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THE IMPACT OF ICE COVER ON TWO LAKE-EFFECT SNOW EVENTS IN THE EASTERN GREAT LAKES REGION

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1. Introduction

Temporal and spatial variations of Great Lakes ice cover are known to affect lake-effect systems by limiting surface heat and moisture exchanges and altering mesoscale circulation development, evolution, and morphology. Despite the noted importance of ice cover to winter weather forecasting in the Great Lakes region (Niziol et al. 1995, Rauber and Ralph 2004), the influence of extensive ice cover on lake-effect boundary layers and mesoscale systems has only recently begun to be investigated. Gerbush (2005) found that estimated surface fluxes increased rapidly to near open-water values as the ice concentration decreased from near 100% to about 80% using aircraft measurements from over Lake Erie during the Great Lakes Ice Cover - Atmospheric Flux (GLICAF) study.

These recent observations suggest that significant positive heat fluxes may exist in regions where high ice concentrations (percent of unit area of lake covered by ice) exist and that the development of lake-effect circulations can be supported without the presence of open-water areas. Additional support for this concept was provided by Laird and Kristovich (2004) when they examined nearly 200 historical lake-effect snow events with ice cover present on the Great Lakes and noted eleven events occurred when the underlying lake had high ice concentration over the entire lake.

Great Lakes ice cover is often very transitory during the winter, particularly in mid-lake areas where freeze-up and break-up events, snowfalls, and winds can move, compact, and melt the ice. Although most of the Great Lakes rarely form a continuous-unbroken ice cover over their areas, extensive regions of high ice concentration often develop. Assel (1999) showed that ice usually begins to form on the Great Lakes in December and January and reaches the maximum spatial coverage in February or early March. Ice cover records for Lake Erie, the shallowest of the Great Lakes, show > 90% of the lake is typically ice covered by early January (Assel 1999).

Investigations of lake-effect systems in the Great Lakes region have primarily focused on events that have occurred over ice-free regions. This study presents two significant lake-effect snow events which occurred downwind of Lakes Erie and Ontario on 12-14 February 2003 and 28-31 January 2004. For each event, snowfall totals of 30-45 cm and 200 cm occurred along the shores of Lakes Erie and Ontario, respectively, during time periods when Lake Erie had widespread ice cover and Lake Ontario was predominantly ice-free. In both cases, the significant Lake Ontario snowfall totals that caused more than $1.3 million in property damage were expected; however the noteworthy lake-effect snowfalls in the vicinity of Lake Erie were unanticipated due to extensive ice cover.

2. Data & Methods

Snow spotter reports from the National Weather Service (NWS) at Buffalo, NY provided snowfall data for the two events (Fig. 1). Level II WSR-88D radar reflectivity data collected at Buffalo, NY, Montague, NY, Cleveland, OH and Detroit, MI were used to examine the regional distribution, intensity, and duration of lake-effect snowfall for Lakes Erie and Ontario.

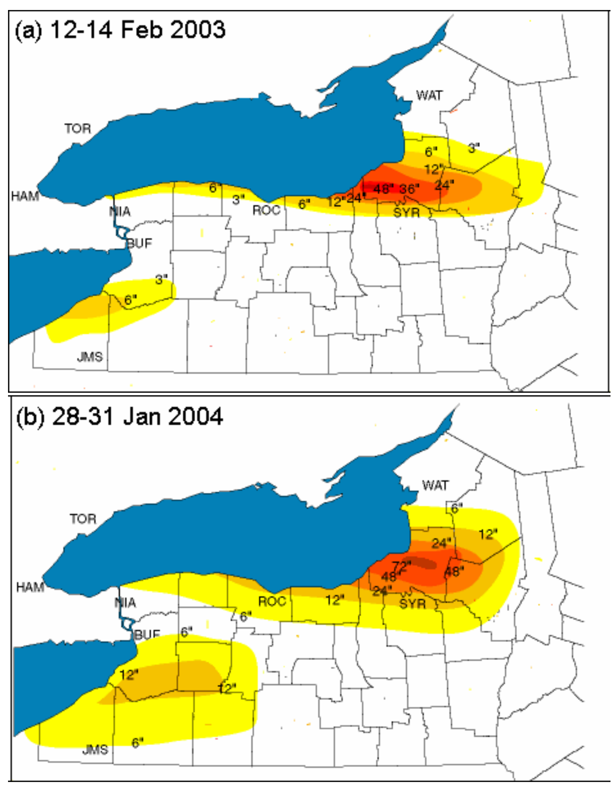

Fig. 1. Estimated lake-effect snowfalls (Buffalo NWSFO)

