling program included remote sensing, radiosondes, and traditional observer networks. Three experimental sites were equipped with advanced remote-sensing equipment including: Doppler radar, radiometer, 915-MHz wind profiler, two 405-MHz wind profilers, ceilometer, and Radio Acoustic Sounding System (RASS). Atmospheric soundings were taken at mobile and fixed sites. Surface conditions were monitored using an observer network, microbarographs and precipitation gauges.

Despite an unusually inactive lake-effect snow period, the project team plans to evaluate the performance of the remote-sensing technology, analyze several case studies, and model the lake-effect process.

1. INTRODUCTION

The field phase of the Lake Ontario Winter Storms Project (LOWS) was conducted in the Lake Ontario basin between 5 January and 1 March 1990 to study lake-effect storms. An overview of the project is presented in this paper.

Lake-effect snowstorms were the primary focus of LOWS. Lake-effect snowstorms bring localized but extremely heavy snowfalls and whiteouts to areas near the Great Lakes. In the eastern basin of Lake Ontario the storms cannot be observed with good resolution using current, standard meteorological sensors and observations because of their small vertical and horizontal extent.

Lake-effect snow research has been conducted in the eastern basin of Lake Ontario in the past with monitoring networks with more resolution than the standard network (McVeil and Peace, 1966). Previous work has indicated that mesoscale features such as the shape of the shoreline, topogrpahy, and convergence contribute to the location, orientation, and movement of lake-effect snowbands (Peace and Sykes, 1966).

Accordingly, Niagara Mohawk Power Corporation (NMPC) prompted and provided primary support for this study. The general goal was to determine if advanced remote sensors could be used to find an effective way to deal with the impacts of lake-effect snowstorms in NMPC service territory.

The objectives of LOWS are threefold:

(1) Technology transfer -- demonstrate the utility of a meso-beta array of specialized remote sensors for monitoring and predicting lake-effect snowstorms;

(2) Improve mesoscale prediction through better physical description and understanding of factors driving lake-effect storm evolution;

(3) Determine the utility of the remote sensors for monitoring and predicting the nature and evolution of subsynoptic features of synoptic-scale storms producing freezing rain.

In order to meet these objectives, a consortium of 13 organizations was formed (Table 1). Project elements included an array of six specialized remote sensors, and a full contingent of project-specific and standard meteorological observing systems, as well as the support of a unified operations center, forecasters, and numerical modeling.

2. CHARACTERISTICS OF LAKE-EFFECT SNOW EVENTS

Lake Ontario is particularly conducive to severe lake-effect storms because it remains unfrozen in winter and its east-west orientation gives prevailing winds a long fetch over the longest axis of the lake. Lake-effect snow is caused when flow across the lake is de-stabilized by the flux of moisture and heat from the relatively warm lake into cold, typically arctic, air. Lake-effect snow is localized, 5-20 km wide, and shallow, 2-4 km. When combined with orographic lifting the snowfall rate is enhanced significantly.

Features of lake-effect snow make it important for the region and interesting for meteorologists. Intense snowfall rates are the most important feature, snowbursts that deposit 70cm in 48-hr are not uncommon (Figure 1). A well-developed snow band develops its own self-perpetuating circulation with convergence flow into the band and significant variations of wind speed and direction across the band. However, even in well-developed bands there are fluctuations as the band moves or oscillates in response to small features. Lake-effect snow forms either in single or multiple bands. In typical arctic

Table 1. LOWS Participants and Their Contributions

Participants	Contributions
Atmospheric Env. Ser.	C-band Doppler Radar, Nowcaster, and Supplemental Radiosondes
Galson Technical Ser.	Surface Observer, Microbarograph, and Weighing Precipitation Gauge Networks, Forecast Committee, and Nowcasters
Kaman Sciences, Inc.	Administrative Management
National Weather Ser.	Lead Forecaster, Supplemental Radiosondes and Nowcasters
NYS Dept. Env. Cons.	Forecast Committee and Nowcasters
Niagara Mohawk Power	Forecast Committee and Nowcasters
NOAA Wave Prop. Lab.	Operations Director, X-Band Doppler Radar, 915 MHz Profiler, and Radiometer
Penn. State University	Nowcaster, RASS, and 404 MHz Profiler
Pulaski Academy	Surface Observations
SUNY at Brockport	Mobile Radiosondes and Forecast Committee
SUNY Env. Sci, & For.	Snow Surveys
SUNY at Oswego	Observation Center, Mobile Radiosondes, Forecast Committee, and Nowcasters
Tycho Technology, Inc.	404 MHz Profiler

