A SATELLITE AND SOUNDING PERSPECTIVE OF A SIXTY-THREE INCH LAKE EFFECT SNOW EVENT

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Abstract

A major lake effect snow event at Sault Sainte Marie, Michigan on 8-11 December 1995 is described utilizing a combination of surface data, satellite imagery and radiosonde observations. The study highlights the utility of high-frequency, multi-channel meteorological satellite imagery in detecting and diagnosing important features of lake effect snowstorms. Satellite imagery is used to identify features in the absence of radar, and to locate the most active portions of lake effect snowbands. Satellite-derived cloud top temperatures are used in conjunction with forecast and observed temperature profiles to estimate the depth of moist convection and thus, infer snowfall intensity. Finally, a 3.9 μm satellite imagery product is examined as a means of identifying regions of supercooled water at cloud top. The importance of supercooled water to snowfall totals is discussed from a cloud physics perspective.

1. Introduction

Heavy snowfall can significantly impact all aspects of human activity. A listing of negative physical effects includes such items as trauma from traffic accidents, heart attacks, exposure, and back injuries. Economic impacts can also be staggering. There are a myriad of important and potentially expensive decisions to make whenever public safety is threatened, and in most cases accurate weather forecasts can play a significant role in mitigating a storm's worst effects. By knowing start times and periods of heaviest snowfall in advance, schools and businesses can make decisions on special closings and emergency managers can make preparations to deal with complex logistical problems such as alerting police departments, fire departments, hospitals, ambulance services, and power companies (Reinking et al. 1993).

In a general sense, short-range numerical weather prediction models can reasonably predict the occurrence of synoptic-scale flow patterns that are responsible for broad scale snowfall events (e.g., Sanders 1987, Smith and Mullen 1993, or Grumm 1993). However, mesoscale factors — such as uneven terrain or unfrozen inland lakes — can significantly alter standard Quantitative Precipitation Forecast (QPF) totals. Lake Effect Snow (LES) events are notoriously capricious, often bringing localized snowfall accumulations significantly greater than those which occur on broader spatial scales. These localized events focus snowfall into narrow bands (on the order of a few kilometers wide) such that a region receiving several inches of snow per hour can be adjacent to an area with light snow, or sometimes even clear skies (Niziol 1987). Thus, there is also a significant risk of over warning, and the ramifications of a mistake in that direction are almost as serious as failing to forecast the occurrence. Not only are credibility issues at stake, but there can be important, negative economic impacts as well. For example, large payrolls will be wasted if road clearing crews sit parked in their plows alongside highways, waiting for a snowstorm that doesn't materialize.

This paper describes a lake effect snow event which took place in the Upper Peninsula (U.P.) of Michigan (Fig. 1) over a 3-day period that began on the late afternoon of 8 December, and continued through the late evening of 11 December 1995. It developed within a period of general snowfall for the upper midwest during which locations not directly affected by the Great Lakes received between 3 and 7 in. of snow. For the purpose of illustration, much

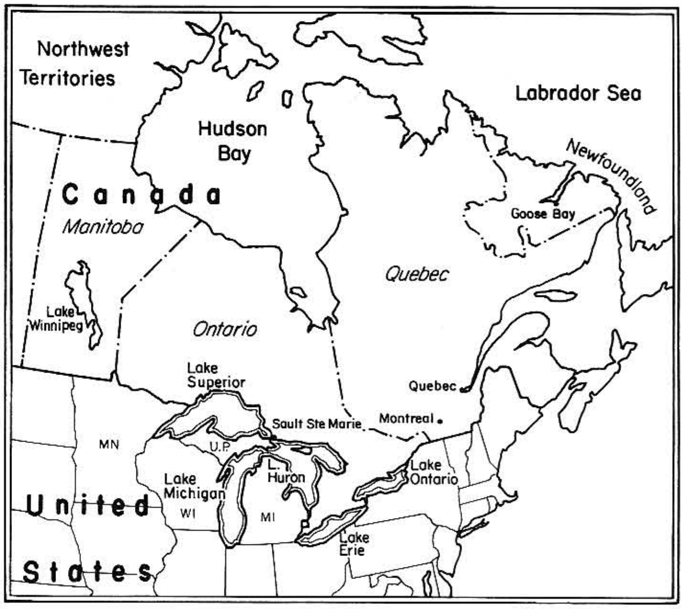

Fig. 1. Map showing political and geographical features mentioned in this paper.

of the discussion is focused on Sault Sainte Marie, Michigan (Y62). That city received a total of 63 in. of snow over the 3-day period discussed.

Significant snowfall at Y62 began with southeasterly surface flow across Lake Huron in advance of an approaching surface low and cold front. There was a lengthy respite as winds shifted with the passage of the front. Heavy snowfall returned when cold, west-northwesterly surface flow across Lake Superior created a large LES band that remained in place for more than 24 hours. The discussion concentrates primarily on the second period during which 32 in. of snow fell at the National Weather Service (NWS) office at Y62. That period of interest is the 30 hours from 0530 UTC on 10 December 1995 through 1200 UTC on the 11th. It was chosen because both unobstructed Geostationary Operational Environmental Satellite (GOES) imagery from GOES-8 and in-situ radiosonde data were available.

2. Event Evolution and Satellite Overview

a. Southeasterly flow segment

A large, negatively-tilted trough (MacDonald 1976) dominated the mid and upper-tropospheric flow pattern over most of the north-central United States on the days leading up to the LES event (Fig. 2). By 0000 UTC on 9 December 1995, the 500-mb trough axis was positioned from the central Northwest Territories in Canada to the upper midwest region of the United States, with 12-h height falls upstream of the Great Lakes as high as 220 meters at Saint Cloud, Minnesota (STC).

At the surface, an extratropical cyclone was moving eastward from northern Minnesota, with cold air advecting southeastward in its wake (Fig. 3). Ahead of the approaching cyclone, lower-tropospheric winds were from the southeast. This meant that the eastern portions of the U.P. were immediately downwind of Lake Huron's major axis. Surface air temperatures across the region ranged from -11C to -4C, and the 850-mb temperatures, as measured by soundings released at White Lake, Michigan (DTX) and Y62, were -8C and -13C, respectively. Meanwhile, lake surface temperatures ranged from +4C to +6C. The air-lake temperature contrasts, along with the orientation of the low-level flow, resulted in a strong and persistent mid-lake, Type I LES band (Niziol et al. 1995) that developed early on the 8th, and remained in place most of the day (Fig. 4). Note the cloud line at the south end of the lake in Fig. 4. Animated imagery revealed that this cloud line originated early in the day near the southeast shore of Lake Huron, and was probably associated with a land breeze.

Composite and animated satellite imagery also indicated that the downwind end of the LES band stayed mostly south of Y62 throughout the afternoon. However, extrapolation algorithms applied to the animated imagery revealed that the feature was moving very slowly northwestward, and would reach Y62 by dusk if the motion remained constant. Unfortunately, cirrus cloudiness moved into the region as this was occurring. Though movement of the band could be observed through the thin cirrus using visible satellite imagery, it could not be followed after dark due to the fact that the satellite's 10.7 μm channel (a window channel used for nighttime viewing) only "sees" a few centimeters into the cold cirrus. Objects beneath the cirrus deck are completely blocked from view. Since there was no radar coverage over the area, and because the lake effect clouds were hidden by cirrus after 2200 UTC, the subsequent evolution of the LES band cannot be analyzed effectively. All that can be said about this period is that heavier snow began at about 0250 UTC 9 December at Y62 and continued through 1550 UTC, with many Y62 hourly surface observations indicating snowfall rates of 1 inch per hour or greater. Overnight snowfall at Y62 totaled 24.7 in., most of which fell in the 6-h period from 0645 to 1245 UTC.

