AN EXAMINATION OF AN INTENSE WEST-EAST ORIENTED LAKE-EFFECT SNOW BAND OVER SOUTHEAST LOWER MICHIGAN

Michael S. Evans[1] and Richard B. Wagenmaker

NOAA/National Weather Service
Detroit, Michigan

Abstract

On several occasions each year, an intense west-east oriented lake-effect snow band develops over lake Michigan, and extends east for a distance of over 200 km, affecting areas in southeast lower Michigan that are usually east of the traditional lower Michigan "snow belt". Localized snow accumulations of 50 to 150 mm (2 to 6 in.) frequently occur over southeast Michigan in these events. Radiosonde observations associated with seven sample cases are presented, indicating that these bands typically occur under conditions that are known to be favorable for lake-effect snow; i.e., a lake surface / 850-mb temperature difference greater than or equal to 13°C, limited low-level directional wind shear, ample low-level moisture, and an inversion height of at least 1 km. A more detailed case study from one of these events is also presented. It is shown that an intense snow band evolved in association with the development of a strong lower-tropospheric convergence zone across southern lower Michigan. It is hypothesized that the band formed when westerly wind around the southern end of Lake Michigan acquired a strong ageostrophic flow component resulting from ground-produced frictional effects in the shallow, cold airmass southeast of the lake, and also due in part to an isallobaric contribution that naturally occurs over southern Michigan whenever a cold westerly flow traverses Lake Michigan. This subsequently resulted in a significant lake-induced frontogenetic process, with enhanced convergence and upward vertical motion developing along a boundary between the shallow, stable, strongly sheared airmass southeast of the lake, and a more well-mixed airmass directly downwind of the lake. Additionally, an examination of NCAR/Penn State MM5 numerical weather prediction model forecasts for this event indicated that the MM5 was able to simulate the relatively narrow convergence zone associated with the snow band. However, model difficulties with the forecast thermal structure of the lower-troposphere resulted in significant errors with the forecast placement of the band. Nonetheless, it is suggested that there is much potential value to be gained from a local model in predicting the development and trends of certain features that may be critical to formation of these significant weather phenomena.

[1]Current affiliation, NOAA/National Weather Service Office, State College, PA

1. Introduction

Lake-effect snow occurs across the lower peninsula of Michigan numerous times each winter when a southwest through northwest flow of cold air occurs across Lake Michigan. Typically, significant snow accumulations are confined to the western half of the state, close to the lake. However, on several occasions each year, a west-east oriented lake-effect snow band develops over the southern third of the lake, and extends east over 200 km, bringing significant snow to portions of southeast Michigan that are usually east of the traditional lower Michigan "snow belt" regions. In cases where a band remains relatively stationary, localized snowfalls of 50 to 150 mm (2 to 6 in.) can occur over southeast Michigan in less than 12 hours, with even heavier amounts to the west across the traditional "snow belts". The most favored part of southeast Michigan for this type of band is the area directly east of the widest part of Lake Michigan. The threat area includes several major Michigan cities (Flint, Pontiac, Ann Arbor and Detroit) that collectively constitute a population approaching five million. In the following sections, this paper will present a brief and limited background climatology as context for a more detailed examination of a special case of an intense west-east oriented lake-effect snow band that occurred on 10-11 January 1997.

2. Background

Local experience with these events indicate that they occur under typical conditions known to be favorable for lake-effect snow. These include: 1) 850-mb temperature / lake surface temperature differential (ΔT) $\geq$ 13°C, 2) cyclonic lower-tropospheric wind with limited directional shear through the convective boundary layer (CBL), 3) lower-tropospheric moisture sufficient for moist convection, and 4) a subsidence inversion located at least 1 km above the surface (Rothrock 1969; Dockus 1985; Niziol et al. 1995). In addition, strong ($\geq$ 20 knots) west to northwest winds are typically present across southern Michigan at the 850-mb level.

For this particular study, seven events over southeast Michigan were identified and examined during the period from January 1995 through December 1997 in order to identify their common characteristics. In order to qualify, each event had to be associated with a persistent (lasting at least three hours), west-east oriented lake-effect snow band over southeast Michigan as indicated by

Table 1. A summary of seven west-east oriented lake-effect snow bands in southeast Michigan from 1995 to 1997.

Date	Maximum 24-hr Snowfall	Location
1/3/95	102 mm (4.0 in.)	Fenton (Genessee Co.)
3/26/96	58 mm (2.3 in.)	White Lake (Oakland Co.)
11/11/96	58 mm (2.3 in.)	Ann Arbor (Washtenaw Co.)
1/06/97	127 mm (5.0 in.)	Chelsea (Washtenaw Co.)
1/10/97	140 mm (5.5 in.)	Owosso (Shiawassee Co.)
1/11/97	64 mm (2.5 in.)	Milford (Oakland Co.)
11/12/97	71 mm (2.8 in.)	Howell (Livingston Co.)

WSR-88D radar data. In addition, each event must have been associated with localized 24-hour snowfalls of at least 50 mm (2 in.) somewhere in southeast Michigan. Radiosonde observations from the nearest sounding site were then collected for each example in order to identify common characteristics among the events. Table 1 shows the date of each event, and the maximum 24-hour snowfall amount/location associated with each event. Table 2 shows selected radiosonde data observed from the White Lake, Michigan (DTX) site associated with each event in Table 1.

Many of the conditions that are typically present when intense west-east oriented lake-effect snow bands occur across southeast Michigan are highlighted in Table 2. Despite the limited sample, the results are consistent with those from other studies of lake-effect snow events (Rothrock 1969; Niziol 1987). The radiosonde observations used in this study were at the times most closely corresponding to the most intense snow bands as indicated on the KDTX WSR-88D data. Table 2 indicates that 850-mb temperatures ≤-10°C occurred in each case, with the warmer cases occurring at times of the year when southern Lake Michigan water temperatures are climatologically warmer. These 850-mb temperatures were then compared to climatological water temperatures to create a proxy for over-water stability (ΔT). Ideally, observed water temperatures would be used for this purpose, but this data was not available for the study. Instead, it was decided to employ a "projected ΔT" utilizing the climatological water temperatures to estimate over-water stability. In all cases, "projected ΔT" values between 850 mb and climatological lake surface temperatures were from 16°C to 21°C. These findings are consistent with actual ΔT values associated with heavy snowfalls in studies by Rothrock (1969), Holroyd (1971), and Dockus (1985). In all but one case, lapse rates between 925 mb and 850 mb were 4.0° C km^{-1} to 5.6° C km^{-1}, which constitute rates that are moist adiabatic or steeper (at the relatively colder temperatures associated with the cases in this study). The top of the CBL was above 850 mb for all cases and above 700 mb for 2 of the 7 cases. CBL

Table 2. A summary of radiosonde observations from White Lake, Michigan (DTX) for each of the seven events listed in Table 1. Observations are for the date and time (UTC) of the nearest snow band occurrence and its maximum intensity (as indicated on the KDTX WSR-88D) and for 925-mb, 850-mb, and 700-mb temperature (degrees C), wind direction (degrees), wind speed (knots), and relative humidity (%). Also listed are 925-mb to 850-mb lapse rates (degrees C km^{-1}), normal southern Lake Michigan water surface temperature (Tw.; degrees C), inversion height (meters), and "projected" lake surface to 850-mb temperature difference (ΔT) (degrees C).