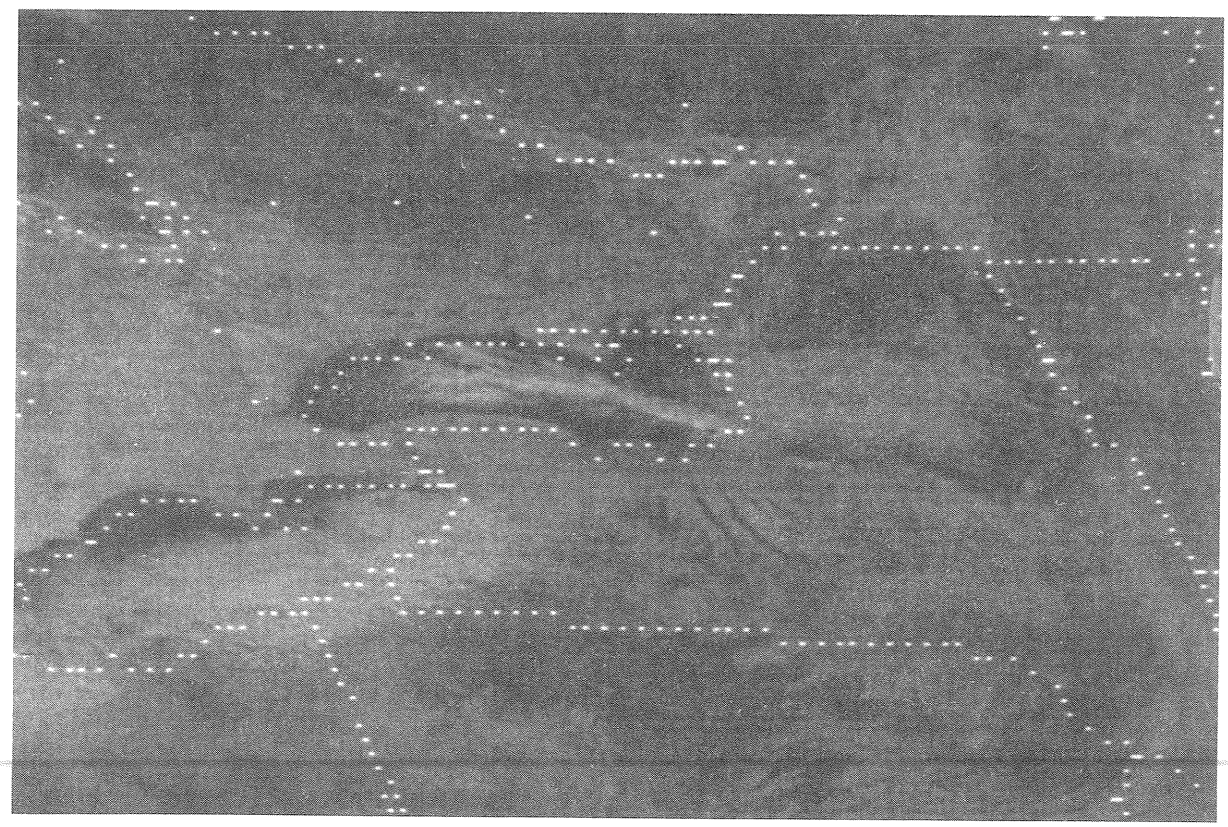

Figure 1. Visible satellite image from 1931 Z 25 Jan 1987. This single-banded snowstorm deposited up to 130 cm during a two day period.

air episodes a well-defined capping inversion forms. The height of this inversion can limit development.

In order to understand lake-effect snow the following aspects must be considered: timing of onset and dissipation, type of banding, movement, intensity and loaction of bands. The primary forecast variables are described by Niziol (1987). These include cyclonic vorticity advection and low-level flow, the boundary layer structure and evolution of the capping inversion, steering level wind direction and speed, and directional shear between the surface and 700mb.

3. LOWS OPERATIONS AND MEASUREMENTS

The primary focus of the LOWS research effort was the eastern end of Lake Ontario (Figure 2). As described in Reinking et al. (1990) an experimental array of remote sensors, conventional observations, and mobile field teams was organized to collect data during intensive sampling periods (Figure 3).