The majority of the heavy snowfall during this period may be best classified as a "combination" LES event (Dockus 1985). Such events occur when synoptic or meso-α scale (Orlanski 1975) lifting mechanisms supplement an otherwise marginal environment for LES in the boundary layer over the lake. These situations are often characterized by modest instability and/or low capping inversions which tend to limit the intensity of "pure" lake effect snow. In this case, temperature differences between the Lake Huron surface and 850-mb ranged from 12C to 19C, meeting generally accepted criteria for lake effect snow development (Rothrock 1969). However, the base of the capping inversion at Y62 (sounding not shown) was situated at about 850 mb — somewhat lower than what is considered ideal (Byrd et al. 1991).

b. West-northwesterly flow segment

For the 19 hours following the southeasterly flow segment of the event, snowfall was light at Y62. The surface cyclone moved slowly northeastward, causing a gradual transition from southeasterly surface flow to westerly. The beginning of the west-northwesterly segment of the event

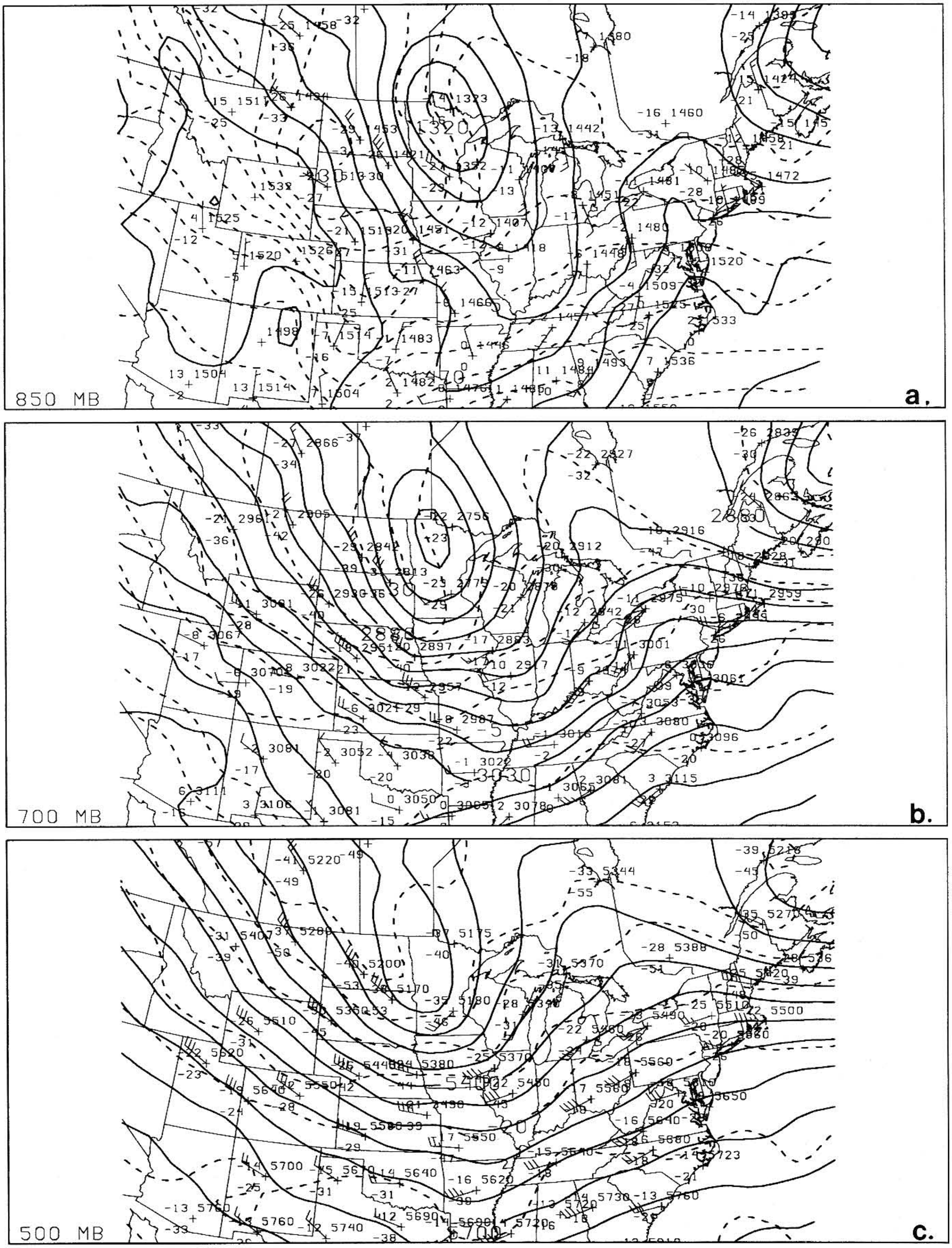

Fig. 2. Height (meters) and temperature (degrees C) analyses for 0000 UTC 9 December 1995 at: a) 850-mb, b) 700-mb and c) 500-mb levels. Plots and analyses are based on standard United States conventions.

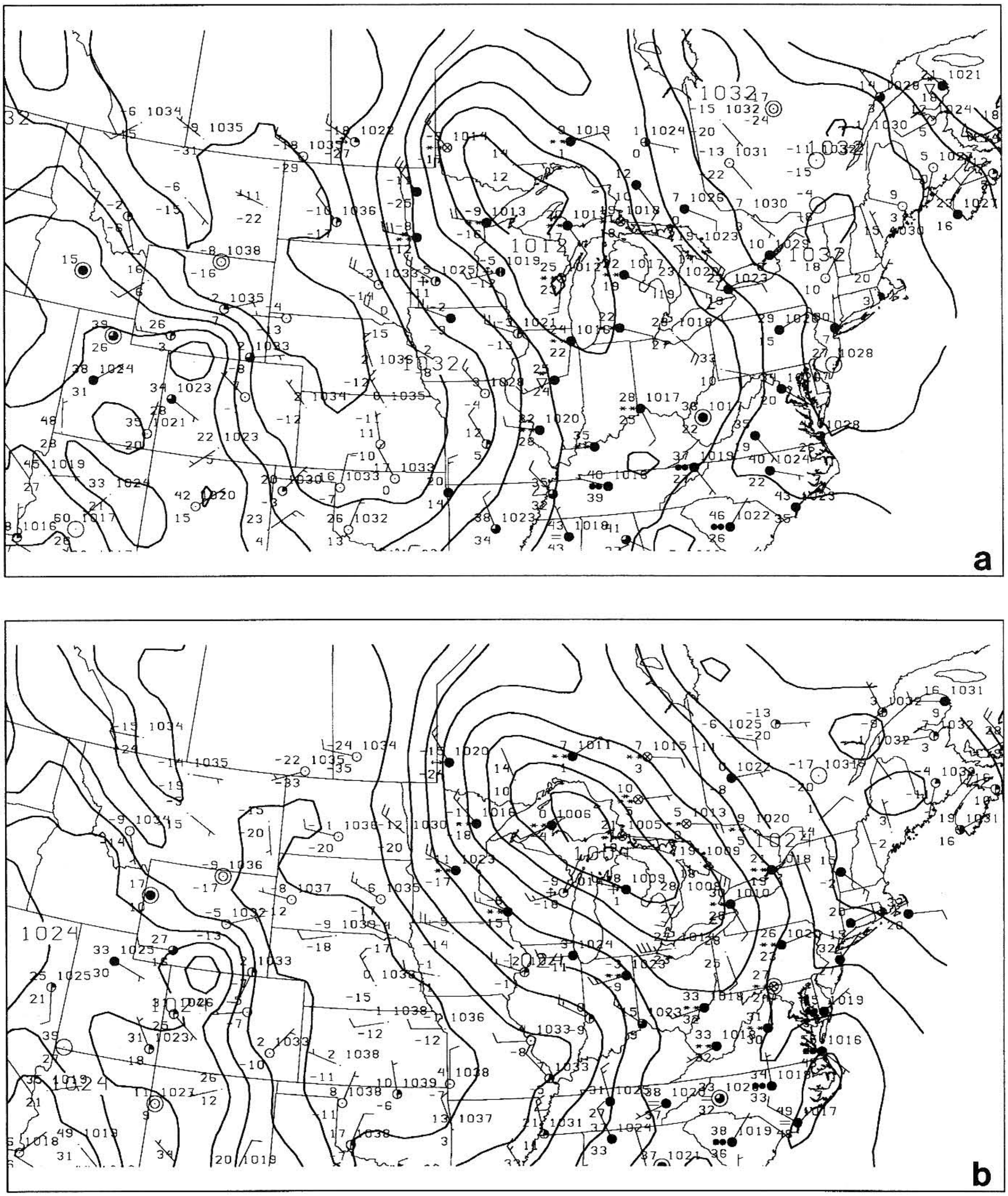

Fig. 3. Mean sea level pressure (mb) analysis at: a) 0300 UTC 9 December 1995 and b) 1200 UTC. Plotting conventions are based on standard United States station models. Isobars are at 4 mb increments.