Date Time	1/3/95 1200	3/26/96 1200	11/12/96 0000	1/6/97 1200	1/10/97 1200	1/11/97 1200	11/12/97 1200
925-mb temp	-10.3	-12.9	-6.3	-11.1	-8.3	-13.4	-5.6
850-mb temp	-14.5	-17.5	-11.7	-16.7	-12.3	-15.9	-11.3
700-mb temp	-20.9	-22.9	-22.7	-10.5	-19.7	-19.9	-22.5
925-mb wind	270/20	275/15	295/23	280/25	270/20	270/23	280/10
850-mb wind	270/31	260/22	300/19	280/37	280/28	290/36	300/22
700-mb wind	265/53	245/53	290/23	285/52	270/36	290/44	300/16
925-mb RH	97	97	72	77	92	92	68
850-mb RH	97	97	92	98	95	82	80
700-mb RH	38	25	95	67	89	88	84
925-850 lapse rate	4.2	4.6	5.4	5.6	4.0	2.5	5.7
Normal Tw.	4.4	2.7	8.7	4.2	4.1	4.0	8.7
CBL height	1524	1645	2865	1005	3353	1920	2682
ΔT 850-lake sfc	18.9	20.2	20.4	20.9	16.4	19.9	20.0

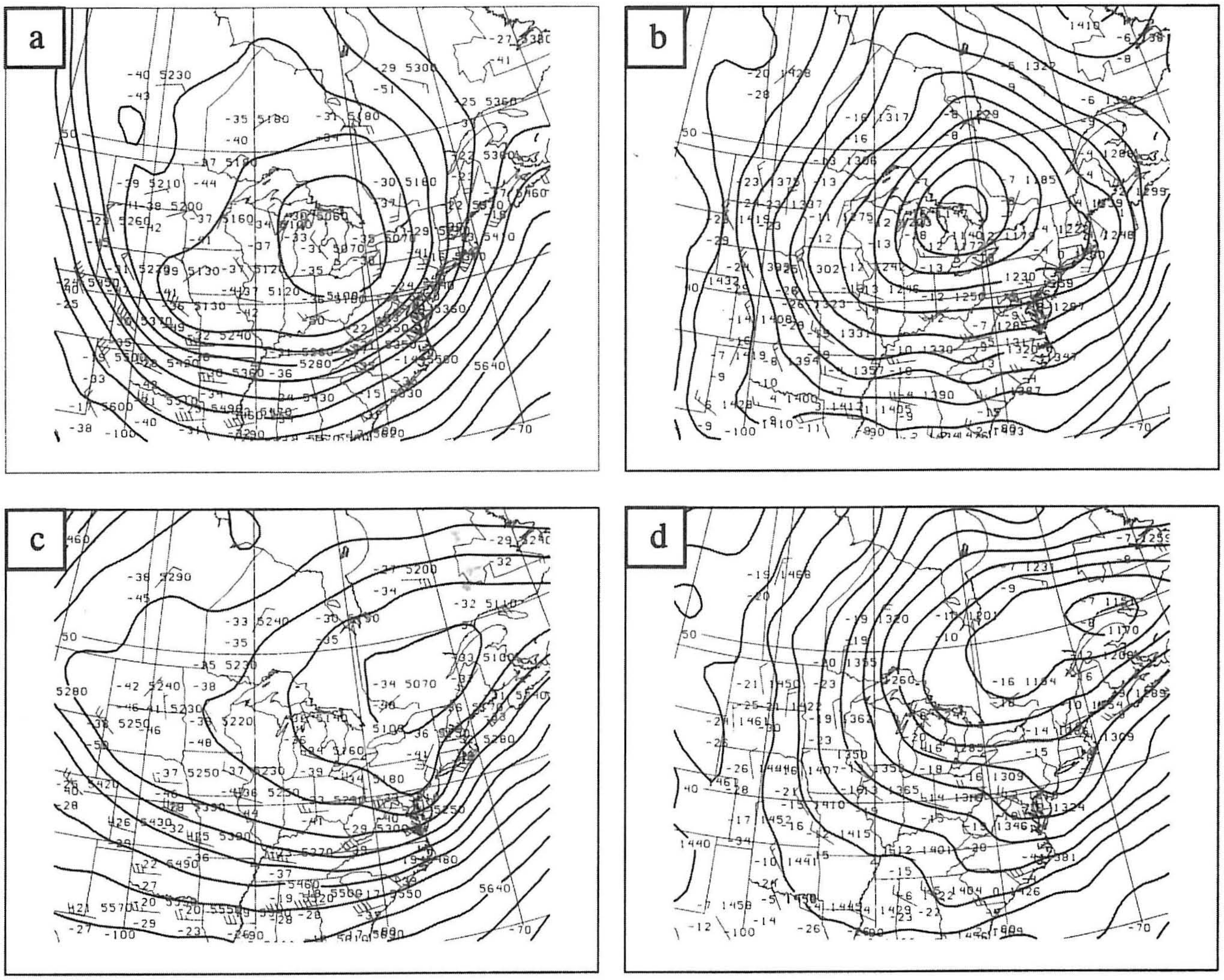

Fig. 1. Contoured geopotential heights (m) from the 00-h MM5 forecast and observed geopotential height (m), temperature (°C), and wind (kt) plots at: a) 500-mb level valid 1200 UTC 10 January 1997, b) 850-mb level valid 1200 UTC 10 January 1997, c) 500-mb level valid 1200 UTC 11 January 1997, and d) 850-mb level valid 1200 UTC 11 January 1997.

heights ranged from 1.0 km above ground level (AGL) to 3.4 km AGL. These findings are also consistent with accepted minimum criteria for significant lake-effect snows (Byrd et al. 1991). Observed winds from 925 mb through 700 mb ranged from 260° to 300° with speeds of ≥ 20 knots in all cases. Directional shears within the CBL were also found to be minimal. The directional difference between wind at 925 mb and wind at 850 mb was always observed to be 20 degrees or less. Lastly, 925-mb relative humidity was observed to be ≥ 80 percent for 4 of the 7 cases, 850-mb relative humidity was observed to be ≥ 80 percent for all cases, and 700-mb relative humidity was ≥ 80 percent for 4 of the 7 cases. These findings are consistent with those of Evans (1996) which showed that occurrences of heavy lake-effect snowfall in southwest lower Michigan were highly dependent on over-water lower tropospheric lapse rate and sufficient 850-mb relative humidity values.

In addition to these characteristics, it was noted that these events were generally accompanied by a persistent west-east lower tropospheric convergence zone, with southwest winds to the south of the convergence zone, and west to northwest winds to the north. It has been hypothesized (Wagenmaker and Smith 1995) that this convergence zone develops when west to east air-parcel trajectories result in a relatively well-mixed boundary layer wind profile (westerly) downwind of Lake Michigan, while to the south, the boundary layer is not as well mixed, and a larger ageostrophic component (southwesterly) to the lower-tropospheric or near-surface wind occurs. It is believed that this process is crucial for initiating and maintaining the snow bands as far east as southeast Michigan. The processes responsible for the formation and maintenance of this feature are discussed further in section 3.