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Temperature, dew point temperature, and wind speed and direction information were collected from surface stations along the shorelines of Lakes Erie and Ontario. Lake temperature information was obtained from the Great Lakes Environmental Research Laboratory (GLERL). Heat and moisture fluxes were estimated for Lakes Erie and Ontario using bulk transfer methods similar to those used by Kristovich and Laird (1998). Open-water fluxes were estimated using a water temperature of 0ºC for Lake Erie during both events due to significant ice concentrations. Lake Ontario water temperatures were estimated as 2.5ºC and 4.0ºC for the 2003 and 2004 events, respectively.

Great Lakes ice charts from the National Ice Center and the Canadian Ice Service provided ice concentration and thickness information. MODIS and GOES satellite imagery provided additional information on ice coverage, specifically locations of open water. Figure 2 shows the ice charts for Lakes Erie and Ontario prior to and during each lake-effect event.

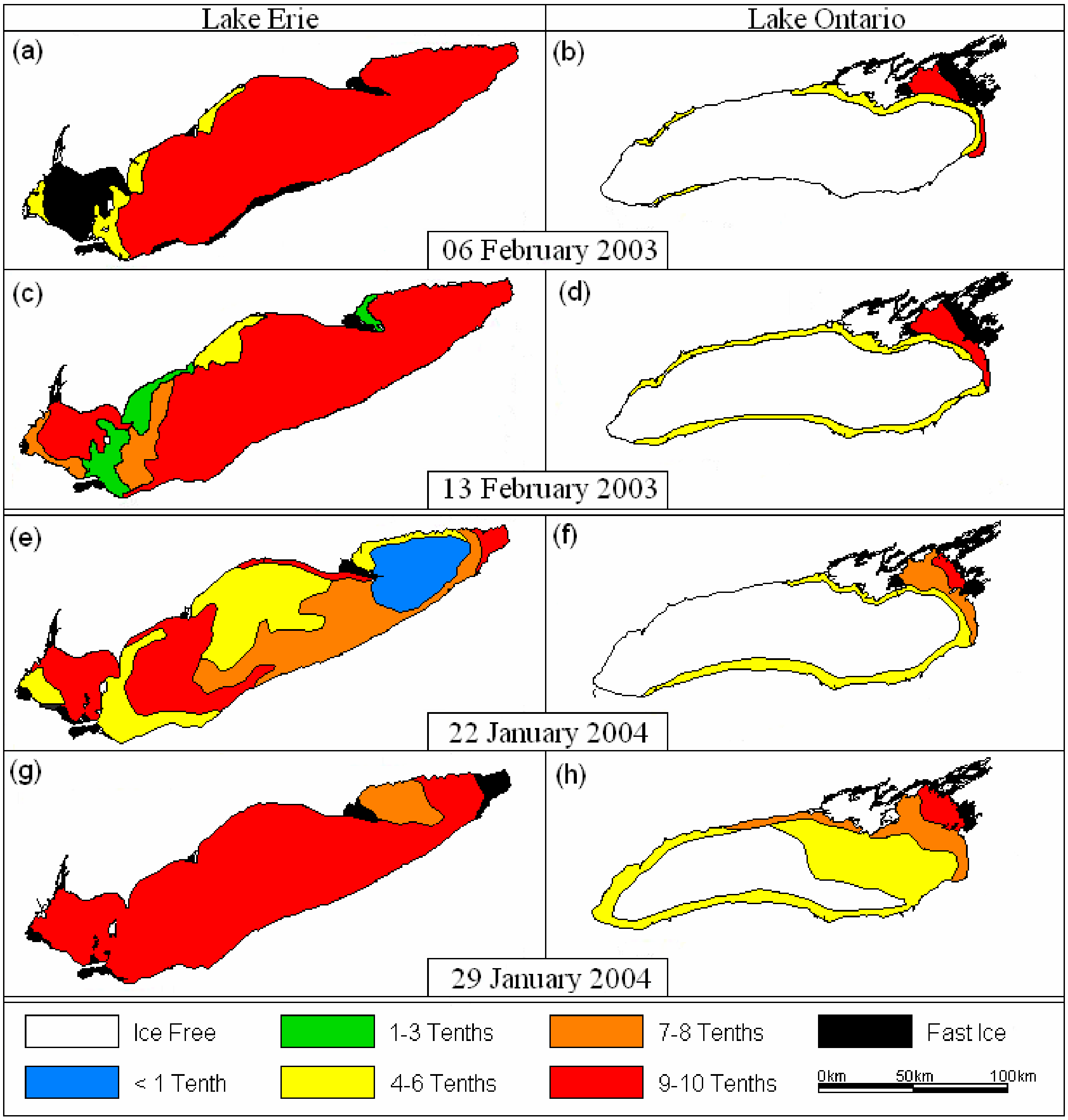

Fig. 2. Lakes Erie and Ontario weekly ice concentration analyses for 2003 and 2004 cases. Pack ice concentrations are specified in tenths of unit area of lake covered by ice. (Data courtesy of the National Ice Center).

3. Case 1: 12 – 14 February 2003

a. Ice Cover and Energy Transfer