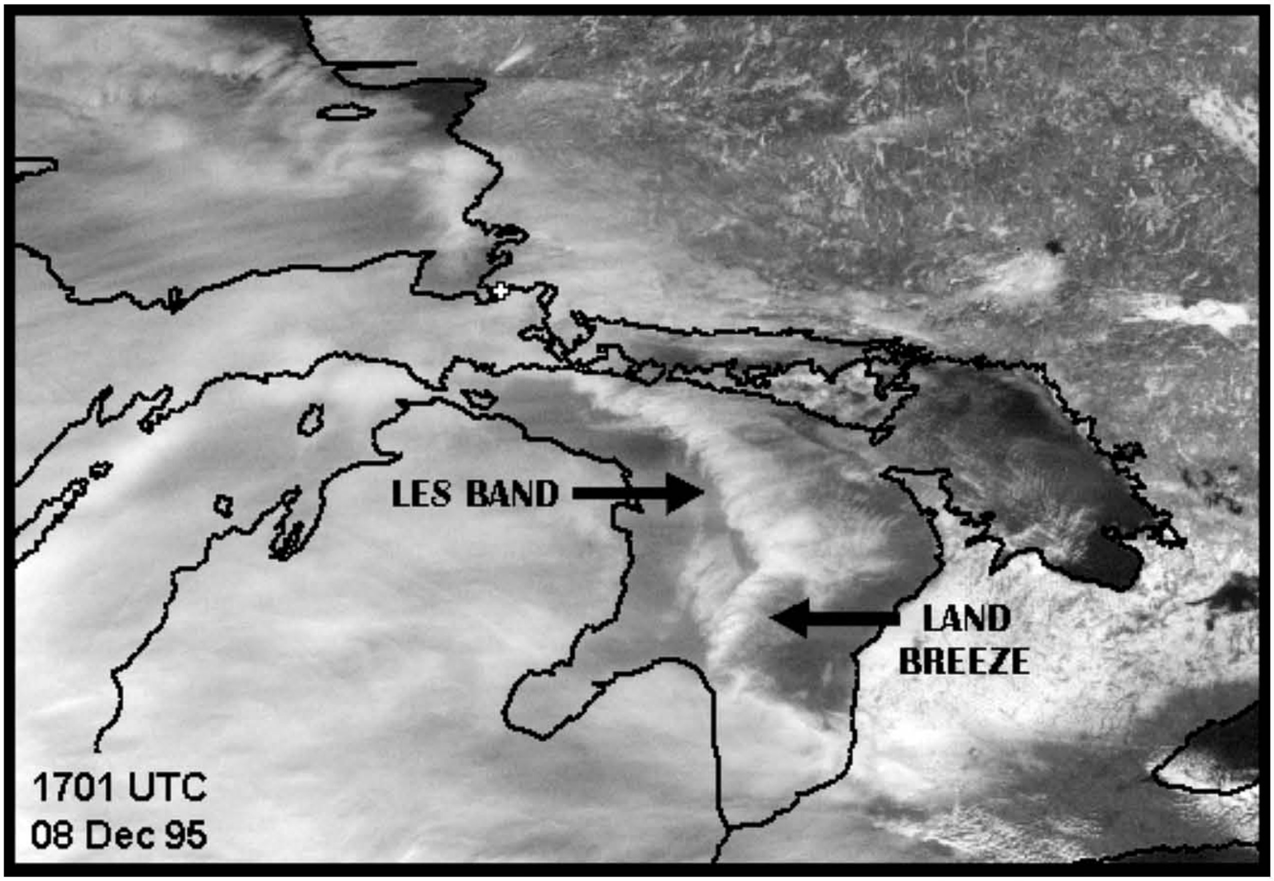

Fig. 4. GOES-8 visible satellite image from 1701 UTC 8 December 1995 showing a mid-lake LES band over Lake Huron. White cross denotes Sault Ste. Marie (Y62).

was first noted on 10.7 μm infrared satellite imagery which showed mid-lake (Type I), as well as shorter, wind-parallel Type II bands (Niziol et al. 1995) forming and intensifying off the northwest coast of Lake Superior. Type II wind-parallel multiple bands are a common phenomenon on Lake Superior, constituting nearly 70% of LES events for that lake (Kristovich and Steve 1995). Satellite imagery can provide a means of timely detection, especially when such development is expected. In this case, development could first be seen distinctly on the imagery at around 0530 UTC on 10 December (Fig. 5). The bands grew steadily with time, and at approximately 1000 UTC an embedded mid-lake band reached the southeastern shoreline of the lake. A special observation made at 1043 UTC indicates that heavy snowfall began almost immediately. During the period from 0950 UTC to 1353 UTC, observations at Y62 indicated that visibility gradually decreased from 3 statute miles in a light snow shower to 1/4 statute mile in heavy snow showers. Moderate to extremely heavy snow continued throughout the entire day and into the night, resulting in a total of 32 inches of new snow by the morning of the 11th.

Rapid-scan (7.5-min interval) visible satellite imagery reveals many interesting features over the Great Lakes region which are most evident when the imagery is viewed in animation. Persistent features can also be illustrated using a visible image "composite", i.e., an image made by averaging brightness values for several sequential images. A composite image made for the period 1515 UTC through 1815 UTC on 10 December highlights some of the more persistent and intense features for this segment (Fig. 6). In particular, the bright, dominant band embedded within the area of weaker wind-parallel multiple bands is clearly evident over eastern Lake Superior and the Sault Sainte Marie area. Also apparent in Fig. 6 is the prominent role played by the region's topography in modulating LES events. Of particular interest is the possible importance of upwind/downwind bay features and shoreline irregularities in the development and maintenance of dominant LES bands. These and other features can be seen in several locations in Fig. 6, including: a) central Lake Huron, where an LES band originated downwind of Saginaw Bay near the tip of the Michigan "thumb"; b) northern Lake Huron, where an LES band originated just downwind of the Straits of Mackinac and appeared to merge with the dominant Lake Superior band where it crossed the eastern U.P.; c) northern Lower Michigan, where a smaller but persistent LES band was anchored over Little Traverse Bay on northeastern Lake Michigan; d) southern Lake Michigan, where the lack of lake effect cloud bands reflects low upstream relative humidities over Wisconsin, likely delaying the onset of moist over-lake convection; e) western Lake Erie, where a significant band developed in a short over-water trajectory after modification of dry upstream boundary layer air by Lake Michigan; and f) central Lake