3. Examination of an Intense West-East Lake-Effect Snow Band, 10-11 January 1997

In this section, one of the cases from section 2 will be examined in greater detail. Model output from The Pennsylvania State University - National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) (Anthes et al. 1987; Grell et al. 1995) will be compared with observations to evaluate that model's performance during the event. A discussion will also be presented on the physical mechanisms responsible for this event.

a. Synoptic-scale and radar features

Figures 1a and 1b show 500-mb and 850-mb level data for the region at 1200 UTC 10 January 1997. At the surface, low pressure was located over Lake Huron, with a westerly flow in its wake across lower Michigan (Fig. 2a). Surface temperatures across southern Michigan, northern Indiana and northern Ohio were mostly from -5 °C to -8 °C (upper teens to low 20s Fahrenheit). Examination of the surface wind field indicates that a convergence zone was developing over far southern lower Michigan, with southwest flow to the south, and westerly flow to the north. At the 850-mb level, winds at DTX were from the west at 25 knots, and the temperature was -12°C. The 1200 UTC 10 January 1997 DTX sounding (Fig. 3a) indicated high relative humidity through the lower troposphere, with no significant temperature inversions through the lower atmosphere. Lake-effect snow was widespread across Michigan at this time.

Radar imagery from 1200 UTC 10 January 1997 (Fig. 4a) indicated a significant, west-east oriented snow band located roughly along Interstate-94, from Jackson (JXN) to Ann Arbor (ARB) to Detroit (DTW) with light flurries scattered across the rest of southeast Michigan. By 1800 UTC on the 10th the band had broadened and intensified (Fig. 4b), and had shifted north to a position covering the area from Pontiac/White Lake (DTX) north to Flint (FNT) and Lansing (LAN). Again, little if any precipitation was occurring on either side of the band.

Figure 5 shows the surface plots over the area at 1800 UTC 10 January 1997. Note the well-defined east-west convergence zone extending across southern Michigan. By 0000 UTC 11 January 1997 (Fig. 4c), the band was rapidly losing its structure, weakening, and becoming very broad. During the subsequent overnight hours, the band gradually disintegrated into weak multiple bands. Snow accumulations of 25 to 100 mm (1 to 4 in.) were widespread across southeast Michigan on the 10th as the

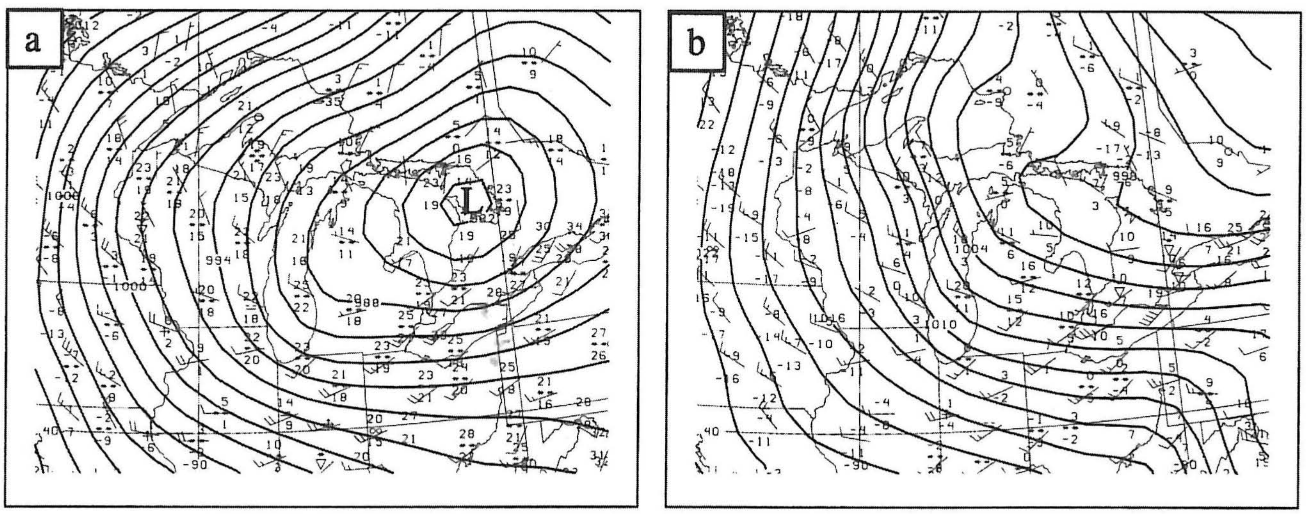

Fig. 2. Surface plots and isobaric analysis (2 mb interval) valid at: a) 1200 UTC 10 January 1997 and b) 1200 UTC 11 January 1997.

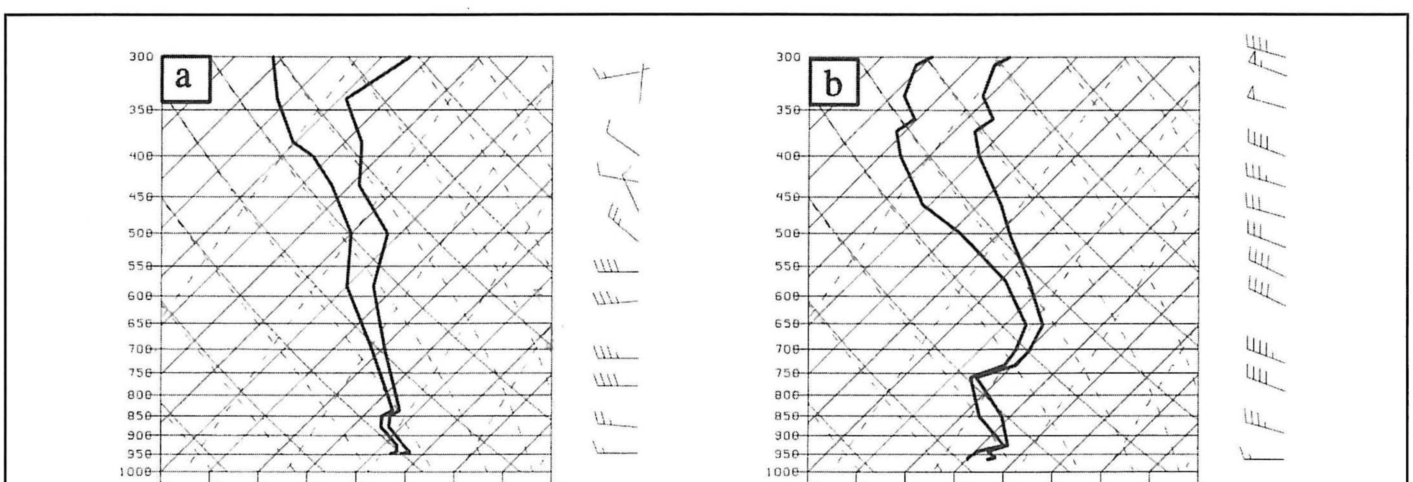

Fig. 3. Soundings from radiosonde observations at White Lake, Michigan (DTX) valid at: a) 1200 UTC 10 January 1997 and b) 1200 UTC 11 January 1997.