Panels a-d on Fig. 2 show the temporal evolution of ice cover over Lakes Erie and Ontario from 06 February to 13 February. Leading up to the event, ice concentrations decreased in the Western Basin of Lake Erie from 40-60% on 06 February (Fig. 2a) to 10-30% on 13 February (Fig. 2c). The largest area of lowest ice concentrations (2,900 km^2 at 30%) was found between the Western and Central basins in the southern part of the lake. The rest of Lake Erie (~20,000 km^2) was 90% to 100% ice covered. MODIS satellite imagery on 09 February at 1625 UTC confirmed a moderately sized (500 km^2) open water area in the northwest portion of Lake Erie (Fig. 3). Ice charts estimated ice thicknesses over the Eastern Basin of 30-60 cm and thinner values (7 to 15 cm) north of Cleveland in the Western Basin.

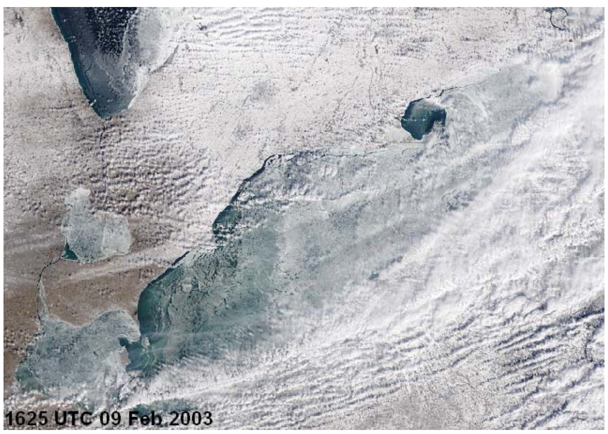

Fig. 3. MODIS visible image of Lake Erie.

Lakes Erie and Ontario water temperatures of 0 ºC and 2.5 ºC, respectively, resulted in maximum total heat fluxes of nearly 250 W m^{-2} for Lake Erie and 400 W m^{-2} for Lake Ontario. Total energy transferred from the lake surface to the overlaying atmosphere (product of total heat flux and area of open water) was significantly reduced over Lake Erie when taking the extensive distribution of ice cover into account. On 13 February Lake Erie's total energy output was decreased 85% (from 6,500 GWatts) to 975 GWatts due to ice cover, assuming negligible energy release from ice surfaces. A smaller impact on total energy transfer from Lake Ontario resulted from the limited ice cover. Total energy transfer from Lake Ontario decreased by 19% to 6,480 GWatts. Even with significant reductions in energy transfer from Lake Erie extended periods of lake-effect snow bands developed and led to 30 cm of snowfall over regions of western New York State.