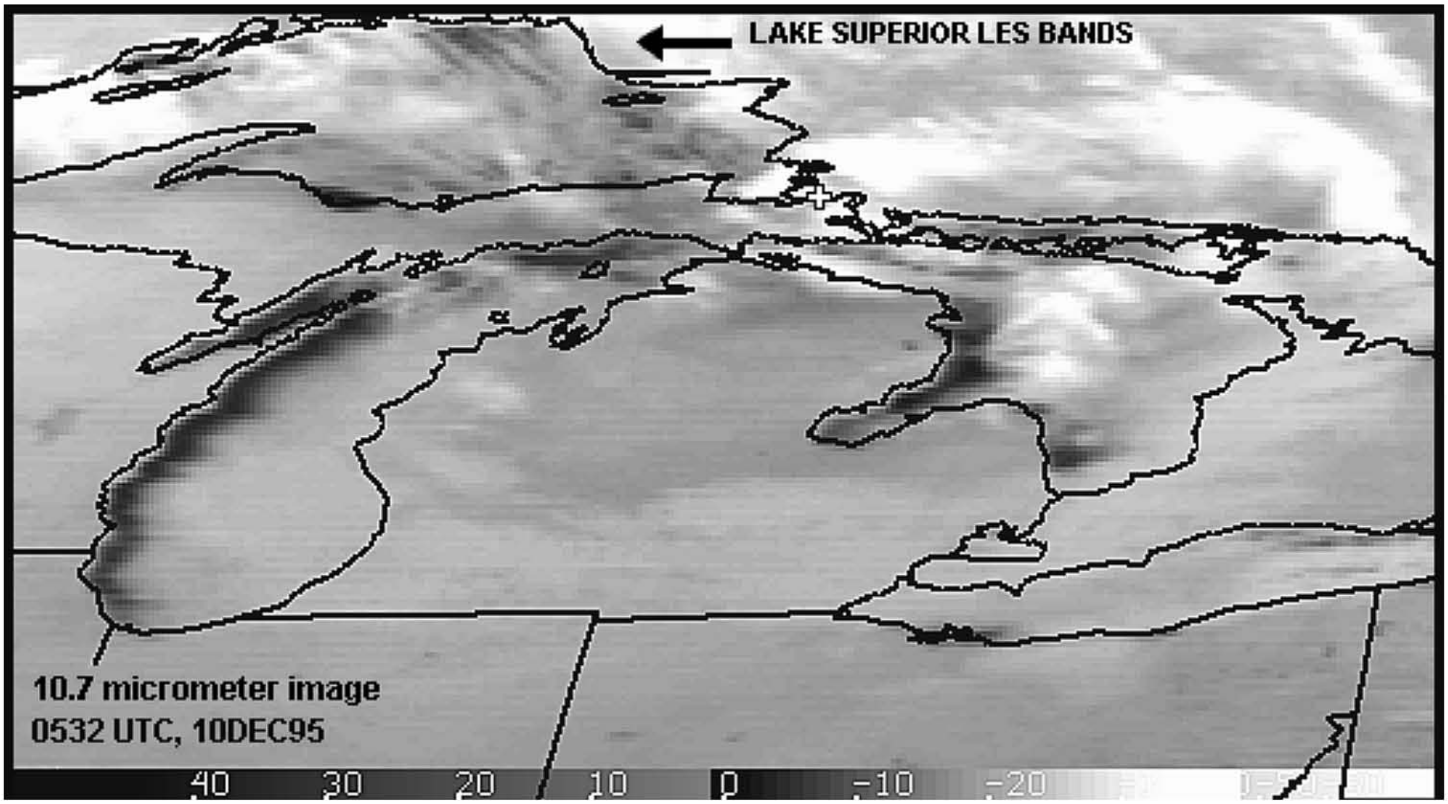

Fig. 5. GOES-8 10.7 μm image at 0532 UTC 10 December 1995 showing LES bands developing over Lake Superior.

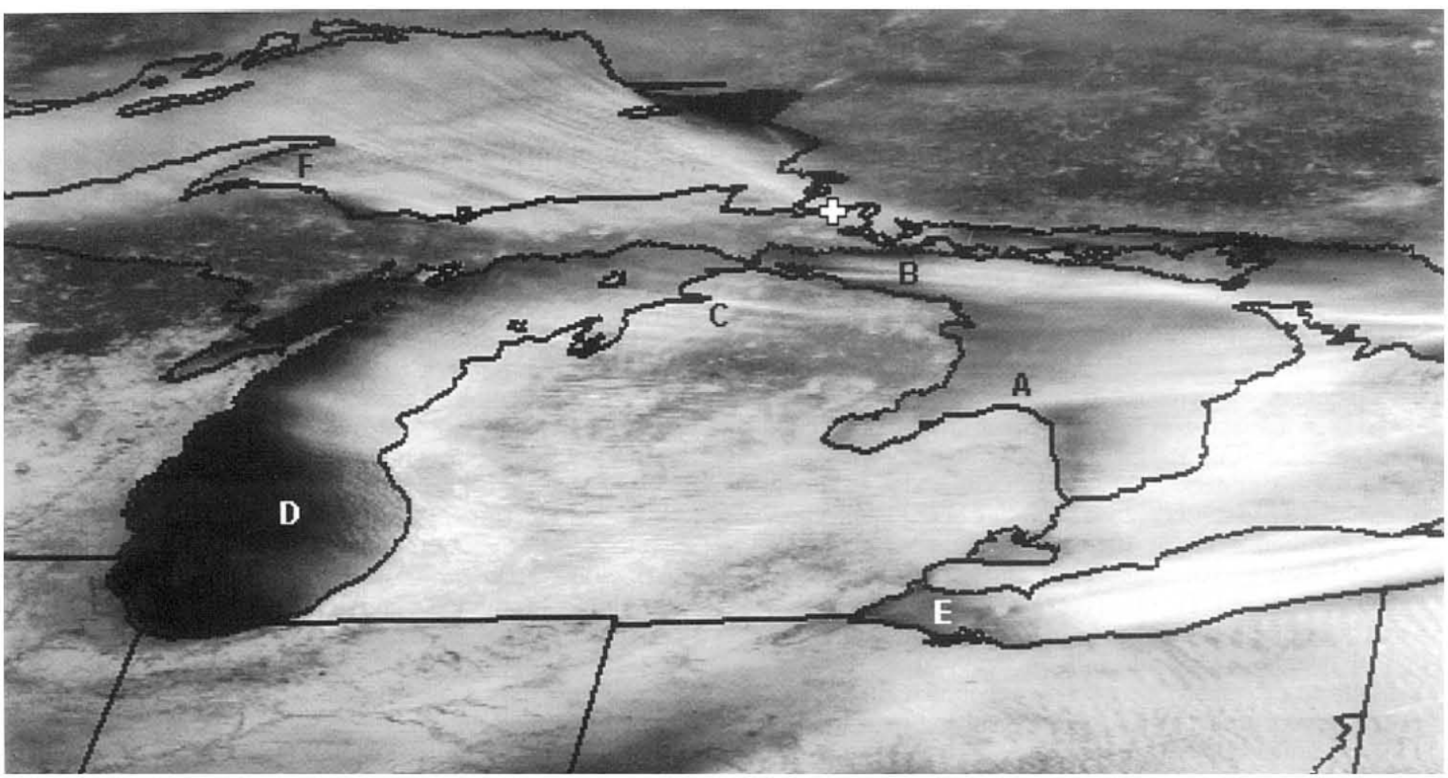

Fig. 6. Average of brightness counts from GOES-8 visible images for the period 1515 UTC through 1815 UTC on 10 December 1995. Bright areas show persistent cloud features. Bold lettering refers to: A) LES band originating near the "thumb", B) LES band originating near Straits of Mackinac, C) small LES band originating off Little Traverse Bay in northern Lake Michigan, D) delayed onset of LES band formation over southern Lake Michigan, E) LES band over western Lake Erie aided by upstream air modification by Lake Michigan, F) convection breaking through the cap downwind of Keweenaw Peninsula, and a dominant LES band over northeastern Lake Superior and Y62 (cross).

