Observations of Lake-Induced Convection During the Lake Ontario Winter Storms Project (LOWS)

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ABSTRACT

Between 05 January and 01 March 1990, several components of the Penn State Cloud Observing System (COS) were deployed near the southeast shore of Lake Ontario as part of the Lake Ontario Winter Storms Project (LOWS). A 404 MHz wind profiler, a first generation Radio Acoustic Sounding System (RASS), laser ceilometer and standard surface instrumentation were operated nearly continuously to monitor the mesoscale wind and temperature structure in the lake storm environment.

Data were collected for two intense single band storms, two weak, multiple band events and six submarginal events. Meso-β and meso-γ structure revealed by the high resolution wind profiles obtained during the intense storms of 12-13 and 13-14 January include a transverse mesoscale circulation associated with the convection, and a low-level jet. Wind measurements confirm the existence of a low-level (~0.5 -1.3 km) mesoscale pressure trough and marked wind shift zone in active snowbands. RASS data indicate that the level and strength of any capping inversion may be more important in regulating these disturbances than the degree of thermal instability.

1. INTRODUCTION

Recent advances in ground-based atmospheric remote sensing technology have directly led to considerable progress in our understanding of complex mesoscale weather phenomena. While traditional upper air sounding systems provide wind and temperature profiles only twice daily at a spacing of ~500 km, measurements may be obtained from remote sensors at high spatial and/or temporal resolution necessary for the study of meso-α, meso-β and meso-γ scale systems. Wind profilers are clear air radars which are capable of producing a complete wind profile in a few minutes time, and the Radio Acoustic Sounding System (RASS) makes virtual temperature profiles available at similar temporal resolution. Typically, these systems have been used to provide wind and temperature profiles every hour or half hour for mesoscale meteorological studies.

Lake-effect snowstorms often take the form of organized bands of precipitation, originating over the lake or a downwind shore. On Lakes Ontario and Erie, strong single bands result when the air crosses the lake along its major axis; weaker but more numerous bands affecting a widespread area result when the flow crosses the major axis at a substantial angle. These disturbances have typical horizontal scales of between 2 and 40 km in width, 50-150 km in length, and rarely exceed 4 km in depth. They may last from hours to days. Lake-effect storms are truly a mesoscale phenomenon and represent a complex interaction between cloud scale, mesoscale, and synoptic scale processes. The temporal and spatial resolution available from wind profilers and RASS make detailed mesoscale analyses of these weather systems possible. Mesoscale kinematic structure may be inferred through the careful application of time-space conversion techniques. Mesoscale thermodynamic structure may be examined with the RASS.

While much of this technology has been developed at the National Oceanic and Atmospheric Administration's (NOAA) Wave Propagation Laboratory (WPL), the Department of Meteorology at Penn State University (PSU) is also actively involved in the development and application of these remote sensing systems. During the past decade, the department has been developing a suite of remote sensors which, when used together, are capable of giving a detailed description of boundary layer clouds and their associated wind and thermodynamic environment. This Cloud Observing System (COS; Albrecht et al, 1991) includes a 94 GHz cloud radar, a number of acoustic sounding systems, three 50 MHz wind profilers, a "portable" 404 MHz wind profiler, a RASS, 9-channel scanning microwave radiometer and numerous other instruments. A subset of COS was deployed in support of the Lake Ontario Winter Storms project (LOWS). LOWS was conducted in the Lake Ontario basin from 5 January through 1 March 1990 in order to demonstrate the utility of a meso-β scale array of remote sensors for real-time monitoring of lake-effect snowstorms and their precursors, and to improve short range (0-12 h) prediction of these disturbances through better physical description and understanding of factors influencing evolution of these storms. Over 15 organizations participated in the experiment.

This paper presents some of the results obtained from analysis of wind profiler and RASS data obtained during LOWS. The core scientific objectives of this study are presented in section 2. The measurements, data processing and analysis techniques are briefly described in section 3. Key observational results are summarized in section 4. Finally, the conclusions from this study and plans for future research are presented in section 5.

2. SCIENTIFIC OBJECTIVES

Lake-effect phenomena have been recognized since the beginning of organized weather observations in the Great Lakes region. The availability of abundant satellite imagery and mesoscale observation systems in the 1960s allowed the structure of these disturbances to become better understood. Earlier observational studies have suggested that interesting and complex mesoscale structure accompanies these storms (Peace and Sykes, 1966; Sykes et al 1971). Surface observations indicate that a narrow convergence zone or wind shift line, from 1/2 to 3 km wide, is associated with intense storms. A "snow wall" may mark either edge of this zone, a very sharp demarcation of cloud and falling snow. High winds, thunder, lightning and heavy snow or graupel may accompany the most severe storms. It has been suggested that a low-level jet may develop during intense storms. Observations suggest that instability generated phenomena such as "snowspouts" and "mesolows" may be generated and propagate along the bands, accompanied by gusty winds, snowbursts and near-zero visibility. Although the land breeze has been suggested to play an important role in storms over Lake Michigan (Ballentine, 1982), it has not been investigated for Lake Erie or Ontario disturbances where the prevailing flow is along the major axis of the lake. Meso-β and meso-γ scale structure is not well documented. Since previous studies have relied upon surface measurements, information on vertical structure is lacking. Finally, the operational forecast criteria used today (Niziol, 1987) have been developed based on measurements made at sites frequently removed from major lake-effect activity. The conditions measured at standard NWS sites may not be well representative of those in the lake-effect environment.