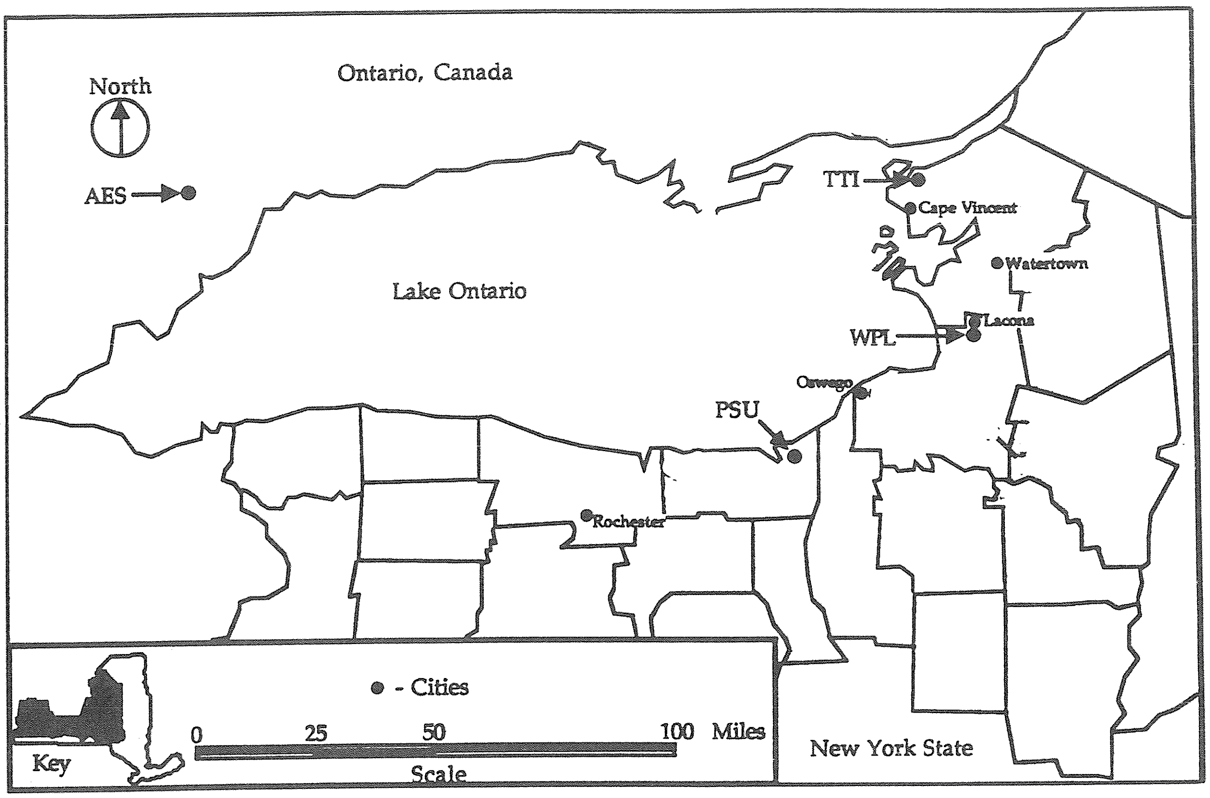

Figure 2 Lake Ontario Winter Storms Remote Sensing Installations

NOAA/WPL provided continuous measurements from three sensors near Lacona, New York (WPL, Fig. 2). Storm morphology, precipitation intensity, wind field information in the cloud system, and the height of the melting level, if any, within a 100 km radius were provided by an X-band (3.2 cm) dual-polarization, Doppler radar. Winds in the boundary layer and aloft were measured using a developmental 915 MHz wind profiling radar. A three-channel, passive, scanning microwave radiometer measured vapor and cloud liquid water integrated along the scan path.