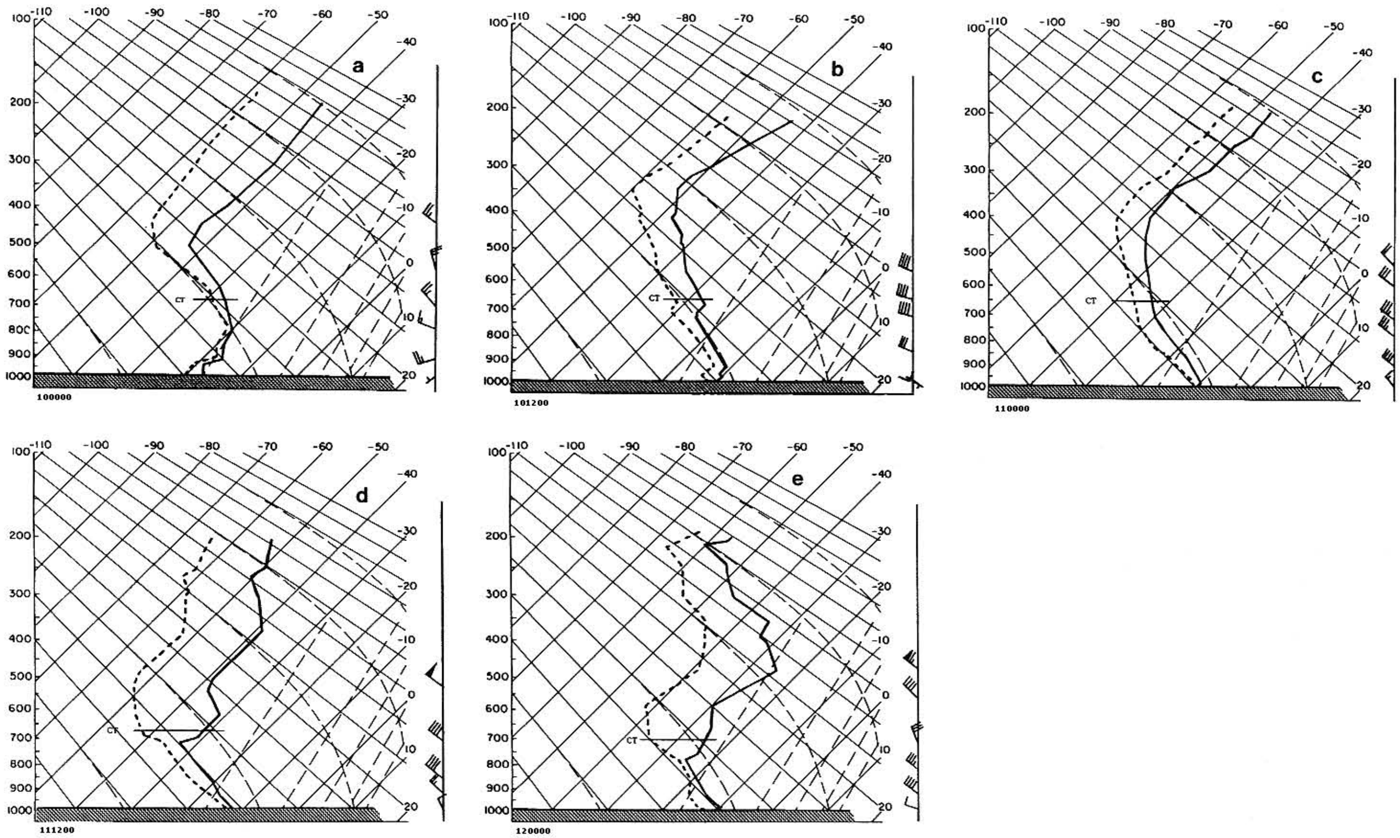

Fig. 7. Radiosonde data from Sault Sainte Marie, Michigan (Y62; 72734) plotted on Skew-t/Log-P diagrams. Times shown are a) 0000 UTC 10 December 1995, b) 1200 UTC 10 December 1995, c) 0000 UTC 11 December 1995, d) 1200 UTC 11 December 1995, and e) 0000 UTC 12 December 1995. Horizontal line segment intersecting temperature curve is satellite estimated cloud top (CT). Temperature and dew point in degrees C and pressure in mb.

Superior, where enhanced brightness and higher cloud tops indicate lake effect convection breaking through the capping inversion.

3. Cloud Physics Aspects and Snowfall Intensity

At the time of this event, Y62 was an NWS radiosonde release site. Thus, the depth of the cold air, changes in static stability and other crucial parameters regarding the vertical structure of the atmosphere can be reasonably estimated for the period of interest. The following discussion focuses on the radiosonde plots shown in Fig. 7. Cloud top heights used in the discussion are derived from comparisons between soundings and cloud top temperatures as measured by the 10.7 μm satellite imager. Snowfall amounts are as reported at the Y62 NWS office.

The radiosonde released from Y62 at 0000 UTC on 10 December 1995 (Fig. 7a) shows the local temperature, dew point, and wind profiles prior to the beginning of the west-northwesterly period of lake effect snowfall. The sounding was taken during the period when the surface flow was southwesterly, and shows very cold air throughout the depth of the troposphere. In fact, the entire temperature profile was much colder than the relatively warm temperature range (~ -15C, or warmer) where both capped columnar and dendritic snow crystals form most efficiently (see Fig. 8)[1]. Both of these crystal types can be important to the production of heavy snow in LES events, since they provide the best 'seeds' for graupel (Krauss et al. 1987). Also, heavy riming can occur within this warmer temperature range (Braham 1990). This is important because heavily-rimed graupel and rimed dendritic aggregates characterize the snowfall in many heavy LES events — those producing deep convection with strong updrafts (Jiusto and Weickmann 1973). Dendritic snow crystals by themselves typically produce lesser, but still potentially significant, snowfall accumulations in LES bands with shallower convection (Braham 1990)[2].

At the time of the 0000 UTC sounding, very light snow was occurring at Y62. It was falling from middle- and upper-level clouds associated with a deep synoptic trough (Fig. 9), which was seen on satellite imagery as a broad area of cold, cirrus cloudiness. A few hours after this sounding, the trough moved east, the lower-tropospheric flow shifted to the west-northwest, and the higher cloudiness which had been obscuring the satellite view moved off to the east. Shortly thereafter, NW-SE oriented LES bands began forming over Lake Superior.

Despite the strong, lower-tropospheric, cold air advection, the Y62 1200 UTC sounding on the morning of

[1] Laboratory and observational studies find crystal habitat to be independent of season, and depends only on temperature and degree of supersaturation (Nakaya 1954; Byers 1965).

[2] A good example are snowfalls that occur in relatively intense wind-parallel multiple band events which occur frequently on the eastern shore of Lake Michigan.

10 December 1995 (Fig. 7b) found a significant portion of the vertical temperature profile to be warmer than -15C. This warming occurred because, in a west-northwesterly flow situation, Y62 is directly downwind from a 400 km-long fetch of open lake. In cases of relatively warm lake temperatures, buoyant mixing combines with shear-induced mechanical mixing to transfer latent and sensible heat upward and downwind, thereby creating a deep boundary layer of relatively warm, moist air (Chang and Braham 1991). The favored dendritic growth region in this case was centered around 1.7 km (mid-cloud level). It is hypothesized that the air within the LES band near Y62 had warmed enough from 0000 UTC to 1200 UTC 10 December 1995 to make capped column and dendrite production likely. At the same time, the mean mixing ratio in the layer between the surface and 850-mb level nearly doubled, which, at these relatively warm temperatures, would serve to increase the amount of supercooled water available for riming within the cloud. These factors combined to increase precipitation intensity in the main LES band over Y62, especially from 1100 UTC to 1800 UTC on 10 December 1995.

Satellite imagery helps illustrate another important consideration when nowcasting in LES events; namely, advection as a factor in estimating ground location for snowfall in remotely-detected LES bands. Given expected fall speeds of ~ 1 m s^{-1} (Byers 1965), dendritic snow crystals forming and riming at or above 1.7 km would require a minimum of 15 to 30 min to fall to a height of 0.5 km, the approximate height below which the winds within the band became light and variable (Fig. 7b). In this case, winds above 0.5 km were northwesterly at speeds of approximately 30 kt (16 m s^{-1}), meaning falling particles would advect horizontally 15 to 30 km over the 1.2 km fall distance from 1.7 km. Figure 10a shows the 1145 to 1745 UTC average of infrared images. Note that the most persistent cold tops in the vicinity of Y62 are roughly 22 km west-northwest of the station. The most active portion of the band appeared to be in a good position for depositing heavy precipitation on the city. There is a second per-