b. Snowband & Mesoscale Evolution

Figure 4b shows shorelines bands downwind of Lake Erie existed during four different time periods in 2003. The first three shoreline bands, numbered 2, 5, and 6, affected a collocated region in southwestern New York. Similarly, Figure 4a shows two of three horizontal roll convection (HRC) regions (numbered 1 and 3) affected the same area in southwestern New York. The collocation of these 5 areas of snowfall contributed to the localized high snowfall totals in Sinclairville, Dunkirk, and Perrysburg, New York.

Unlike shoreline bands 5 and 6, band 2 did not initiate over and downwind of Lake Erie. Band 2 extended northwestward across the Western Basin of Lake Erie and into southern Lower Michigan with an origination over Lake Michigan. Surface winds across Lower Michigan confirm the development of a convergence zone which aided in priming atmospheric conditions for lake-to-lake banding. It is likely this band additionally intensified with a fetch incorporating low concentrations of ice cover in the Western Basin of Lake Erie. Maximum reflectivities associated with this band on the Buffalo, NY WSR-88D radar were 30 dbz or greater for four hours over southwestern New York.

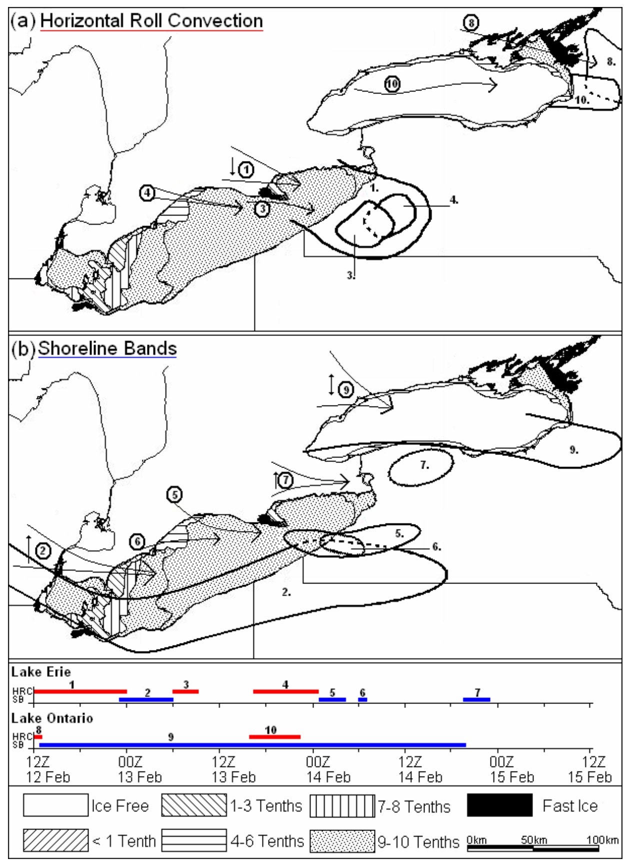

Fig. 4. Locations and timing of lake-effect snow bands for 2003 event. (a) Horizontal roll convection and (b) shoreline bands. Ice concentration on Lakes Erie and Ontario shown. Wind directions during periods of lake-effect activity are also shown. Label numbers identify snowfall regions and corresponding wind directions.

4. Case 2: 28 – 31 January 2004

a. Ice Cover and Energy Transfer

Similar to the 2003 case, Lake Erie has extensive ice cover. Panels e and g on Fig. 2 show the ice concentrations significantly increased over Lake Erie from 22 January to 29 January. Areas having ice concentrations $<$ 80% the week prior to the event accounted for more than half the total surface area of the lake (15,900 km^2), while during the event these regions accounted for 1,400 km^2 (Eastern Basin) of the total lake surface area. On 29 January, the second day of the event, an extensive area of Lake Erie was covered with 95% ice concentrations. Figure 5 shows a MODIS satellite image on 29 January that indicated a region of open water in the Eastern Basin, an area not shown on ice charts. Ice thicknesses were generally 15-30 cm across most of the lake, with the thickest (thinnest) ice along the southern (northern) shore.