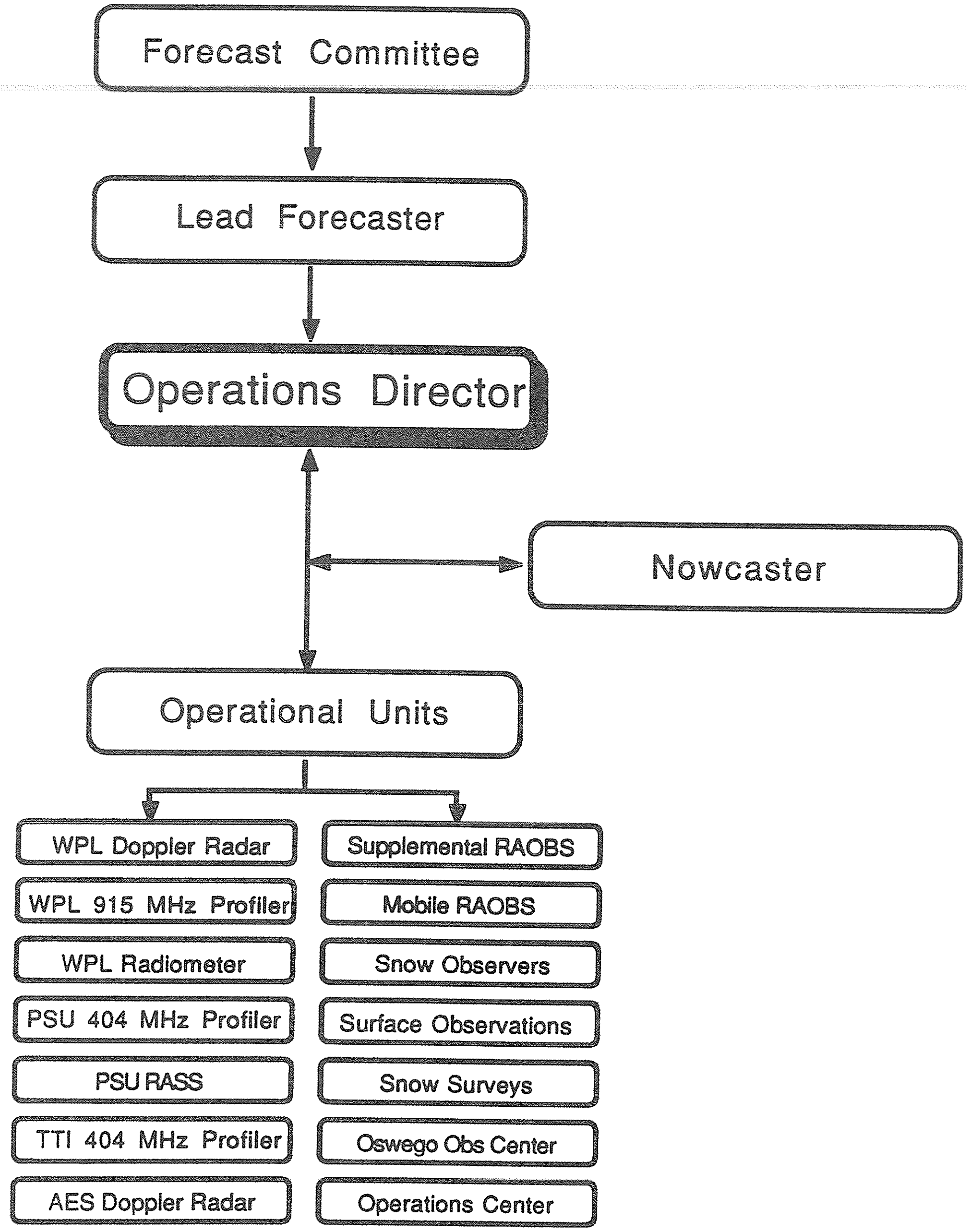

Figure 3. Lake Ontario Winter Storms Organization Chart

The remote-sensing array was completed with real-time measurements at three other sites. Wind and virtual temperature profiles were measured on the southeast shore with a 404 MHz profiler and a Radio Acoustic Sounding System (RASS) provided by Pennsylvania State University (PSU, Fig. 2). Winds were also sampled on the northeast shore from a 404 MHZ profiler provided by Tycho Technology, Inc.(TTI, Fig. 2). Upwind, at King City, Ontario, 40 km northwest of Toronto, the Atmospheric Environment Service provided 5 cm Doppler radar surveillance (AES, Fig. 2).

```
439
FPUS3 KBUF 111528
STATE FORECAST DISCUSSION
NATIONAL WEATHER SERVICE BUFFALO, NY
1018 AM EST THU JAN 11 1990

COLD FNT MVG ACRSS STATE THIS AFTN WITH MUCH COLDER AIR. SWIS SHOWS
SOME BREAKS COULD WORK INTO WESTERN ZNS AFT 18Z WITH DRY SLOT. TEMPS
LOOK GOOD. LOWERED WNDS A BIT THIS AFTN EAST ZNS SINCE SHLD REMAIN SOUTH
MUCH OF DAY AND FRNT NOT EXPECTED TO PASS SYR TIL EVE. VERY COLD AIR
BEHIND FRNT AND LINED UP WELL SO LAKE EFFECT SQUALLS SHLD DEVELOP LATE
TNGT AND FRI..SEE FOLLOWING DISCUSSION. WNDS LOOK CLOSE FOR HIGH WIND
WARNG THIS EVE AT LEAST ZNS 1/21 BUT WILL WAIT FOR LOOK AT NGM.

LAKE ONTARIO SNOW OUTLOOK
SYNOPSIS...RIDGE OVR AREA MOVG QUICKLY EAST...AS STRGLY DIFLUENT UPPER
FLOW TAKES OVR DURING DAY. VERY DEEP LOW PRES SYS MVS RAPIDLY ACRS ONT
SWEEPING COLD FNT ACRS WNY THIS AFTN. VERY TIGHT PRS GRAD WITH HI WNDS
DRG AND AFT CFP. STRG 22 VORT MAX CNTR CROSSES EAST END OF LK ONT TOO
WITH WELL ALIGNED WNDS AT ALL LVLS. DEEP CYCLONIC FLOW WITH ARCTIC AIR
POURING IN OVR REGION SHUD BE NR PERFECT SET UP FOR XNTD PERIOD LES.


NOW THRU THURSDAY 7PM...NO GO. AIR STILL TO WRM TODAY BEFORE CFP.
THURSDAY 7PM TO FRI 1PM...GO FOR SINGLE BAND EAST OF LK ONT. POSSIBLE
                          MEGA BAND WITH HVY SNWFL AND STRNG WNDS.
FRI 1PM TO FRI 7PM...GO. INDICATIONS FLOW BCMG MORE NW WITH TIME
                     SHIFTING TO MULTIPLE BANDS FROM ROC EAST TO
                     OSWEGO AND SYR...WELL INLAND DUE TO RATHER
                     STRONG WNDS.

TAN/JJP
```

Figure 4. Example Lake Ontario Snow Outlook, 3Z 11 Jan 1990.

Additional measurements were made during intensive sampling periods. Mobile teams from the State University of New York (SUNY) Colleges at Brockport and Oswego released rawinsondes at 3-6 h intervals from strategic points along the south and east shores of the lake. Deployment strategy focussed on a) evolution of the boundary layer during potential and realized lake-effect storms, b) comparison of environments within and adjacent to bands, and d) comparison of measurements with the remote sensors. All of the mesoscale sounding measurements were supported by standard and special NWS and AES (Atmospheric Environment Service) rawinsondes released at 6 h intervals from Flint and Sioux St. Marie in Michigan, Egbert in Ontario, and Buffalo. Weighing precipitation gages provided precipitation rates at selected locations; these were complemented by hourly observations from a volunteer network. Other supporting measurements are indicated in Table 1.

The experiment was organized to intensively sample lake-effect snow storms when they were forecast or observed. Ultimate decisions for operation were made by the Operations Director (OD) supported by the Forecast Committee and Nowcasters (Figure 3). During intensive sampling periods, each research group followed their experimental protocol and continued to operate until the OD ordered sampling to stop. Additionally, the OD issued guidance during the intensive sampling periods to the mobile sampling and remote sensing crews.

Primary forecast support for the project was provided in the Lake Snow Outlook produced by BUF (Figure 4). This product predicted the probability of lake-effect snow over the ensuing 48-hr period four times a day. It was appended to the New York State Forecast Discussion and distributed through normal channels. Each afternoon a member of the Forecast Committee (other meteorologists participating in the project) would call BUF after reviewing comments from the whole committee on an electronic bulletin board. Forecast ideas would be discussed and a forecast consensus developed. Then BUF would brief the OD so that plans for the next 48-hrs could be developed.

During intensive sampling periods operations were directed from the NMPC/Syracuse Operations Center. The Operations Center received all remote sensing measurements in real-time, had access to weather forecast charts, and conventional observations.

The Nowcasters were all volunteer meteorologists. However, the experience levels varied widely. Consequently, each Nowcaster has his own preferred data products to approach the problem. For example, Brian Murphy, Ontario Weather Centre introduced the project team to the AES winter severe weather forecast product FOCN03. This model lists 6-hourly forecasts of freezing level, 850 mb temperature, model winds from 3 levels in the RFE model, and 700 mb and 850 mb winds for specific cities (Murphy, 1989).

4. SUMMARY OF EVENTS

Some 5-7 major lake-effect snowstorms and 10-15 events with whiteout conditions are expected between late November and mid-March in a normal winter in the Lake Ontario region (R. Sykes, SUNY; informal manuscript). In 1989-1990, some lake-effect activity, including one very severe event, occurred in December. However, lake-effect activity was well below climatology while rain events were above normal during the January-February project period. A list of project case studies is given in Table 2.