High temporal resolution wind and profiles obtained from the UHF wind profiler will be used to characterize the local wind field in the vicinity of lake-effect storms and lake-induced convection. After suitable signal processing and careful application of time-space conversion, the wind data will be examined for such mesoscale features as passing troughs, waves, land-lake circulation and convergence zones. Specifically, the data will be used to show that mesoscale snowbands lie in a shallow low-level pressure trough, that there is a mesoscale land-lake circulation during cold air outbreaks which may modulate band structure, and that the bands generally align with the mean boundary layer winds. Temperature data from the RASS will be used to document the role of the low-level capping inversion which is frequently present during cold air outbreaks (CAOs) and regulates the intensity of these storms.

3. MEASUREMENTS AND DATA ANALYSIS

An 80 km triangular remote sensing array, centered in the southeastern corner of the Lake Ontario basin, was established for the experiment. The locations of the three main remote sensing sites are shown in Figure 1. The triangular array was designed to allow the estimation of vorticity, divergence and large scale vertical motion by the kinematic method (Carlson, 1987). UHF (404 MHz) wind profilers were located at Cape Vincent NY (TTI), northeast of Lake Ontario, and at North Rose NY (PSU), southeast of the lake. A developmental 915 MHz wind profiler and X-band Doppler radar were located at Lacona NY (WPL), near the Tug Hill Plateau east of Lake Ontario. The experimental design is described by Reinking et al (1990). The North Rose site was equipped by PSU. A RASS-equipped UHF wind profiler, a laser ceilometer and standard surface instrumentation were provided. Instrumentation was selected in order to provide detailed wind and temperature information in the lower atmosphere, and to allow estimation of thermodynamic properties for cloud studies. The site was selected in order to allow measurement of wind and temperature profiles in the inflow regime of major lake-effect storms which form over the lake, provide opportunity to sample the environment of lakeshore snowbands, and to provide measurements during any transition from single to multiple bands. Mobile rawinsonde teams from the State University Colleges at Brockport and Oswego provided supplemental upper air data.

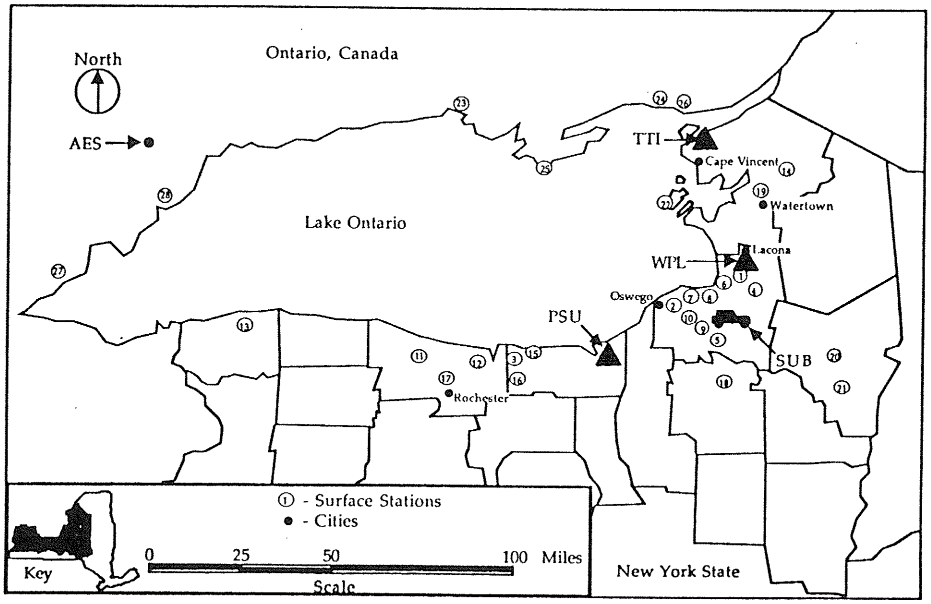

Figure 1. Location of the primary LOWS remote sensing sites relative to Lake Ontario. Surface observation sites are located by the numbered circles.

The operation of wind profiling radars is described by Strauch et al (1984). Unlike 3-10 centimeter wavelength radars designed to detect precipitation, wind profilers operate on wavelengths from 6m to 33 cm, and detect inhomogeneities in the radio refractive index of air due to turbulent mixing of air having slightly different temperature and moisture content. These fluctuations behave as a tracer of the mean wind in clear air. The radar reflectivity η_a for clear air is proportional to the refractive index structure function C_n^2, which is a measure of the variability of the refractive index within the inertial subrange. Variation occurring at one-half the radar wavelength (Bragg scattering) provides for most of the scattering. The radar reflectivity is given by:

$$\eta_a = 0.38 C_n^2 \lambda^{-1/3} \qquad (1)$$

where λ is the radar's wavelength (Ottersten, 1969).