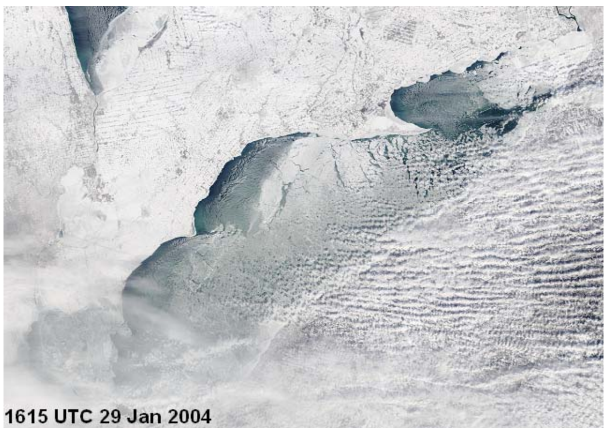

Fig. 5. MODIS visible image of Lake Erie.

Lake Ontario experienced a marked increase in ice cover the week leading up to the event. Panels f and h on Fig. 2 show the ice concentrations over Lake Ontario on 22 January and 29 January. Total ice cover increased from 17% on 22 January to 38% on 29 January, but was relatively thin with thickness values between 5 and 15 cm.

With Lakes Erie and Ontario water temperatures of 0ºC and 4ºC, respectively, maximum total surface heat fluxes for Lake Ontario (450 W m^{-2}) remained nearly double the values found over Lake Erie (200 W m^{-2}). On 29 January Lake Erie's total energy output (product of total heat flux and area of open water) was 175 GWatts due to extensive ice cover while Lake Ontario remained relatively ice free allowing a total energy transfer of 4,340 GWatts.

b. Snowband & Mesoscale Evolution

Even with 95% ice concentrations, open areas and leads in the ice pack still existed allowing for heat and moisture transfers to the atmosphere. The structure and intensity of the resulting mesoscale lake-effect circulations downwind of Lakes Erie and Ontario produced significantly different outcomes.

The January 2004 event downwind of Lake Erie saw two distinct periods of heavy snowfall. Figure 6 shows the occurrence and position of two shoreline bands and three periods of HRC that affected areas south and east of Buffalo, NY. Both shoreline bands, numbered 2 and 4, affected a collocated geographic region east of Lake Erie in southwestern New York. Fetch distances incorporated nearly the entire length of the Lake. The three periods of HRC, that impacted the same region, formed during time periods of west-northwesterly winds.

Three periods of HRC developed downwind of Lake Ontario during the event (regions numbered 6, 8, and 9 on Fig. 6a). The most likely cause of widespread convection was a limited fetch distance across 4-6 tenths ice concentration in the eastern lake basin.