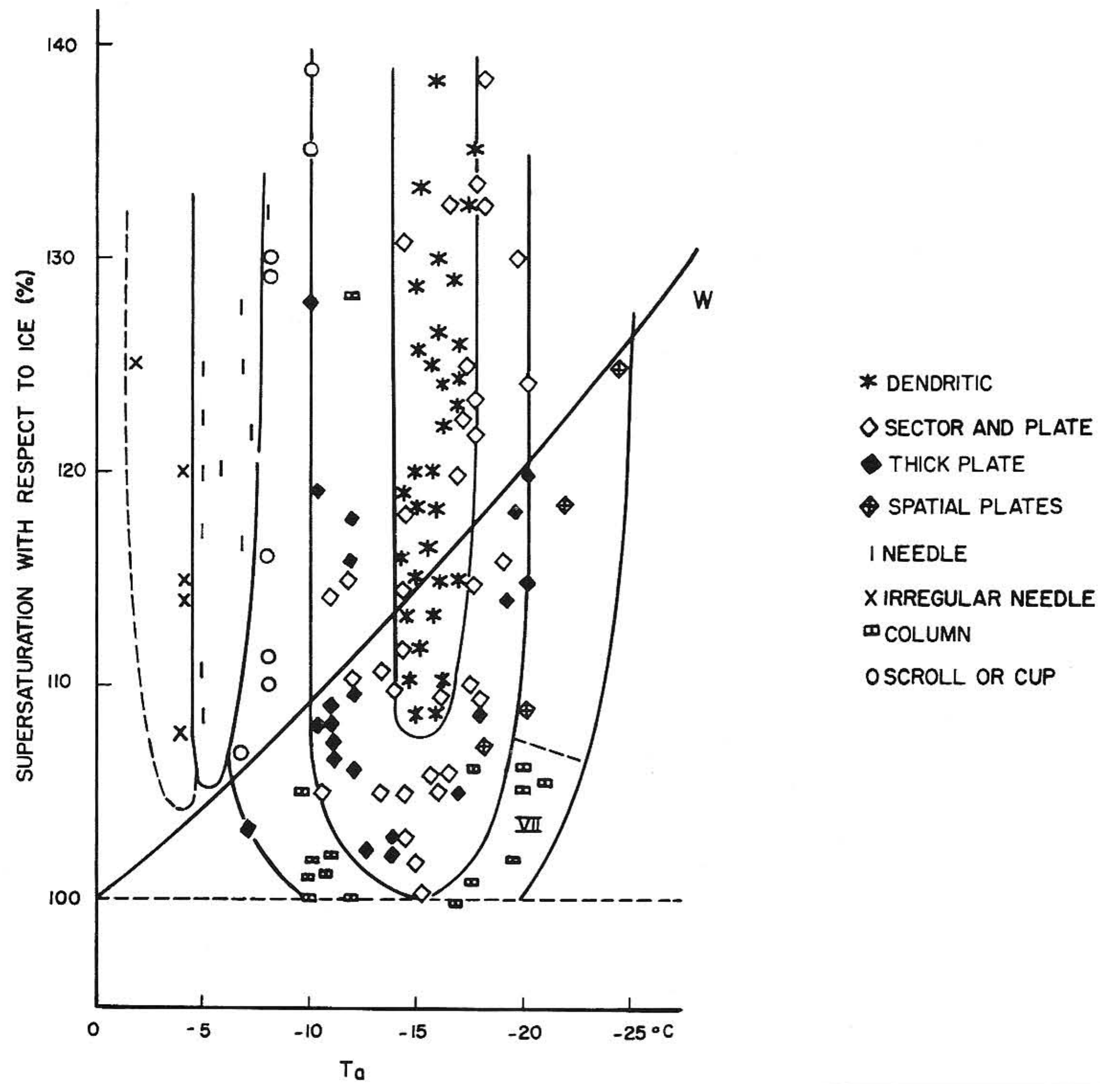

Fig. 8. Crystal growth habitats plotted as supersaturation with respect to ice (%) versus temperature in degrees C. The curve marked "W" gives supersaturation with respect to ice in a water-saturated environment. From Byers (1965), pg 133.

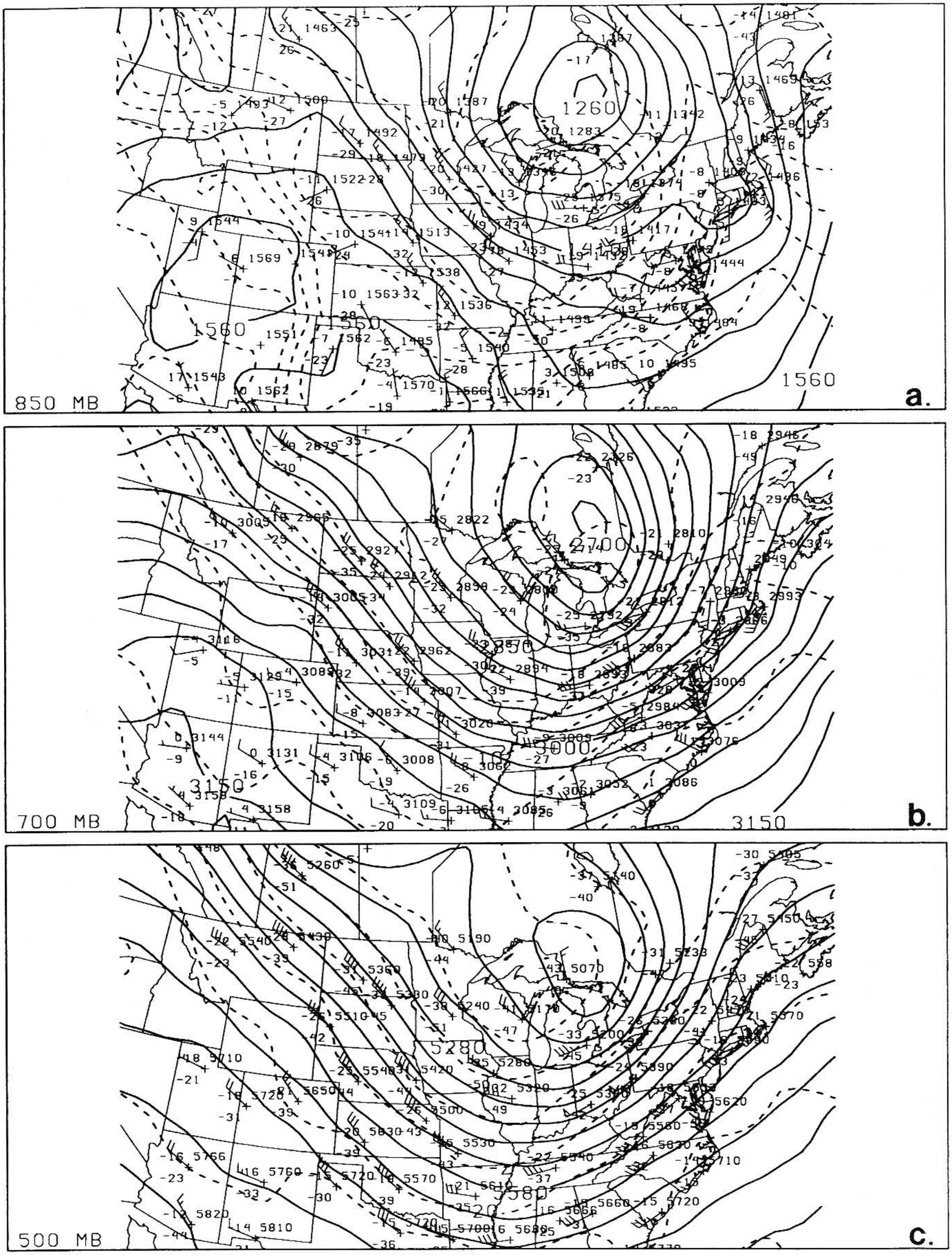

Fig. 9. Same as Fig. 2, except for 0000 UTC 10 December 1995.