The PSU profilers operate with three fixed beams, produced by a pair of coaxial-collinear phased-array antennas. A zenith beam provides direct measurement of vertical velocity, and two orthogonal beams at 75° elevation angles provide the three beams necessary to calculate all three wind components. The signal processing scheme used with these radars is shown in Figure 2. A number of pulses are averaged in the time domain, then transformed to the frequency domain by a 64 point Fast Fourier Transform (FFT). Several spectra are then averaged to obtain estimates of the primary moments (returned power, Doppler shift and spectral width). This is the First Moments (FM) technique, which was developed at NOAA WPL. It is the current standard used in wind profiling. Several spectral moments estimates are then averaged using the random sample consensus method (Fischler and Bolles, 1981) to obtain hourly wind estimates. During LOWS, the profiler operated in a low range mode, providing winds from 390m AGL to 2.55 km AGL with 150m resolution (oversampled to 100m), and a high range mode providing winds from 390m AGL to 5.6 km AGL, with 450m resolution (oversampled to 300m). Subhourly data (raw spectra, moments and wind tables) were available every 3 1/2 minutes during Intensive Operating Periods (IOPs), and hourly wind profiles were available during the duration of LOWS.

The radio acoustic sounding system, or RASS, relies on the same scattering mechanism as the wind profiler, and is operated as an auxillary to the PSU UHF wind profiler. In the RASS technique, the vertical beam, is employed. Since the speed of sound is temperature dependent, by measuring the speed of sound in the medium (air), a temperature profile may be derived if the vertical velocity is known or estimated. Since the moisture moisture is commonly not independently measured the virtual temperature, rather than temperature, is estimated.

The RASS uses signal processing techniques similar to those used by the profiler, except the receiver of the profiler is offset by $\sim 300\ ms^{-1}$ to measure the speed of sound. The virtual temperature is related to the velocity of sound by the relation:

$$T_v = \left(\frac{C_a}{20.047}\right)^2 \qquad (2)$$

Because the RASS uses the same signal processing as that of the profiler, simultaneous vertical velocity measurements were not available. Thus, RASS measurements were not corrected for vertical velocity, and observations suggest the correction would have been small and unnecessary in these cases. Hourly RASS temperature measurements were available during the daytime only (from 1200 UTC until 0000 UTC daily) since the RASS produces an annoying sound.

The operating parameters of the PSU UHF profiler and accompanying RASS system are shown in Table 1. Analyses presented in this paper were all produced with the standard FM technique.

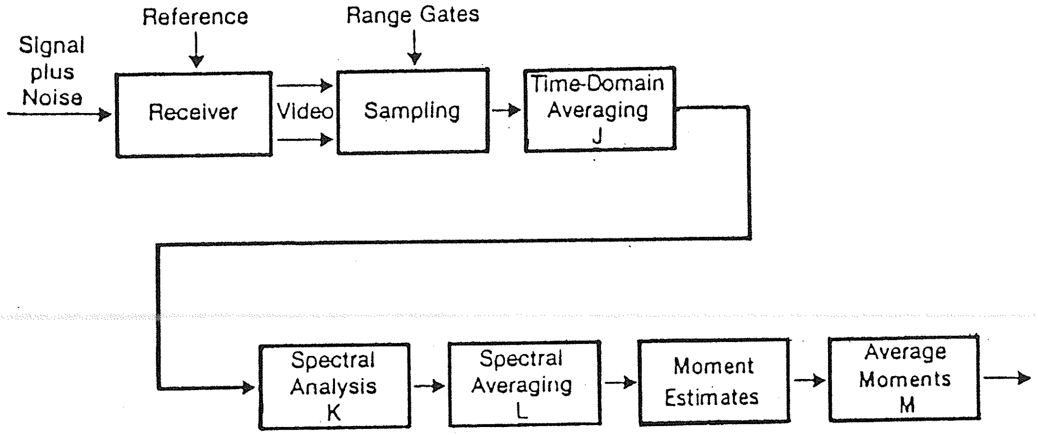

Figure 2. Flow diagram of the conventional signal processing used with wind profiling Doppler radars (from Strauch et al, 1984).

Table 1. Operating parameters and characteristics of the North Rose (PSU) RASS-Equipped UHF wind profiling radar.