Table 2. Case Studies from LOWS - 1990

Event Type	Dates
* Heavy Lake-effect Snow, Single Bands	11-12 January.
* Light Lake-effect Snow, Frontal Boundary Band and Post-frontal Multiple Bands.	25 February
* Light Lake-effect Snow, Multiple Bands	28 February.
* Sub-marginal Lake-effect Events	19, 23, 27 January, 10, 17, 19-20 Feb.
* Freezing Rain	15 February.

5. EXAMPLES OF OBSERVED STORM FEATURES

5.1 Lake Effect Single Bands.

Case of 11-12 January 1990. A series of major single bands produced 30-80 cm of snow in an east-west zone some 50 km wide extending inland over the WPL/Lacona site (Fig. 2) and the rising terrain of the Tug Hill Plateau to the east, and 10-30 cm over adjacent areas. Post-analysis is anticipated to reveal important precursors in the evolution of the water vapor field from the radiometer, the PBL temperature structure from the mobile sondes, and the wind field from the profilers and sondes. WPL radar monitoring revealed that the storm bands that successively developed were only 10-20 km wide and some 80 km long. The Cape Vincent wind profiler showed that bands formed in post-frontal arctic air after 6-7 h of sustained west winds with minimal directional shear (Figure 5).

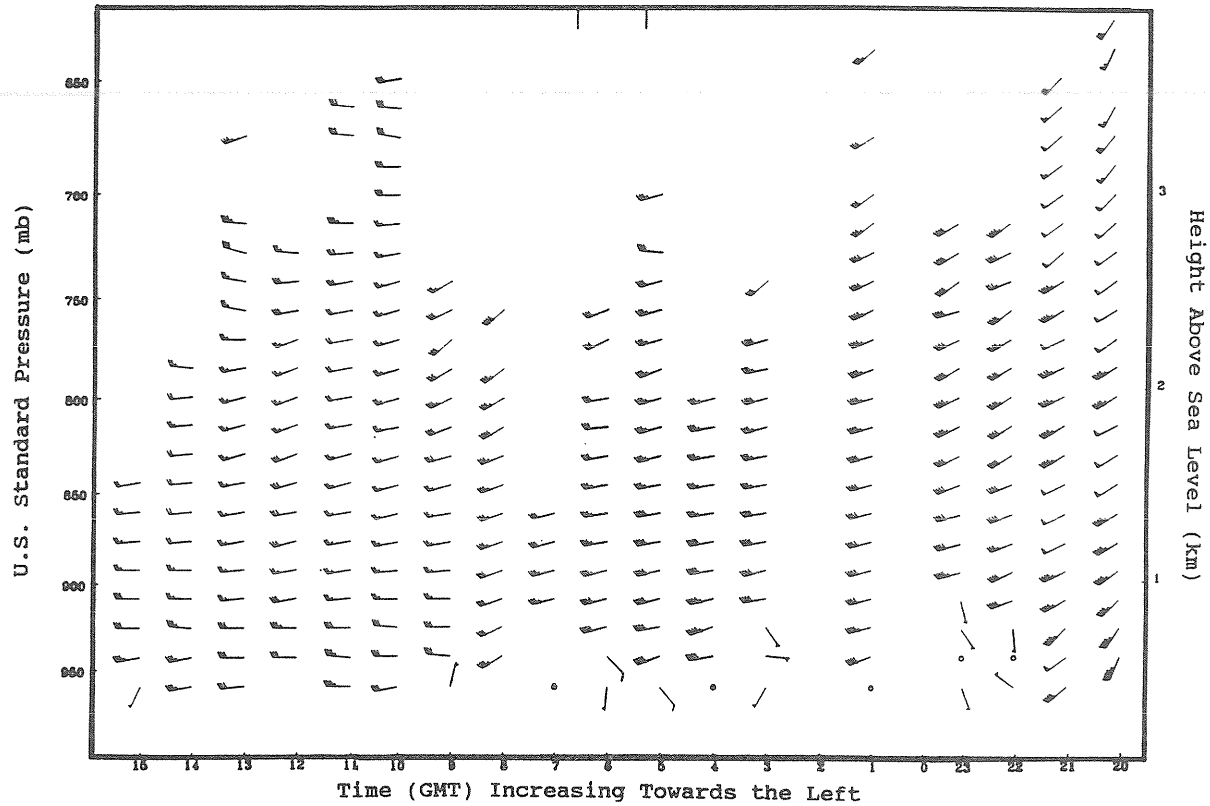

Figure 5. Wind Profiles for Cape Vincent, NY: Jan 11, 20Z through Jan 12, 15Z showing conditions from passage of arctic front (between 21 and 22Z, Jan 11) and development of single band at Lacona (14Z Jan 12).

An initial major band of 3-4 km depth developed over the center of the lake, rotated southward through the southeast shore with a pivot point near Lacona, and dissipated as it continued to rotate inland to Syracuse. This was replaced with a second band which repeated the cycle, apparently in association with temporary veering of the winds in the cloud layer, as observed with the wind profilers. Winds returned to westerly, and small, new, convective cells over the lake organized into a narrower, more convective and snake-like band that maintained an east-west orientation and advected through Lacona for a sustained 9-10 h period.

Intermittent whiteouts occurred during this storm. Within the successive bands, cloud liquid water measurements from the scanning radiometer revealed a steady supply of condensate advecting over Lacona and toward the higher terrain to the east (Fig. 6), and the radar revealed significant orographic enhancement of the resulting precipitation (Fig. 7). Dissipation then occurred as directional wind shear was introduced in the cloud layer and the capping inversion descended from about 3.5 to 2 km above the lake. A more complete outline of the evolution of this storm is presented by Reinking et al. (1990), and analyses of the lake-effect forecasts in relation to the actual event is are underway.