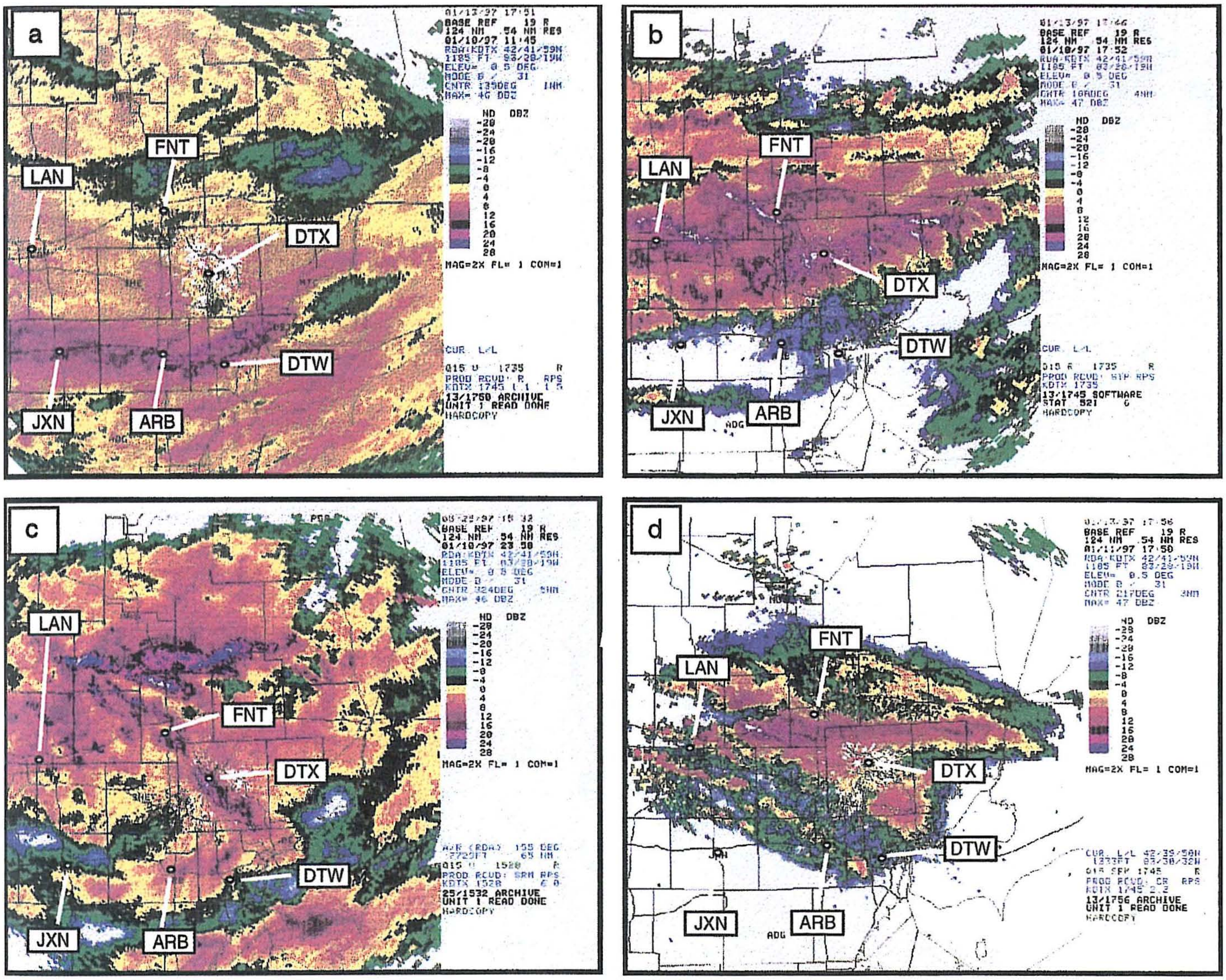

Fig. 4. KDTX WSR-88D radar reflectivity (dBZ) images for: a) 1200 UTC 10 January 1997, b) 1800 UTC 10 January 1997, c) 0000 UTC 11 January 1997, and d) 1800 UTC 11 January 1997. Locations are labeled: FNT - Flint, DTX - White Lake/Pontiac, DTW - Detroit, ARB - Ann Arbor, JXN - Jackson, and LAN - Lansing.

snow band migrated north. The heaviest snow fell in a west-east band through the Flint area, where 100 to 140 mm (4 to 5.5 in.) snowfall totals were recorded during the afternoon.

Figures 1c and 1d show 500-mb and 850-mb level data for 1200 UTC 11 January 1997. By that time, the surface low-pressure center was located far to the northeast of Lake Huron, with a west to northwest gradient-flow continuing in the wake of the low through a deep layer of the troposphere (Fig. 2b). Light southwesterly surface flow was indicated across all of southeast Michigan. The 850-mb temperature at DTX had fallen to -16°C, and a very cold air mass had become established through the lower troposphere, with surface temperatures from -9° to -12°C (10° to 15° F) across southern Michigan, and near -18°C (0°F) farther south, across northern Indiana and Ohio. The 1200 UTC 11 January 1997 DTX radiosonde observation (Fig. 3b) indicated a very shallow stable layer near the ground, then a mixed layer extending to nearly 700

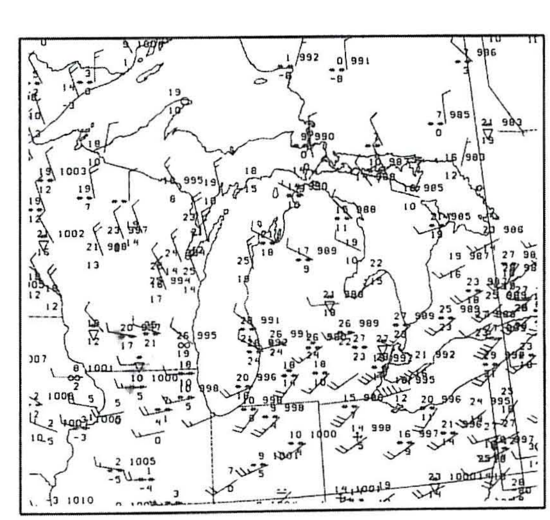

Fig. 5. Plot of surface observations (standard notation) valid at 1800 UTC 10 January 1997.