Radar Characteristics

Frequency	404.37 MHz
Wavelength	0.742 m
Maximum Bandwidth	2 MHz
Peak Power	9.0 kW
Duty Cycle	<25%
Antenna Aperture	47.0 m^2
Antenna Pointing	zenith, 14.5° off-zenith (north, east)
Antenna Type	Collinear, coaxial fixed phase array
Element spacing	0.3125 m
One-way beamwidth	~7°
System noise Temperature	100 K

RASS Acoustic Characteristics

Waveform	FM/CW
Wavelength	0.371 m
Beamwidth	~5°
Radiated acoustic power	10 W (nominal)
Antenna type	1.5 m parabolic dish, horn fed

Operating Parameters

	Low mode	High mode	Vertical
Data Processing			
Pulse width (τ)	1 μs	3 μs	1 μs
Pulse repetition period	100 μs	200 μs	100 μs
Average power	80 W	120 W	80 W
Time domain averaging (n_c pulses)	200	72	200
Spectral averaging (n_s spectra)	12	20	8
Maximum radial velocity (ms^{-1})	±36.99	±51.38	±9.27
Spectral resolution (ms^{-1}) for 64 point FFT (k_3)	1.156	1.605	0.290
Height sampling			
First height	0.39 km	0.39 km	0.40 km
Height spacing	100 m	290 m	100 m
Number of heights	22	18	22

RASS Spectrum Scale

	Max	Mid	Zero	Min
Frequency offset (Hz)	901.44	871.39	841.35	781.25
Sound velocity (m s^{-1})	334.39		312.10	289.80
Temperature (°C)	4.91		-30.93	-64.29

4. OBSERVATIONAL RESULTS

Despite the unusually warm winter, data were collected for two single band storms, two multiple band events, and six submarginal events. During some of the submarginal events lake-induced mesoscale structure was noted in the wind fields, but these events were not well recorded by the NOAA WPL X-band Doppler radar at Lacona. All subhourly wind profiler data (spectra, moments, and wind tables) collected during LOWS by PSU were processed and archived for further post-collection analysis. Standard First Moment (FM) techniques (Strauch et al, 1984) were used in processing the wind and temperature data from the remote sensors. RASS data were supplemented by mobile sounding data collected during the experiment. Time-height sections of the vertical and horizontal hourly winds, and for RASS data when available were constructed for the entire experiment. These observations were combined with standard surface and upper air measurements in order to obtain a complete description of the synoptic and mesoscale conditions accompanying these events. All time-height sections were constructed with time increasing toward the left, such that the resulting profiles represent, in an approximate sense, cross sections of passing weather systems. In addition to examining hourly data, subhourly wind data were examined for the 12-13 January single band event, 13-14 January shoreline band and the two multiple band events in February. The data were of adequate quality such that several general observations could be made regarding the lake-induced convection observed.

The extended period of lake-effect snow that developed between 11 and 14 January 1990 followed the passage of a strong cold front followed by a prolonged period of westerlies which backed slightly with time. A detailed description of this event is given by Byrd and Penc (1992). Hourly wind profiles are presented in time section format in Figure 3a. Several hours of winds with fetch across the major axis of the lake preceded a series of single bands which developed between 0600 UTC and 1800 UTC 12 January. The depth of convective elements passing over the profiler may be noted in the vertical velocity field. Terminal velocities of 50-75 cm s^{-1} represent the modified terminal velocities of falling snowflakes. The first two convective cores to pass over the profiler were very shallow, the third at 1300 UTC extended to the capping inversion (~2.5 km). The fourth core (2100 UTC) extended only to ~1.5 km, restricted in the vertical by the capping inversion at that time. Wind profiles are of highly variable quality since operation of the profiler is highly weather dependent. Experience gained during LOWS has consistently shown that ground clutter returns frequently dominate the meteorological signal in cold, dry air (Penc, 1991).

The times of the four successive snowbands (SB1, SB2, SB3, SB4) are noted in the figure. The corresponding ceilometer trace (Figure 3b) clearly shows the relationship between the convective cores and cloud base lowering during SB2 and SB4. Typical cloud base during the series of snowbands was ~1 km, lowering to ~0.5 km during active convection. Thus, one may infer that the depth of the cloud elements passing over the profiler varied from ~1 km during SB1, to ~2 km during SB2, to ~1 km in SB4.

It is interesting to note the ~30° wind shift in the entire wind profile from 0800-0900 UTC which is associated with passage of a minor shortwave trough. Prior to and coincident with trough passage, snowband SB2 passed over the PSU wind profiler. WPL X-band radar imagery just prior to and after passage of SB2 is shown in Figure 4a and b. The corresponding subhourly (high resolution) wind profiles are shown in Figure 4c. Two mesoscale features may be noted. First, the lower range gates show a distinct southwesterly flow in response to the land-lake temperature contrast. The land to lake flow is consistent with a winter land breeze. Since the land breeze is a density current, it is strongest at low levels. The observed perturbation damps out rapidly with height. Surface mesoscale analyses are consistent with this. Evidence of a land breeze circulation was evident in the wind profiles between 0300 and 2100 UTC, and some evidence of a return flow is periodically present from ~1 km to the height of the capping inversion. These observations are consistent with the theory of Passarelli and Braham (1981) and Ballentine (1982) who attribute the high degree of organization in Lake Michigan lakeshore snowbands to the land breeze. Mid-lake snowbands usually form under weak synoptic flow and may be considerably enhanced by organized synoptic forcing. The strongest snowbands occur under organized synoptic forcing, aided by convergence brought about by the thermal difference between the lake and adjacent land areas. This circulation pattern can be best thought of as a thermal convergence, rather than a pure land breeze in the classic sense.