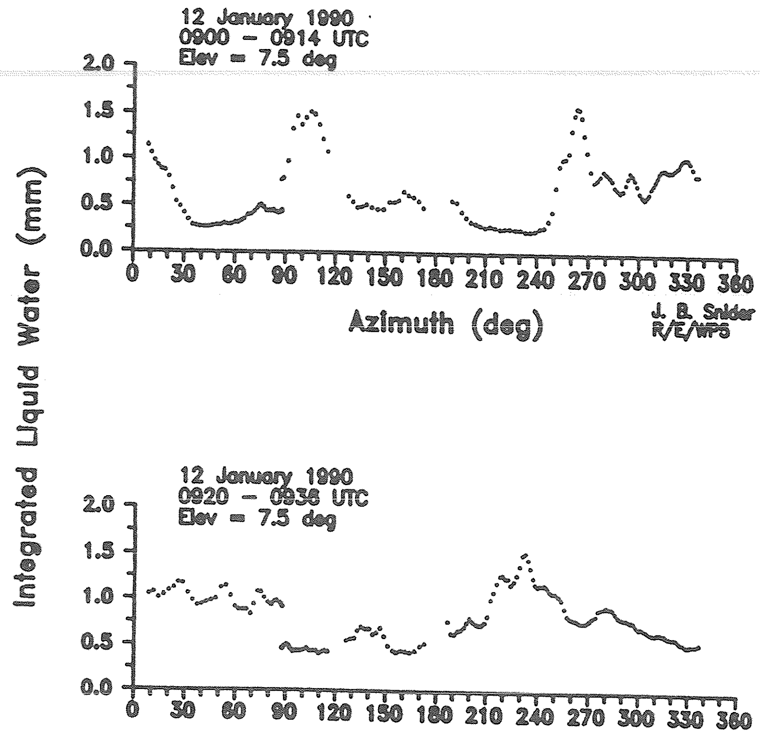

Figure 6. Sequential 360 deg. scans of cloud liquid water showing peaks in the major, single band upwind and downwind of microwave radiometer, and rotation of bands between scans.

5.2 <u>Multiple Bands and Submarginal Lake-effect Events.</u>

General observations suggest that diagonal fetchs across Lake Ontario result in several bands that form and are sustained simultaneously. Such multiple, parallel bands tend to be less intense than the single bands, probably because the shorter fetches allow less time for destabilization and development of a deep mixing layer and the accompanying, responsive confluence and land-lake circulations. Multiple bands tend to be organized as wind-parallel, or possible wind-shear parallel, cloud streets. Directional shear in the mixing layer may also contribute to such multiple rather than single banding, or at least to transitions from single to multiple banding.

For 28 February, radar reflectivities as strong as 25 dBZ depict two bands as they were sustained in northwesterly, cross-lake flow (Fig. 8). These bands were about 30 and 70 km long. Rawinsondes revealed little directional shear but considerable increase in wind speed with altitude in the mixing layer which was capped by a low (1.8 km) inversion. The bands produced light snowfall (2-5 cm) in zones about 20 km wide as they extended inland southeast of the 240 deg radial from the radar. The radial velocity field from the radar clearly defines convergence of low-level air into the stronger band and indicates lifting at the core of the band where radial velocities go to zero. The dynamics of these bands are being studied to reveal temperature, wind and water vapor precursors in relation to the snowfall produced.