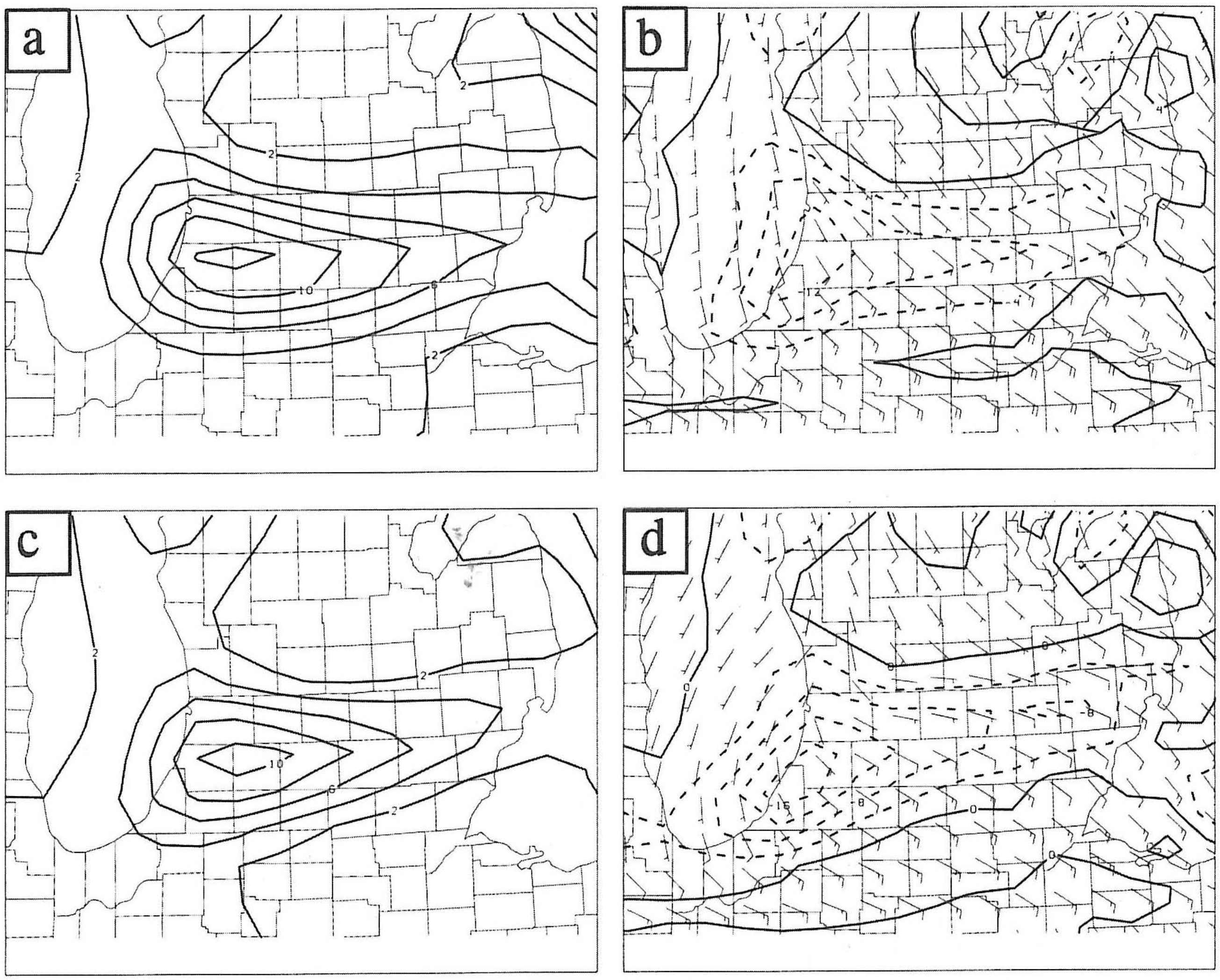

Fig. 6. MM5 18-h forecasts of a) 6-h precipitation (10^{-2} in.) verifying at 1800 UTC 10 January 1997, b) divergence (10^{-4} s^{-1}) and ageostrophic wind (kt) at lowest model sigma verifying at 1800 UTC 10 January 1997. MM5 24-h forecasts of c) 6-h precipitation (10^{-2} in.) verifying at 0000 UTC 11 January 1997, d) divergence (10^{-4} s^{-1}) and ageostrophic wind (kt) at lowest model sigma verifying at 0000 UTC 11 January 1997 (solid isopleths show divergence; dashed isopleths show convergence).

mb (about 1.9 km). The mixed layer was capped by a very pronounced inversion located just below the 750-mb level. The KDTX WSR-88D radar imagery at that time (not shown) indicated weak multiple bands of snow flurries across southeast Michigan with a few pockets of stronger convection north of FNT and LAN. By 1800 UTC on the 11th, an organized west-east oriented snow band had become re-established between DTX and FNT (Fig. 4d). In contrast to the band on January 10th, this band was quite narrow (about 15 km wide) and more transitory. Snow accumulations on the 11th ranged from 25 to 65 mm (1 to 2.5 in.) across the area from near Ann Arbor northward to just south of Flint.

b. Evaluation of NCAR/Penn State MM5 mesoscale numerical weather prediction model output

For this case, output from a locally modified version of the NCAR/Penn State MM5 numerical weather prediction model was utilized for the purpose of: 1) evaluating model utility and 2) assessment of physical processes associated with this event. This version is a non-hydrostatic model with a sigma terrain-following vertical coordinate system. The model contains 23 vertical levels, a 30 km horizontal grid spacing within its inner grid domain and a 90 km grid spacing within its outer grid. The inner grid domain contains the entire Great Lakes area, extending roughly from Minnesota southeast to western Pennsylvania. The model contains 60 grid points over Lake Michigan. The convective parameterization used in the model, a locally modified Kain-Fritsch scheme (Kain and Fritsch 1990), is well-suited for simulating the shallow moist convection associated with lake-effect snow since the scheme only requires a minimum cloud height of 1.0 km and a minimum convective available potential energy (CAPE) of 1 J kg^{-1} in order to produce convective precipitation (Mann 1999). A Blackadar parameterization scheme (Grell et al. 1995) is applied to simulate boundary layer physical processes.

In this case, the MM5 was able to simulate, to a degree, the most important mesoscale feature associated with the event, namely the convergence zone that devel-

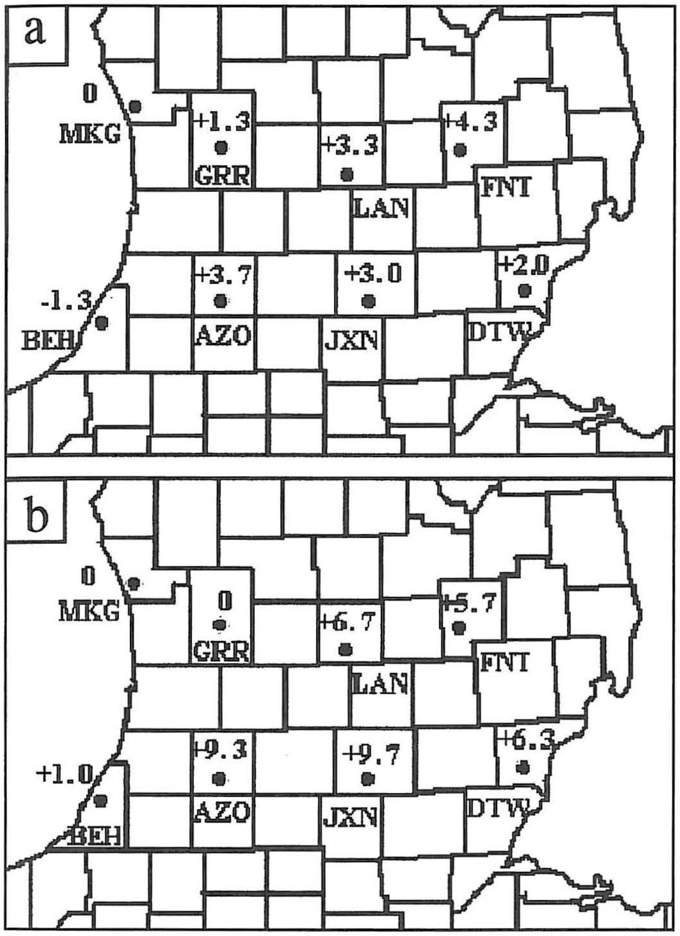

Fig. 7. Plots of mean differences between observed temperature (°F) and a) 12-h and b) 24-h model forecasts from 3 cycles of the MM5 (0000 UTC 10 January, 1200 UTC 10 January, and 0000 UTC 11 January 1997). The sites where data is plotted are Muskegon (MKG), Benton Harbor (BEH), Grand Rapids (GRR), Kalamazoo (AZO), Lansing (LAN), Jackson (JXN), Flint (FNT) and Detroit (DTW).

oped across southern lower Michigan. Figures 6a-d show, from the 0000 UTC 10 January 1997 (hereafter referred to as DD/HH UTC) cycle of the MM5, 18-hour and 24-hour forecasts of wind divergence at the lowest model sigma level, and 6-hour accumulated precipitation verifying at 1800 UTC 10 January and at 0000 UTC 11 January. Note the band of convergence and the associated area of precipitation extending from southern Lake Michigan east across southern lower Michigan. By contrast, Eta model forecasts (80 km grid spacing) for this time indicated only a broad area of light precipitation (not shown), with no tendency for any banding or focusing of the precipitation. A comparison between the 0000 UTC 10 January MM5 lowest sigma level wind divergence and quantitative precipitation forecasts (QPF) with the radar data shown in Fig. 4 indicates that while the MM5 correctly forecast the existence of the band, and correctly forecast that the band would drift north, the band was forecast by the model to occur about 40-50 km too far south. Results from subsequent model cycles also revealed that the model continued to correctly forecast the existence of the convergence zone and its associated snow band, but still continued to forecast the band too far to the south.