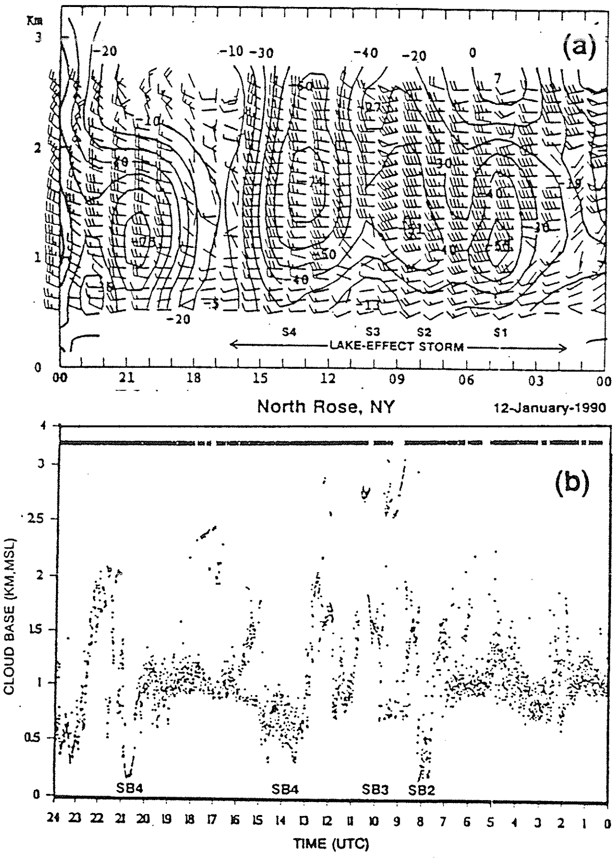

Figure 3. Time-height cross sections of observations made at the PSU/North Rose NY site during the 12 January series of intense bands. Time runs from left to right. (a) Hourly profiler derived winds in the low range mode for 0000 UTC 12 January to 0000 UTC 13 January 1990. Each full barb represents 5 kt (2.6 ms^{-1}), and vertical velocity contours are every 10 cm s^{-1}. (b) Corresponding ceilometer record. Each dot represents a single measurement of cloud base height; asterisks at top indicate sky obscuration, presumably from falling hydrometeors.

Secondly, a sharp northwesterly wind shift was noted with passage of SB2. The wind shift gradually relaxed with time. This observation is indicative of a small (meso-β) scale pressure trough coincident with snowband SB2. The perturbation extended to ~1.5 km AGL. These observations are consistent with the model proposed by Sykes et al (1971) and Peace and