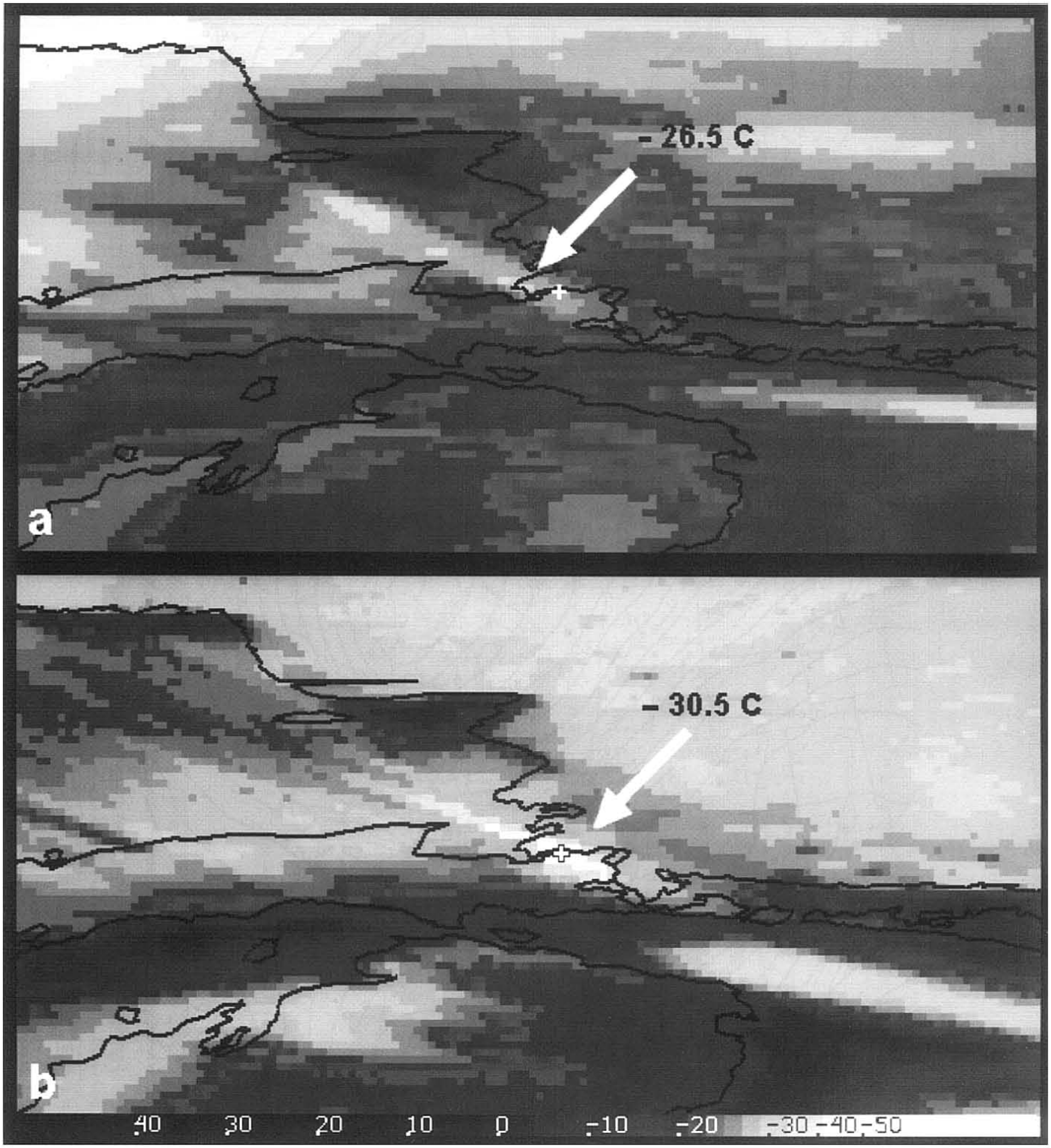

Fig. 10. Average of brightness counts from GOES-8 10.7 μm images for the period a) 1145 UTC through 1745 UTC 10 Dec 1995, and b) 0545 UTC through 1145 UTC 11 Dec 1995. Gray scale represents temperatures in degrees C. Minimum brightness temperatures in the vicinity of Y62 are as indicated.

sistent cold top region further west, but that snow would have been falling into the lake.

Though infrared imagery may be useful in identifying active cores within LES bands, the correlation between satellite-derived cloud top temperatures and snowfall rates is almost never a direct one. Reinking et al. (1993) and Byrd et al. (1991), concluded that most LES band-proximity soundings show a reasonable correlation between snowfall rate and the depth of the convective boundary layer. However, given similar degrees of over-water static stability, a shallow convective boundary layer within a colder thermal profile can easily produce colder cloud tops than a deep convective boundary layer within a warmer thermal profile. *Thus, care must be taken to NOT ASSUME that colder cloud top temperatures always imply deeper moist convection and, therefore,*

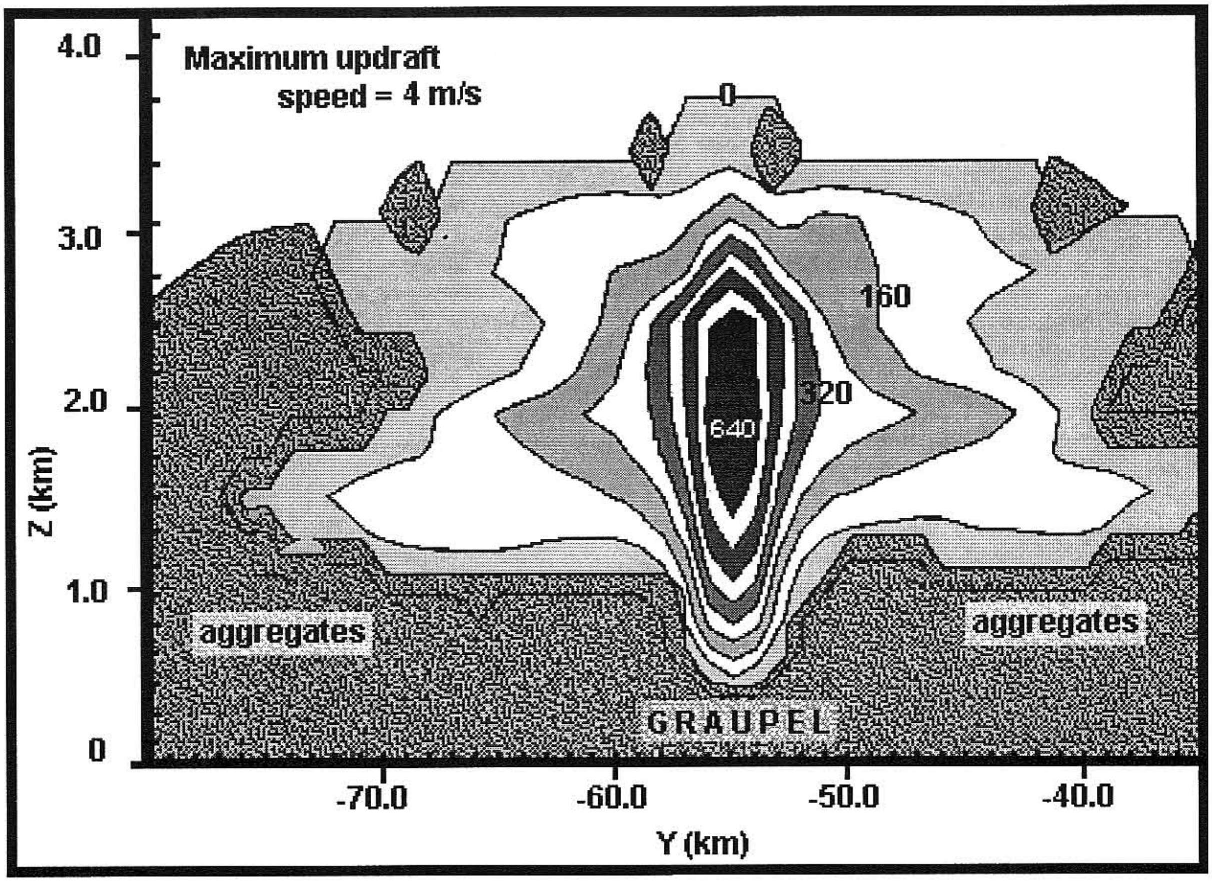

Fig. 11. Results of an idealized cloud model run using the Colorado State University RAMS model for a lake effect snow band. Environmental soundings were from 10 December 1995. This run represents a north-south cross section through an east-west band for a "strong" LES event (maximum updraft speed = 4 m s^{-1}). Solid regions are cloud liquid water with contour intervals of 80 x 10^{-3} gm kg^{-1}. Stippled area shows all ice regions of the storm. The smaller ice areas at cloud top contain less than or equal to 20 x 10^{-3} gm kg^{-1} liquid water equivalent.

greater snowfall rates. On the other hand, while lower satellite-derived cloud top temperatures do not necessarily correlate directly to increased snowfall rates, they may be used by forecasters in conjunction with observed and model-forecast temperature profiles to make more accurate estimates of the depth of the convective boundary layer, and thus to infer snowfall intensity within LES bands. For example, 13 inches of snow occurred at Y62 during the period associated with the 6-h average image in Fig. 10a. Note that the lowest average cloud top temperature associated with the band just upstream of Y62 is -26.5C corresponding to a height of 3-3.5 km (see Fig. 7b). Contrast that with the lowest average cloud top temperature measured during the period associated with the 6-h average image in Fig. 10b. A total of 5 inches fell at Y62 in that 6-h period, with the lowest cloud top temperature measured at -30.5C corresponding to a height of 2-3 km.

4. 3.9 μm Imagery and LES Bands

The 3.9 μm channel on the GOES imager senses both emitted and reflected radiation. At night, the reflected component disappears, and the signal consists solely of energy emitted in the wavelength range of 3.78 - 4.03 μm. A characteristic of radiation from clouds at this wavelength makes the channel extremely useful for sensing water clouds or fog. Specifically, the emissivity for water clouds is less at 3.9 μm than at 10.7 μm. Thus, by subtracting the brightness temperature at 3.9 μm from that at 10.7 μm, clouds with water droplets can be readily identified (at night). This technique forms the basis for the so-called "fog product" received at various NWS offices around the country.

Analysis of dual-channel "difference images" for the Lake Superior LES band (not shown) revealed that the coldest cloud tops during the heavy snow periods were actually mixtures of supercooled water and ice. A few idealized cloud model simulations were made (see acknowledgments) using the Regional and Atmospheric Modeling System (RAMS) mesoscale model (Pielke et al. 1992) which was developed at Colorado State University. Preliminary results indicate that deeper LES clouds, with stronger updrafts (4 m s^{-1} for the test simulations conducted), produce primarily graupel or rimed-dendrites in the vicinity of the storm's updraft. In the layer at and near cloud top, the model produced large concentrations of supercooled water which — after two to three hours — became mixed with ice crystals (Fig. 11). For shallower clouds, with weaker updrafts (0.6 m s^{-1}), the model produced very little graupel. There was more purely dendritic-type growth in and near the updraft, much lower concentrations of supercooled water throughout the cloud depth, and about one-third the amount of liquid water near the top of the cloud. The resultant precipitation was composed almost entirely of ice crystal aggregates. These tentative results may explain the mixture of supercooled water and ice found on the dual-channel imagery for intense LES bands over lakes. They also illustrate why cloud tops a few kilometers inland (where buoyancy is less) often seem to convert primarily to ice. The weakening of convective updrafts and a change in crystal structure occurs frequently, and has been documented in other modeling and observational studies (e.g., Jiusto and Weickmann 1973 and Murakami et al. 1994). One might also expect to find dendritic snowfall on the edges of strong LES bands, and graupel or rimed aggregates near the center, though no observations to confirm this hypothesis were made for this case. It is important to note here that for extremely intense LES bands over water, cloud tops may convert to ice (as seen on 3.9 μm imagery) if and when cirrus anvils develop.