A comparison of observed surface temperatures and the MM5 forecast temperatures at the lowest model sigma level (25 meters AGL) also revealed significant differences that were especially pronounced in the shallow cold air south and west of the Great Lakes. For the purposes of this study, and because the lowest 25 meters of the atmosphere is likely reasonably well-mixed in this case, the lowest model sigma-level temperature is assumed an adequate proxy for the model surface temperature. Figures 7a-b show plots of the differences calculated between the MM5 12 and 24-hour forecasts and the observations for eight locations across southern Michigan. The values are average differences taken from three model runs. The results indicate that the MM5 lower-tropospheric temperatures were consistently warmer than the observed surface temperatures at most locations well east of Lake Michigan. Again, the largest differences were noted over south central Michigan, in the area where shallow cold air advecting northeast around the south end of Lake Michigan eventually made farthest northeastward penetration. In particular, at Jackson (JXN), the MM5 24-hour forecasts averaged nearly 10° F warmer than observed surface temperatures over the three model runs.

To examine these anomalies in more detail, Fig. 8 shows a meteorogram of observed temperature and wind direction at DTW and FNT for the period from 1200 UTC through 2200 UTC 10 January 1997. A pronounced temperature decrease was observed during this 10-hour time period, starting just after 1500 UTC at DTW and just after 1800 UTC at FNT. The temperature decrease was also accompanied by a wind shift from west to southwest at FNT. These and other observations from locations in southwest lower Michigan, northern Indiana, and northern Ohio (not shown) indicate that a wind shift accompanying the temperature decrease tracked from south to north across southern Michigan on the 10th and that the heaviest snow fell along and just north of the wind shift. Figure 9 shows a meteorogram comparing the observed temperature at DTW to the MM5 lowest sigma-level temperature forecast at the same location, and also for the period from 1200 UTC through 2200 UTC 10 January 1997. The meteorogram clearly shows that the MM5 was not aggressive enough with its forecast of the timing and the magnitude of the temperature decrease. Lastly, a comparison between observed and model forecast temperature soundings at DTX, located midway between DTW and FNT, (Fig. 10a) implies a reasonably good forecast verifying at 1200 UTC 10 January, when DTX was north of the convergence zone. However, Fig. 10b shows how poorly the lower-tropospheric cooling was forecast by the MM5 at 0000 UTC 11 January, when the band was north of DTX. Also note how shallow the cold-air was at 0000 UTC 11 January, extending upward from the surface only to near 900 mb.

Presented are three potential explanations for the large differences between forecast and observed lower tropospheric temperatures over southern lower Michigan. One possible explanation is that the model was under-forecasting the amplitude of the thermally-

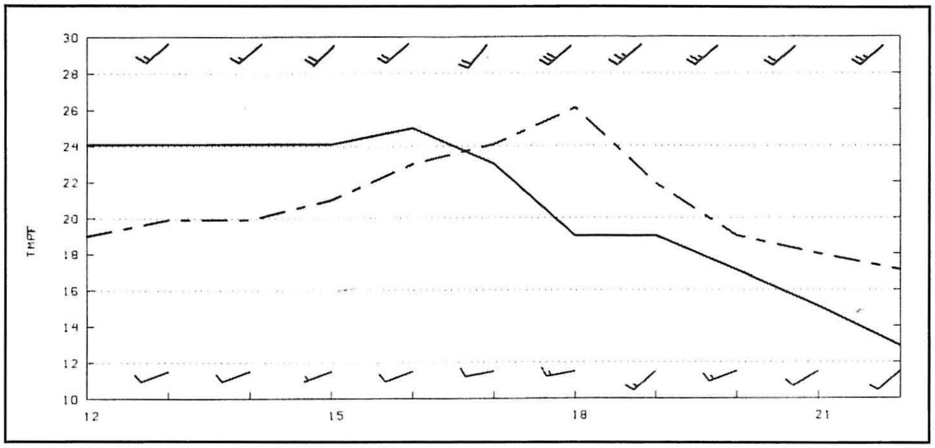

Fig. 8. Times series of observed temperature (°F), wind speed (kt), and direction for Detroit, Michigan (solid and top) and Flint, Michigan (dashed and bottom) for the time period 1200 UTC to 2200 UTC 10 January 1997.

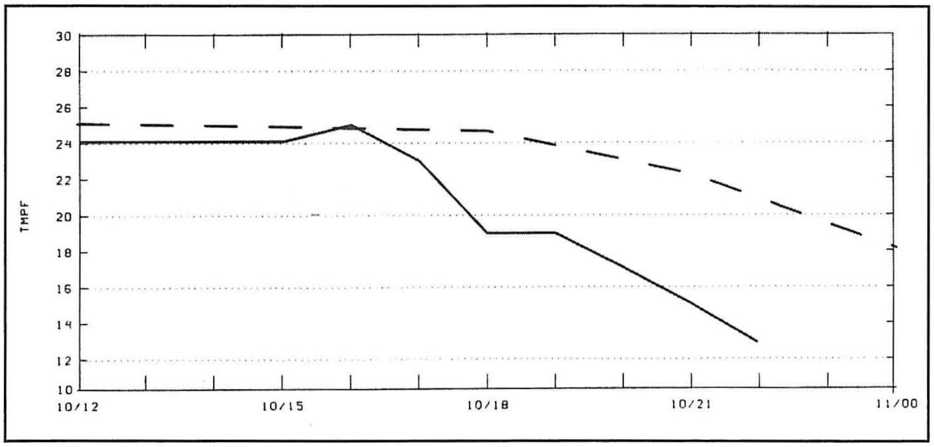

Fig. 9. Time series comparing observed (solid) temperature (°F) and MM5 0000 UTC 10 January 1997 cycle forecast (dashed) temperature (°F) at Detroit (DTW) for the period 1200 UTC 10 January 1997 through 0000 UTC 11 January 1997.

induced lower tropospheric pressure trough that typically forms over or just downwind of Lake Michigan in lake-effect snow environments. This feature normally develops when relatively cold air upstream of the lake advects over the much warmer water surface. Subsequent combinations of sensible and latent heat fluxes across the air-lake interface can be very substantial, exceeding 600 W m^{-2} (Miner et al. 2000). This warming of the surface layer as air passes over the lake produces a dynamical response within the layer by reducing air density and subsequently surface hydrostatic pressure. Thus, the presence of relatively cold air over Lake Michigan in fall and winter will typically induce a lower tropospheric pressure trough over and sometimes immediately downwind of the lake, depending on the strength of the wind and the temperature difference across the air-lake interface.