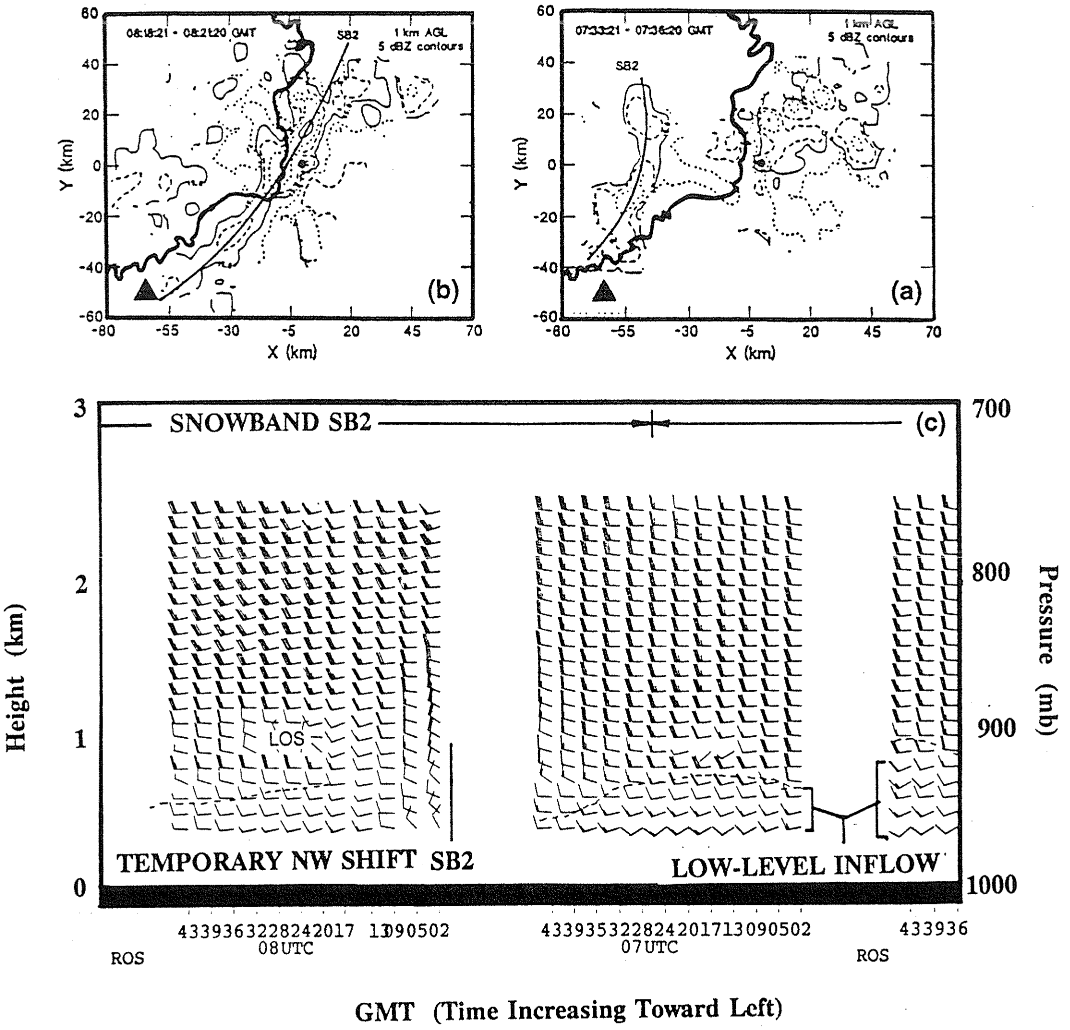

Figure 4. Observations made during the passage of snowband SB2 during the 12 January 1990 initial series of single bands. (a) WPL X-band radar PPI scan at 1 km AGL 0733 to 0736 UTC; (b) same as (a) except for 0818-0821 UTC. Contours are every 5 dBz, solid triangle indicates PSU profiler location. (c) Wind field as measured by the PSU UHF wind profiler, time of snowband passage (SB2) is indicated. Time runs from right to left. Each full barb represents 5 kt (2.6 ms^{-1}).

Sykes (1966) based on mesoscale surface observations. The hypothesis that snowbands lie in a mesoscale low pressure trough is supported by these observations.

Similar structure was noted in the subhourly wind observations during other LOWS cases. A further example is shown in Figure 5, which is a time-height section of winds at North Rose during the 10-11 February 1990 submarginal event. Although not detected by the WPL X-band radar, several weak snowbands passed over the PSU profiler. Low-level wind shifts suggestive of convergence lines accompanied these bands. The vertical extent of these appear to be related to the intensity of the convection. Time-space conversion, using phase speeds derived from the WPL X-band radar (when available) or profiler derived layer-mean winds estimates the size of these features at ~10 to 25 km.

Although not clearly evident in these wind profiles, a low-level jet was identified during the initial series of single bands on 12 January. Preliminary analyses show the core of the jet to be located at between 1.0 and 1.5 km; and of 5-10 ms^{-1} in strength. The presence of a low-level jet in intense storms can account for the observation of

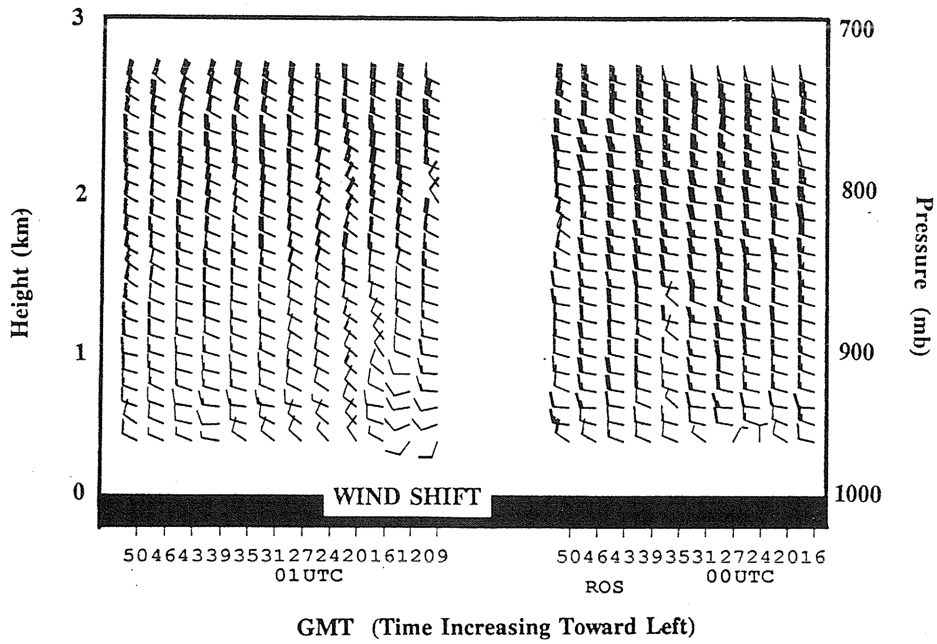

Figure 5. Time section of winds at North Rose as measured by the UHF wind profiler between 0000 and 0200 UTC 11 February 1990. The wind shift zone is indicated just above the time axis. A full barb represents 5 kt (2.6 ms^{-1}).