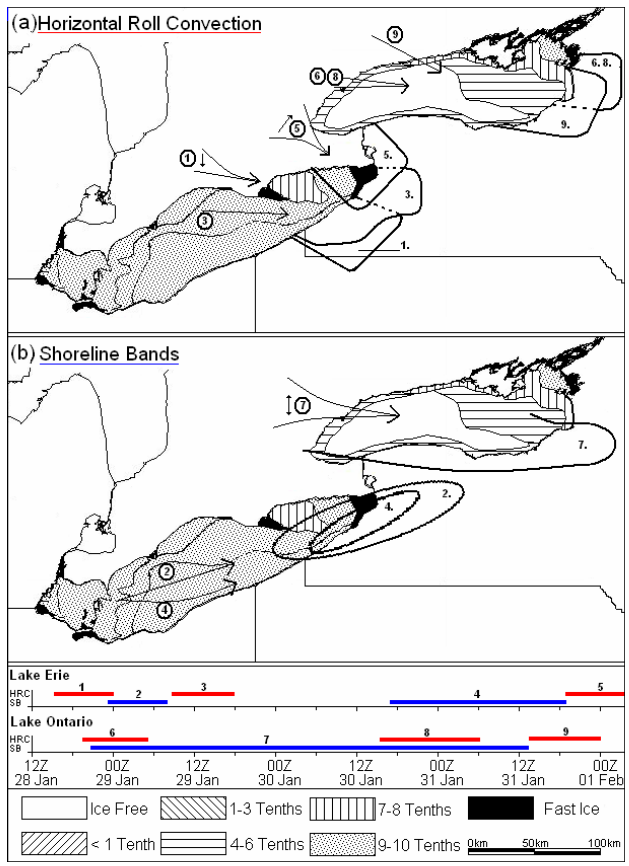

Fig. 6. Locations and timing of lake-effect snow bands for 2004 event. (a) Horizontal roll convection and (b) shoreline bands. Ice concentration on Lakes Erie and Ontario shown. Wind directions during periods of lake-effect activity are also shown. Label numbers identify snowfall regions and corresponding wind directions.

5. Discussion

The long-standing perception that extensive ice cover will entirely inhibit lake-effect snow band development has been shown invalid by the two cases presented in this investigation. Although the intensity of the lake-effect snow bands during these events were significantly greater over primarily ice-free Lake Ontario than extensively ice-covered Lake Erie, noteworthy snowfall amounts developed downwind of Lake Erie.

There appears to be several contributing factors to the Lake Erie snowfall. During both the 2003 and 2004 events, Lake Erie shoreline bands and regions of HRC developed downwind of small areas of low concentration ice cover (1-8 tenths). These small areas of low concentration ice cover were typically along the upwind lake shoreline with extensive areas of high concentration ice cover over the remainder of the fetch to the downwind shoreline. Noting the recent findings of Gerbush et al. (2005), it is likely that the lake-effect systems developed over and downwind of Lake Erie as a result of significant upward sensible and latent heat fluxes from both areas of low and high ice concentrations. The contribution of each of these regions can not be resolved using the observational data available for these cases; however analyses of GLICAF measurements and similar observations used in combination with model investigations could help address this scientifically-interesting and operationally-relavent issue.

A second contributing factor to shoreline band development during the 2003 event was the presence of an upwind moist convergence zone originating over Lake Michigan and extending over Lake Erie. This convergence zone is similar to a lake-end "pseudofront" observed by Baker (1976) in the surface temperature, moisture, and wind fields near the southern end of Lake Michigan. More recently, Rose (2000) used model simulations to examine a heat and moisture plume which extended from southern Lake Michigan toward Lake Erie and its influence on Lake Erie snow band development during a 9-14 November 1996 lake-effect event.

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6. References

Assel, R. A., 1999: Great Lakes Ice Cover (chapter 6), *Potential Climate Change Effects on Great Lakes Hydrodynamics and Water Quality*. D. C. L. Lam and W. M. Schertzer, Eds., American Society of Civil Engineers, 6:1-21.

Baker, D., 1976: The mesoscale temperature and dew point fields of a very cold airflow across the Great Lakes. *Mon. Wea. Rev.*, **104**, 860-867.

Gerbush, M., 2005: *Surface Heat Fluxes Over Lake Erie Pack Ice Fields*. M.S. Thesis, the Univ. of Illinois.

Kristovich, D. and N. Laird, 1998: Observations of widespread lake-effect cloudiness: Influences of lake surface temperature and upwind conditions. *Wea. Forecasting*, **13**, 811–821.

Laird, N., and D. Kristovich, 2004: Comparison of observations with idealized model results for a method to resolve winter lake-effect mesoscale morphology. *Mon. Wea. Rev.*, **132**, 1093-1103.

Niziol, T., W. Snyder and J. Waldstreicher, 1995: Winter Weather Forecasting throughout the Eastern United States. Part IV: Lake Effect Snow. *Wea. Forecasting*, **10**, 61-77.

Rauber, R.M. and F.M. Ralph, 2004: *An Implementation Plan for Cool Season Quantitative Precipitation Forecasting*. United States Weather Research Program, 54 pp.

Rose, B., 2000: The role of upstream lakes in determining downstream severe lake-effect snowstorms. Ph.D. dissertation, Univ. of Illinois, 183 pp.