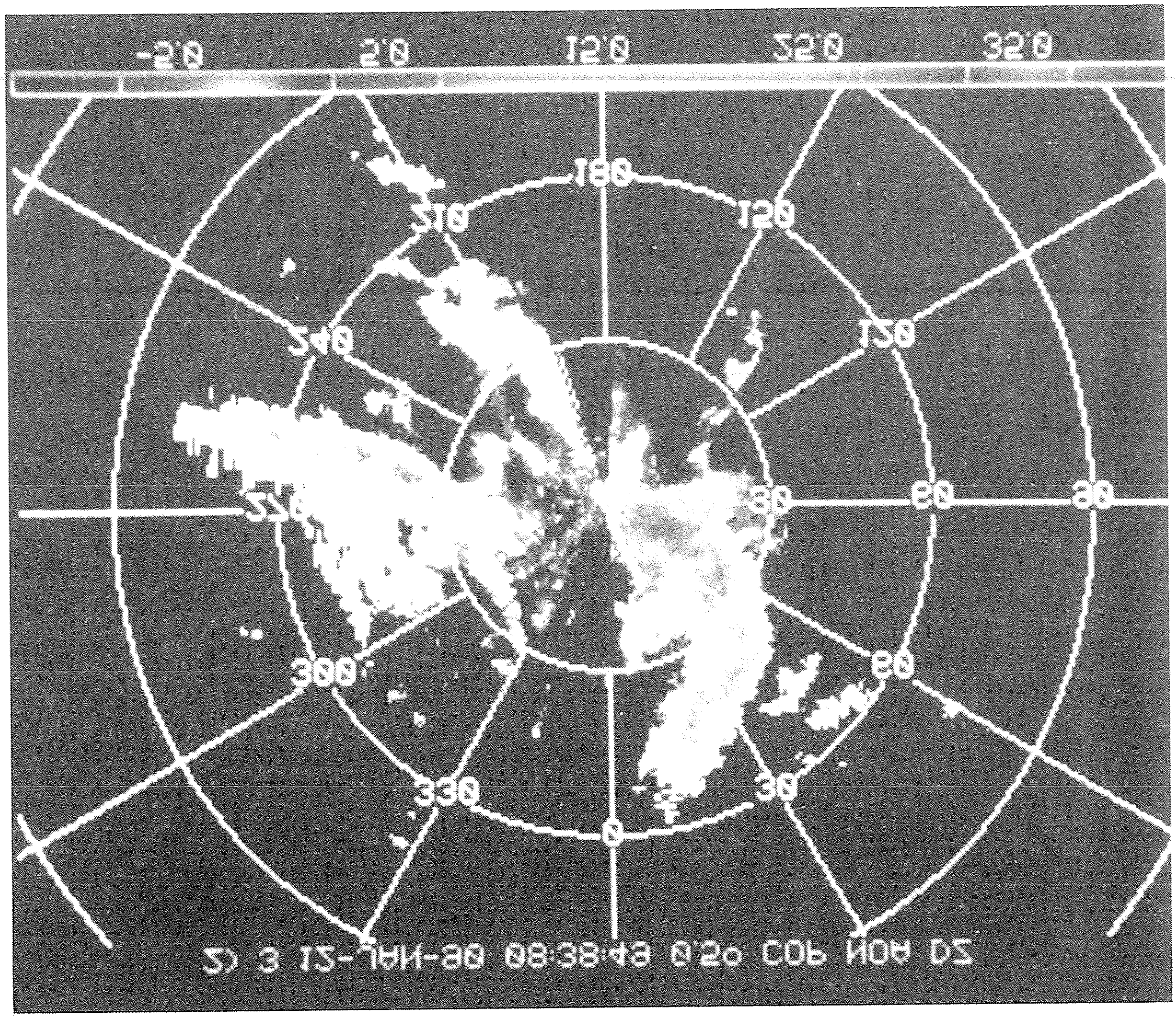

Figure 7. Reflectivity from the WPL/Lacona radar depicting bands that rotated southeastward to impact inland cities south and east of the 240 deg. radial. The band at 210 deg. was dying while that at 260 deg. was intensifying. Orographic broadening of the storm swath and enhancement of precipitation in the area extending to 30 to 40 km east of the radar are also evident.

Several cases with forecasts for a very marginal possiblility of lake-effect snow were monitored; these did not produce significant lake-effect clouds, but the data are useful in analysis and modeling efforts to define and quantify the factors that restrain development. In most of these cases, long over-lake fetches with strong winds developed, but lake-air temperature differences appeared to be too small and the capping inversions too low to allow destabilization and cloud development.