"mesolows" by a process similar to that hypothesized by Hobbs and Persson (1982) for similar structure observed in mesoscale frontal rainbands. Advanced signal processing techniques are being employed in order to better define this feature in the wind field. The presence of ground clutter in the profiler signal also precludes the calculation of derived quantities like perturbation winds and band relative motion. Post-processing of wind profiler spectra with neural networks is currently underway to address these problems and allow calculation of derived fields.

Several conclusions were made from the analysis of RASS data obtained during the multiple band and submarginal events which occurred during LOWS. A boundary layer depth of ≥2 km (cloud depth of 1-1.5 km) appears necessary to support convection which is capable of producing more than light snow showers. This finding supports that of Byrd et al (1991) who analyzed rawinsonde derived temperature profiles for a number of snow producing cases over western New York state during the winter of 1988-89. The intensity of lake-effect snowband activity appears to be more dependent upon the boundary layer depth than on the intensity of the low-level thermal instability. The multiple, parallel snowbands observed here were generated in horizontal rolls aligned with the mean boundary layer wind as measured by the profiler. The empirical 13°C stability criterion of Holroyd (1971) (T_{lake} -$T_{850mb} \geq$ 13°C)appears to be a <u>necessary but not sufficient</u> condition for lake-effect development, in the absence of significant synoptic scale forcing. LOWS data supports the general observation that sustained winds with minimal directional shear with height, and a long over-lake fetch are needed to initiate lake-effect storms.

The above conclusions were strongly supported by RASS and mobile sounding data taken during the multiple and submarginal events monitored during LOWS. Several submarginal events were accompanied by strong low-based temperature inversions. Two such cases are shown in Figure 6. During the 18-19 January CAO, a temperature inversion based at ~1.3 km was detected by RASS, although temperatures at 850 mb were sufficiently cold for lake-effect to occur. A similar inversion limited convective depth during the 17 February CAO. In both cases, significant lake-effect snows failed to develop. The temperature structure was also monitored by RASS for the two multiple band events (Figure

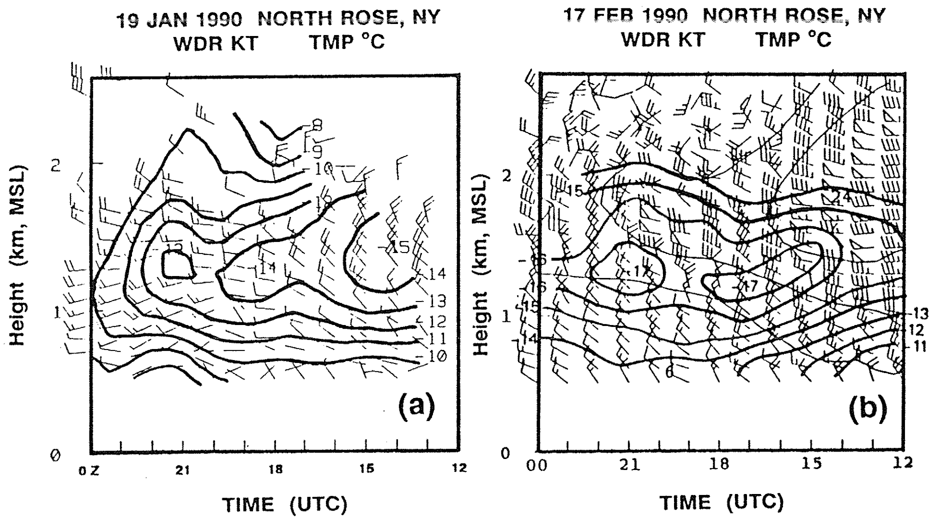

Figure 6. Time-height section of profiler winds and RASS temperatures at North Rose for the low operating mode during two submarginal events. Each full wind barb represents 5 knots (2.6 ms^{-1}). (a) 1200 UTC 19 January to 0000 UTC 20 January 1990. (b) 1200 UTC 17 February to 0000 UTC 18 February 1990.

7). During the 25-26 February case, RASS was barely capable of detecting a temperature inversion at 1.5 km, which limited convective activity despite the lake-850 mb temperature contrast of 23°C. No such inversion was detectable by RASS on 28 February, and some moderate multiple and single band activity developed in this case. Inferred lapse rates (from RASS measurements) in the boundary layer were approximately dry adiabatic in both cases. In nearly all LOWS cases, a low-level inversion was present. Nearly always a wind shear zone was collocated with this inversion.