Under-forecasting the amplitude of this feature could have resulted in the MM5 also under forecasting the degree of southwesterly flow to the east of the trough, and thus would have resulted in an underestimation of the degree of near-surface cold temperature advection into far southern lower Michigan from Indiana and Ohio.

A comparison of observed mean sea-level pressure and the 0000 UTC 10 January MM5 mean sea-level pressure (MSLP) forecasts valid at 1200 UTC and 1800 UTC (not shown) revealed that the MSLP forecasts were 2 to 3 mb too high over much of the region of interest, but with no evident bias toward areas immediately downstream of Lake Michigan. However, since there are no observation points over Lake Michigan, the accuracy of the MM5 forecast surface pressure pattern in this critical region could not be adequately evaluated, nor its possible affect on the forecast surface wind fields.

Temperature differences between the observations and model forecasts with this case also may have been partially the result of poor model initialization of snow cover. The version of the MM5 used for this case initializes with a climatological average snow cover. In this case, the areal extent of the snow cover was larger than the climatological average, since it occurred during the middle of a prolonged cold period, and the Midwest and Ohio Valley regions were completely snow covered. This likely adversely affected the degree of cold air present in the model boundary layers, especially to the south of the Great Lakes region. A last potential source of error could have been a poor model initialization of water temperatures on Lake Michigan. For example, if the water temperature was slightly warmer than the model initialization, the resultant "thermal land breeze" component of the wind near the south end of the lake would have been stronger than forecast, thus resulting in the model again under-forecasting the degree of cold advection into southern lower Michigan.

c. Discussion

Recall from Section 2 that many of these types of lake-effect snow events are associated with a west-east lower-tropospheric convergence zone located over southern Michigan, at the boundary between the well-mixed westerly flow downwind of Lake Michigan, and the southwesterly flow associated with a cold, shallow, stable boundary layer to the south. The figures presented in this paper clearly imply that to be the case for this event. It has also been shown that the MM5 exhibited significant problems resolving the degree of shallow cold air south of the convergence zone, which likely contributed to its misplacement of the convergence zone throughout the event.

Despite some of the problems with the MM5 forecasts, the model still produced a very useful product in that it

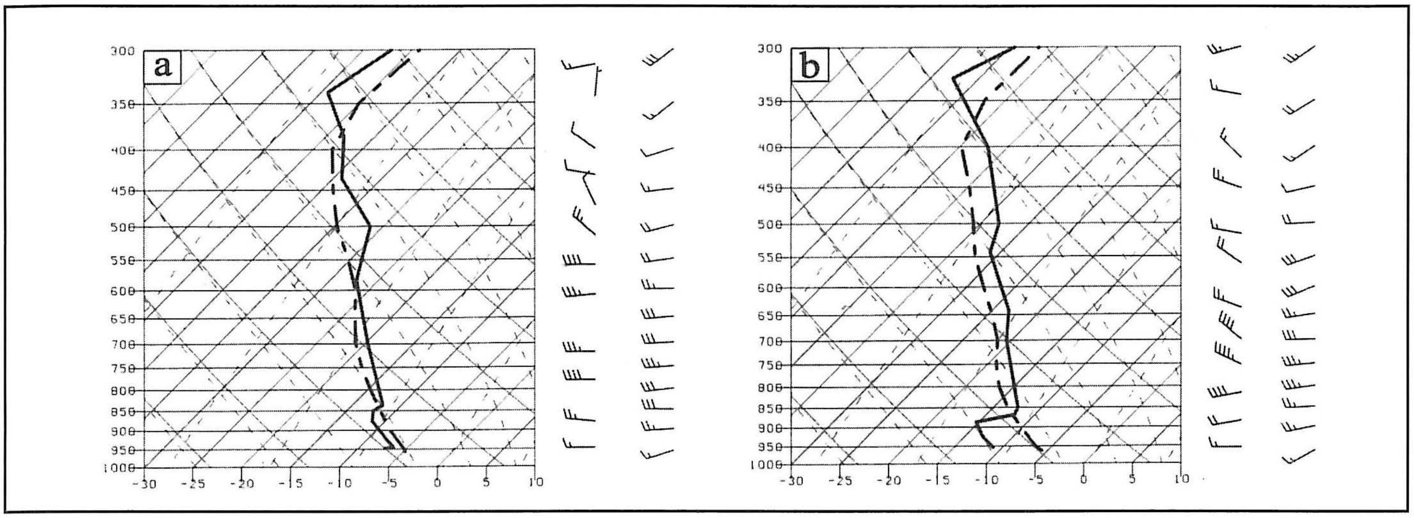

Fig. 10. Observed (solid) and the 0000 UTC 10 January 1997 MM5 cycle forecast (dashed) soundings at White Lake (DTX) valid at: a) 1200 UTC 10 January 1997 and b) 1200 UTC 11 January 1997. Forecast winds (standard notation) on the left and observed winds on the right for each respective sounding.

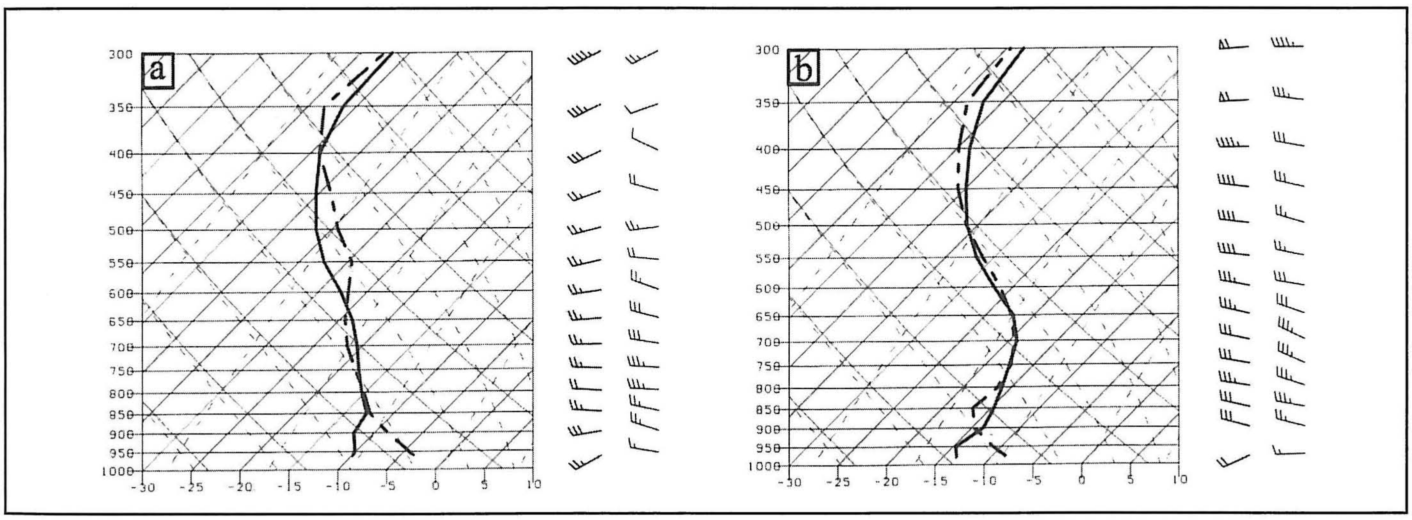

Fig. 11. Soundings from a) 0000 UTC 10 January 1997 MM5 forecast cycle verifying at 1800 UTC 10 January 1997 at Fort Wayne, Indiana (solid, winds (kt) to the left) and Lansing, Michigan (dashed, winds (kt) to the right), and b) 0000 UTC 11 January 1997 MM5 forecast cycle verifying at 1800 UTC 11 January 1997 at Toledo, Ohio (solid, winds (kt) to the left) and Flint, Michigan (dashed, winds (kt) to the right).

was able to simulate successfully the presence of the very pronounced west to east convergence zone and snow band extending across southern Michigan. Therefore, a look at select model forecast parameters from this case should still yield important insight on the actual structure of the atmosphere during the event and possible mechanisms responsible for the formation of the snow band. The relation of band placement to the lower-tropospheric thermal structure was especially well illustrated by the events on 10-11 January 1997.