More sophisticated model simulations are being planned to coincide with cases having archived proximity sounding data and GOES-8 satellite imagery. These studies may prove useful in helping to understand the microphysics occurring within active LES bands, and help define how best to use the 3.9/10.7 μm, dual-channel imagery in the future. A daytime dual-channel product is also being investigated in this regard.

5. Summarizing Remarks

A major lake effect snow event occurred at Sault Sainte Marie, Michigan between 8 December and 11 December 1995. The total snow accumulation was 63 inches as measured at the National Weather Service observing site in Sault Sainte Marie, Michigan (Y62). This study looks at post-analyses of GOES-8 satellite imagery and in-situ radiosonde data which together provide insight into the storm's evolution. The event can be conveniently divided into two distinct organizational segments; a southeasterly flow segment off Lake Huron, and a west-northwesterly flow segment off Lake Superior.

The southeasterly flow segment began in the evening hours of 8 December in advance of an approaching cold front and surface low over the upper Mississippi valley region. In the hours preceding the onset of snow at Y62, visible satellite imagery showed a developing mid-lake LES band over Lake Huron. The band was greater than 100 nm in length. Although the band stayed south of Y62 most of 8 December, animated visible imagery revealed it to be moving steadily northward as over-water surface winds gradually increased and became more southeasterly. Most of the band's afternoon movements could be viewed with visible imagery through an advancing layer of thin cirrus clouds. However, tracking became impossible after dark due to the fact that the GOES 10.7 μm channel (a window channel used for nighttime viewing) only "sees" a few centimeters into the cold cirrus. Objects beneath the cirrus deck are completely blocked from view. Unfortunately, moderate to heavy snowfall began at Sault Sainte Marie right at dusk on 8 December, when visible imagery could no longer be used. The snowfall increased throughout the night with the gradual approach of the surface front. By the end of this segment (late morning of 9 December 1995), 24.7 inches of snow had fallen at Y62.

Following a 19 hour respite, west-northwesterly, low-level flow developed across the region, and the second segment of the event began. Lake effect snow began in the early morning hours of 10 December and continued through the morning of 11 December, resulting in an additional 32 inches of snow at Y62. Satellite imagery revealed several interesting features during this portion of the event, especially during the morning hours of 10 December 1995. Of particular interest is the prominent role played by topography in modulation of the intensity and location of LES bands. This included significant air mass modification and destabilization by upstream lakes, and the apparent role of upwind and downwind bay features (or other shoreline irregularities) in the development of persistent and dominant LES bands.

Satellite imagery was useful in a variety of other ways, including: 1) determination of cloud top temperature to compare with the lake surface temperature and sounding data for buoyancy and boundary layer depth estimation, 2) positioning the lake effect band in the absence of radar, 3) locating the most active convection in the line to infer locations with the highest snowfall rates, and 4) using the 3.9 μm imagery to identify active LES bands with detectable liquid water near cloud top. Results from this study have shown how a combination of 3.9 μm satellite imagery and mesoscale computer model output may one day lead to a new and greater understanding of the kinematics and microphysics occurring inside LES bands, with potential for improvements in the short range forecasting of lake effect snowfall accumulations.

Acknowledgments

This research was conducted under NOAA Grant #NA37RJ0202. The authors would like to acknowledge the many useful comments made over the course of several drafts by Lewis D. Grasso (CIRA). Dr. Grasso also provided the idealized model results discussed in the text. Thanks are due to James LaDue at the NOAA/NWS OSF/OTB, Norman, Oklahoma for his insightful comments on the evolution of LES events, and to Dave Watson (CIRA) and Darin Figurskey (NOAA/NWS Detroit, Michigan) for their data collection efforts. Thanks are also due to *National Weather Digest* reviewers as well as several "informal" reviewers for their helpful comments and suggestions. Finally, we would like to acknowledge the Great Lakes Environmental Research Laboratory whose home page at "www.glerl.noaa.gov" became a useful source for lake surface temperatures.

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References

Braham. R.R., Jr., 1990: Snow particle size spectra in lake effect snows. *J. Appl. Meteor.*, 29(3), 200-207.

Byers, H.R., 1965: *Elements of Cloud Physics*. The University of Chicago Press, 191 pp.

Byrd, G.P., R.A. Ansett, J.E. Heim, and D.M. Usinski, 1991: Mobile sounding observations of lake-effect snowbands in western and central New York. *Mon. Wea. Rev.* 119 (9), 2323-2332.

Chang, S.S., and R.R. Braham, Jr., 1991: Observational study of a convective internal boundary layer over Lake Michigan. *J. of the Atmos. Sci.*, 48(20), 2265-2279.

Dockus, D.A., 1985: Lake effect snow forecasting in the computer age. *Nat'l. Wea. Dig.*, 10(4), 5-19.

Grumm, R.H., 1993: Characteristics of surface cyclone forecasts in the aviation run of the global spectral model. *Wea. Forecasting*, 8(1), 87-112.

Jiusto, J.E., and H.K. Weickmann, 1973; Types of Snowfall. *Bull. Amer. Meteor. Soc.*, 54(11), 1148-1162.

Krauss, T.W., R. Bruintjes, J. Verlinde, and A. Kahn, 1987: Microphysical and radar observations of seeded and non-seeded continental cumulus clouds. *J. Clim. and Appl. Meteor.*, 26(5), 585-606.

Kristovich, D.A.R., and R.A. Steve, III, 1995: A satellite study of cloud-band frequencies over the Great Lakes. *J. of Appl. Meteor.*, 34, 2083-2090.

MacDonald, N.J., 1976: On the apparent relationship between convective activity and the shape of 500 mb troughs. *Mon. Wea. Rev.,* 104(12), 1618-1622.

Murakami, M., T.L. Clark, and W.D. Hall, 1994: Numerical simulations of convective snow clouds over the Sea of Japan; Two-dimensional simulations of mixed layer development and convective snow cloud formation. *J. Meteor. Soc. of Japan*, 72(1), 43-61.

Nakaya, U., 1954: *Snow Crystals: Natural and Artificial.* Harvard University Press, Cambridge, Massachusetts, 510 pp.

Niziol, T.A., 1987: Operational forecasting of lake effect snowfall in western and central New York. *Wea. Forecasting*, 2(6), 310-321.

_________, W.R. Snyder, and J.S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part IV: Lake Effect Snow. *Wea. Forecasting*, 10(1), 61-77.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.*, 56 (5), 527-530.

Pielke, R.A., W.R. Cotton, R.L. Walko, C.J. Tremback, W.A. Lyons, L.D. Grasso, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J. Lee, and J.H. Copeland, 1992: A comprehensive meteorological modeling system — RAMS. *Meteor. and Atmos. Phys.*, 49, 69-91.

Reinking, R.F., R. Caiazza, R. Kropfli, B. Orr, B. Martner, T. Niziol, G. Byrd, R. Penc, R. Zamora, J. Snider, R. Ballentine, A. Stamm, C. Bedford, P. Joe, and A. Koscielny, 1993: The Lake Ontario Storms Project. *Bull. Amer. Meteor. Soc,* 74(10), 1828-1849.

Rothrock, H.J., 1969: An aid in forecasting significant lake effect snows. *ESSA Tech. Memo. WBTM CR-30*, Nat'l. Wea. Service Central Region, Kansas City, MO, 12 pp.

Sanders, F., 1987: Skill of NMC operational dynamical models in prediction of explosive cyclogenesis. *Wea. Forecasting*, 2(6), 322-336.

Smith, B.B, and S.L. Mullen, 1993: An evaluation of sea level cyclone forecasts produced by NMC's nested-grid model and global spectral model. *Wea. Forecasting*, 8(1), 37-56.