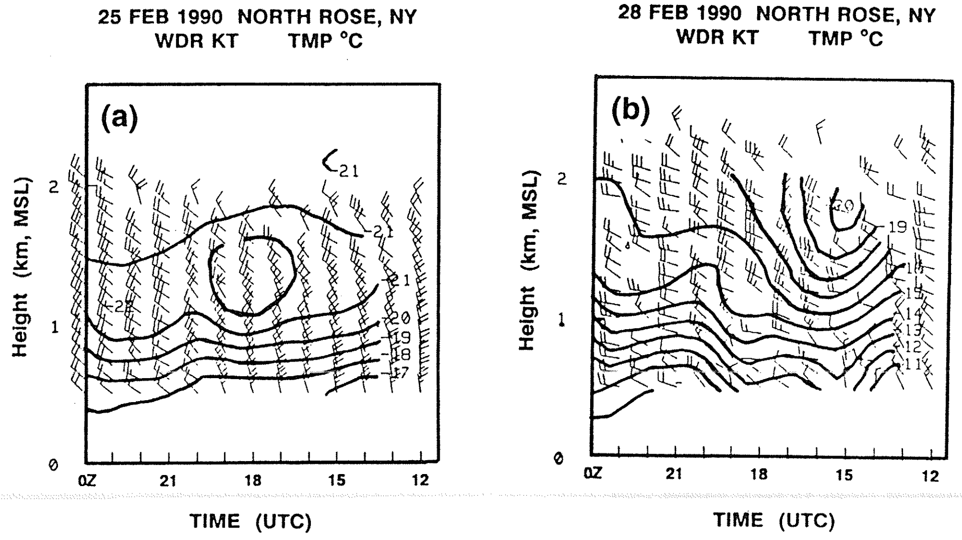

Figure 7. Time-height section of profiler winds and RASS temperatures at North Rose for the low operating mode during two multiple band events. Each full wind barb represents 5 knots (2.6 ms^{-1}). (a) 1200 UTC 25 February to 0000 UTC 26 February 1990. (b) 1200 UTC 28 February to 0000 UTC 01 March 1990.

5. SUMMARY AND PLANS FOR FUTURE RESEARCH

A RASS-Equipped 404 MHz wind profiler was used to study the mesoscale wind and temperature structure during episodes of lake-induced convection and lake-effect storms. Several key observations were made from data processed with standard FM techniques. Data analyzed from LOWS shows evidence of the development of a transverse circulation, observed at the North Rose site during the single band storms and some minor lakeshore oriented snowbands. This observation supports the work of Passarelli and Braham (1981) and Ballentine (1982) who attribute the organization of single bands over Lake Michigan to land-breeze convergence. Wind profiles obtained by PSU at North Rose suggest the land breeze plays a similar role over Lakes Ontario and Erie. The development of a land breeze circulation "turns off" the boundary layer roll mechanism, and concentrates the energy in the boundary layer into a single overlake band. Perturbations in the low-level wind field were noted at the time of passage of major, and some minor snow bands. This observation is consistent with the model of Sykes et al (1971) who postulate that lake-effect snowbands lie in a low-level mesoscale pressure trough. Application of time-space conversion shows that this feature is approximately 10-20 km wide. Its depth varied from 1-1.5 km. The flow field in the vicinity of the snowbands observed here is consistent with that derived from surface measurements by Peace and Sykes (1966) for a similar situation. Profiler data allows observations to be made on vertical structure and depth. RASS hourly temperature profiles suggest that the height (and intensity) of the capping inversion regulates the strength of lake-effect activity through restriction of convective depth. This result is supported by mobile sounding data taken during the experiment.

All results presented in this paper were obtained with standard FM techniques. Experience gained from LOWS shows that frequently the ground clutter return dominates the atmospheric return, particularly in low signal (i.e., cold and dry) conditions such as those typical of inducing lake-effect precipitation. This loss of signal is visible as randomly oriented low velocity winds in the time sections shown here. Since raw spectra were archived during all IOPs, application of advanced signal processing is possible. Analysis and manual editing of each individual spectrum is a tedious task. It can be considerably simplified through application of pattern recognition techniques. Currently, work at PSU is proceeding with development of a neural nets technique for processing wind profiler spectra. Here, manual analysis is necessary on only a few days of data in order to "train" the algorithm. Preliminary analysis shows that considerable information may be recovered since ground clutter can effectively be removed. For example, a low-level jet has been observed during the development of the initial series of snowbands on 12 January (not shown) which was difficult to identify with the conventional FM signal processing. All LOWS wind profiler and RASS data collected by PSU will be reprocessed with this technique. Perturbation wind fields and band relative motion will then be calculated in order to further quantify the mesoscale structure.

Data obtained from the various instruments will be combined to describe convective characteristics. Cloud base data from the ceilometer will be combined with estimates of boundary layer depth from the profiler reflectivity, RASS temperatures, and radiosonde data to investigate the convective character. Cloud-surface coupling will be studied similarly to that done by Albrecht et al (1990). The structure of the capping inversion will be related to the convective depth.

At present all numerical modeling of the phenomenon has been accomplished with hydrostatic models, which may not be appropriate to these scales of motion where vertical accelerations are important. The availability of a nested grid version of the Penn State/ NCAR mesoscale model (Anthes and Warner, 1978) should provide considerable improvement in the simulation of lake-effect storms. This is the subject of a further research proposal.

6. ACKNOWLEDGEMENTS

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