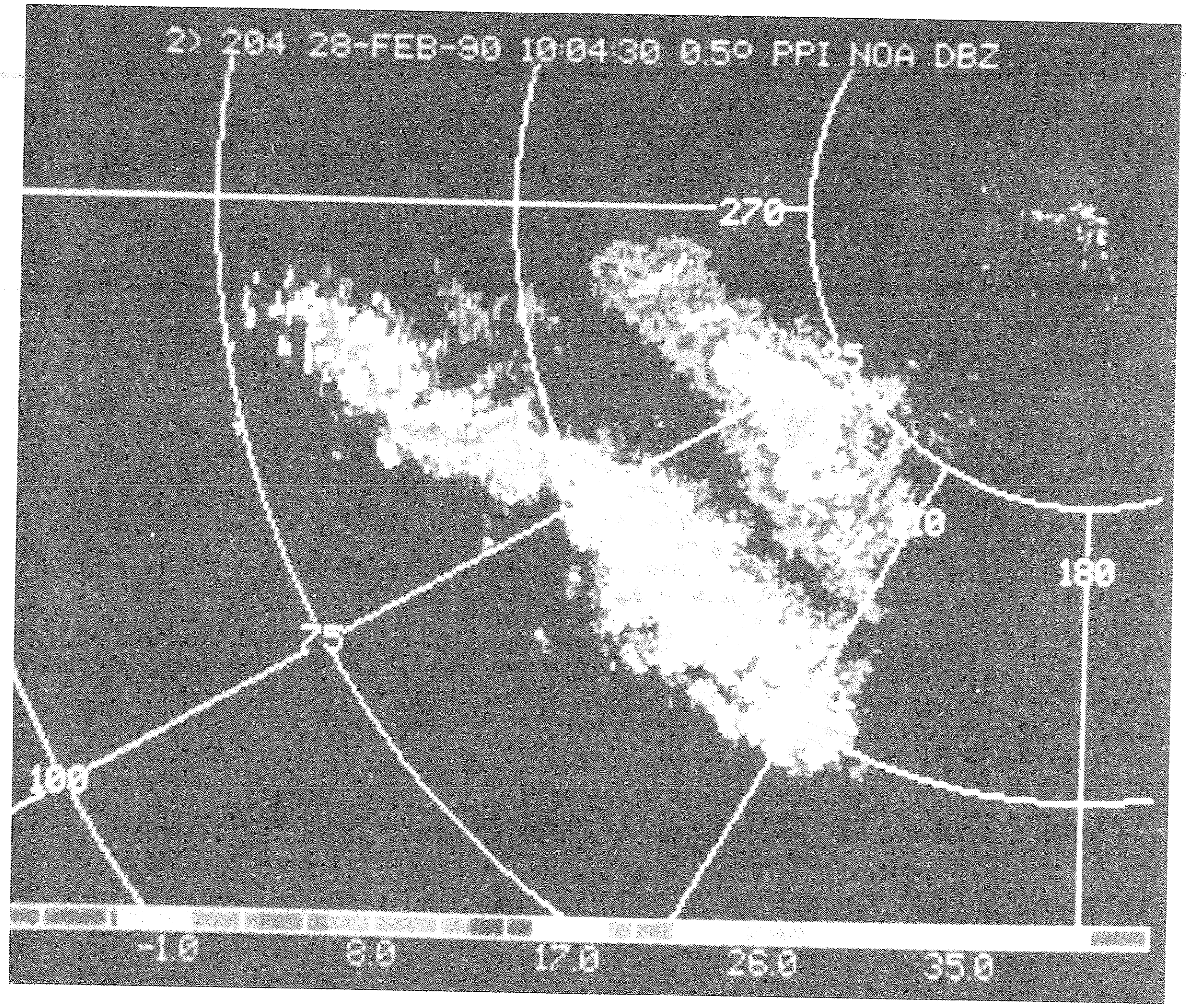

Figure 8. Radar reflectivity depicting parallel bands in northwesterly flow.

6. NUMERICAL MODELING

The SUNY Oswego Mesoscale Model will be used in LOWS analyses to simulate the development of lake-effect snowbands. In initial experiments, the model will predict wind, potential temperature, and specific humidity at 10 layers on a 45 x 31 unit horizontal grid with a 10-km mesh covering the Lake Ontario area. Flat terrain will initially be assumed. A 12-h simulation of the 11-12 January storm will be initialized using LOWS rawinsondes, profiler winds and Doppler radar data. This first test will determine if the model can produce snowbands of the same size, orientation and location as those observed. Model wind, temperature and humidity profiles and model precipitation will be compared with LOWS observations. Subsequent sets of experiments will a) test the model's sensitivity to changes in lake temperature, surface fluxes, latent heat releases, and initial conditions to learn more about the relative importance of the physical factors influencing the development of snowbands; b) include the effects of synoptic-scale forcing by using time-dependent lateral and upper boundary conditions to test the weakening or strengthening of observed snowbands; and c) include realistic terrain to test the model's ability to enhance precipitation over the Tug Hill plateau east of the lake.

In addition, the PSU/NCAR mesoscale model (MM4) is being applied. The structure and physics of this model are described by Anthes and Warner (1978). MM4 is hydrostatic and employs a terrain-following sigma coordinate system with 15 vertical levels. Provisions are included for variable terrain and high resolution boundary layer physics. A nested grid version of the model with 90 km and 30 km grid spacing was run in real time to examine model performance in the forecast mode for several of the LOWS cases. Also, case study analyses and sensitivity tests will be conducted with MM4 to study the physics and dynamics of the lake effect snow bands on detailed scale using a 2 km grid. Additional model development will incorporate the non-hydrostatic effects of latent heat releases on band development and morphology.

7. DISCUSSION

In post-analysis, there will be a careful examination of the technology transfer in terms of what succeeded what must be done differently or refined and what steps are needed to go to the operational mode, (e.g., remote sensor performance and practicality, remote sensing mesoscale coverage, and forecaster use of real-time integrated data products). First examinations of the data, while revealing some surmountable challenges like low profiler signals in cold clear air, demonstrate that a mesonet like that of LOWS would significantly improve locale-specific nowcasting of lake-effect snow. Steps to improving lake-effect storm forecasts along with the real-time monitoring will come from comparisons of the LOWS forecasts and observations and from examination of the data for precursors and physical factors that determined location of formation, movement, area of impact, intensity of whiteouts, and quantities of precipitation. The observations will be interfaced with the numerical modeling components in this effort.

The LOWS data set is available to the scientific community.

ACKNOWLEDGEMENTS

Primary support for LOWS came from Niagara Mohawk Power Corporation's Research and Development Department. The NOAA Wave Propagation Laboratory; National Weather Service Eastern Region; Atmospheric Environment Service; Pennsylvania State University; State University of New York Colleges at Brockport, Oswego, and Environmental Sciences and Forestry at Syracuse; Galson Technical Services; and New York State Department of Environmental Conservation all cost-shared the project to make this research possible. The SUNY mobile sondes and numerical modeling are supported by the National Science Foundation Grant ATM 89-14546. Additional support was provided by the Great Lakes Research Consortium. B. Orr, B. Martner, R. Zamora, J. Snider and P. Neiman of NOAA/WPL all made contributions to this manuscript. The staff of the Buffalo NWSFO and volunteers of the surface meteorological and snow measurement network provided essential support.

REFERENCES

Anthes, R.A. and T.T. Warner, 1978: Development of hydrologic models suitable for air pollution and other mesometeorological studies. Mon. Wea. Rev.,106: 1045-1078.

Hjelmfelt, M., and R.R. Braham, Jr., 1983: Numerical simulation of the airflow over Lake Michigan for a major lake-effect snow event. Mon. Wea. Rev., 111: 205-219.

McVehil, G.E., and R. L. Peace, Jr.,1966: Project Lake Effect. A study of lake snowstorms. Final Report Contract CWB-11231, Cornell Aeronautical Laboratory, Inc., 52pp. [Available from Calspan Corp. Buffalo, NY].

Murphy, B.P., 1989: Forecasting lake-effect snow in Ontario. Ontario Region Technical Note, Atmospheric Environment Service, Toronto.

Niziol, T.A., 1987: Operational forecasting of lake effect snowfall in western and central New York. Weather and Forecasting, 1: 311-321.

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

Reinking, R.F., R.A. Kropfli, B.E. Martner, and R. Caiazza, 1990: Initial findings from the Lake Ontario Winter Storms (LOWS) experiment. Preprints, 4th Conf. Mesoscale Processes, June 25-29, 1990, Boulder, Colorado. Amer. Meteorol. Soc., Boston (in press).