Figure 11a shows the model forecast soundings at Fort Wayne, Indiana (FWA) and Lansing, Michigan (LAN) verifying at 1800 UTC 10 January. South of the convergence zone, at FWA, the boundary layer is forecast to be colder and more stable, and the flow is forecast to be more ageostrophic (Figs. 5 and 6), and decoupled from the mid-tropospheric flow. Meanwhile, north of the convergence zone, at LAN, the boundary layer is forecast to be significantly deeper and well mixed. By 1200 UTC 11 January, very cold lower-tropospheric air had advected northeast to cover all of southeast Michigan. At that time, the boundary layer across the entire area was stable, and was characterized by a highly ageostrophic southwesterly flow, with no pronounced convergence zones. Recall that the 1200 UTC 11 January DTX sounding (Fig. 3b) indicated a very shallow stable layer near the ground, with a mixed layer above. The stable layer was likely even more shallow to the north of DTX, and deeper to the south, since the core of the cold air was still located to the southwest, across the northern Ohio Valley. Later that morning, the wind at FNT shifted from southwest to west, indicating that the shallow northern edge of the stable layer probably mixed. However, farther south, the stable layer was deeper and the flow remained strongly ageostrophic, resulting in a strengthening of the convergence zone south of FNT. Figure 11b shows the 18-hour

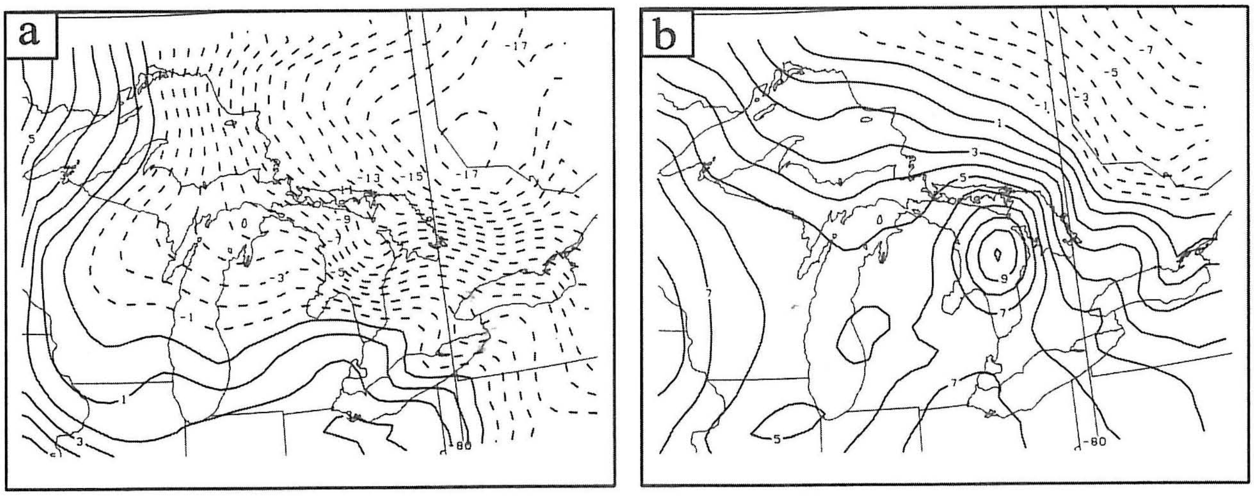

Fig. 12. The 0000 UTC 10 January 1997 MM5 cycle forecasts of 12-h surface pressure changes in isallobars (1 mb intervals) verifying at: a) 1200 UTC 10 January 1997 and b) 0000 UTC 11 January 1997.

MM5 forecast soundings at Toledo, Ohio (TOL) and at FNT, verifying at 1800 UTC 11 January. As was the case with the FWA forecast sounding, a relatively cold, deep stable layer was forecast south of the convergence zone at TOL . The boundary layer appears decoupled from the layers above, and the depicted forecast surface flow was again highly ageostrophic (southwesterly). By contrast, the forecast sounding at FNT shows a surface-based mixed layer extending upward to near 850-mb. In Figures 11a and 11b, the model is thus implying a significant zone of surface convergence and frontogenesis to the south of FNT and LAN.

For this event, the strong mesoscale convergence zone across southern lower Michigan appears to have developed largely in response to the occurrence of a very strong ageostrophic southwesterly flow component across northern Indiana, northern Ohio and far southern Michigan. Clearly, the effects of surface-produced friction and limited boundary layer mixing played significant parts in the development of this component of the wind, since the ageostrophic wind was strongest in areas where the boundary layer was most decoupled from the lower and middle-troposphere.

It can also be shown that the magnitude of the ageostrophic wind is proportional to the gradient of geopotential tendency (Holton 1992) with the ageostrophic wind vector generally directed down the gradient toward the largest geopotential height falls (or pressure falls, on a constant height surface). Across southern Michigan, this isallobaric component of the ageostrophic wind is naturally directed from south to north in cases characterized by a cold, westerly geostrophic flow since larger pressure falls (or relatively smaller pressure rises) typically occur downwind (east) of Lake Michigan than over areas farther to the south. Figure 12 shows the 0000 UTC 10 January MM5 cycle forecast surface pressure tendencies verifying at 1200 UTC 10 January and 0000 UTC 11 January and Figs. 6b and 6d show the MM5 forecast lowest sigma-level ageostrophic wind and divergence, verifying at 1800 UTC 10 January and 0000 UTC 11 January. Based on these model simulations, it can be hypothesized that such isallobaric accelerations were contributing to the development and strengthening of the lower-tropospheric ageostrophic wind.

In summary, the development and positioning of the lower-tropospheric convergence zone and its associated snow band on 10 January 1997 through 11 January 1997 were driven by interactions between the background synoptic-scale flow, local geography, and the thermal structure of the lower-troposphere. These interactions caused the development of a strongly ageostrophic component in the west to southwesterly surface winds immediately south of the Great Lakes. This ultimately led to the development of strong lower tropospheric frontogenesis and upward vertical motions across southern Michigan where cold, dry, southwesterly winds to the south of Michigan converged with relatively warmer, more moist, west and northwesterly winds immediately downstream of Lake Michigan. The resultant snow band stretched completely across the lower peninsula of Michigan and produced significant snowfalls in areas that are well outside of the region's traditional lake-effect snow belts.

4. Summary and Conclusions

Several times each year, a west-east oriented lake-effect snow band develops over Lake Michigan, and extends east across southern lower Michigan, bringing significant snow to areas east of what is usually considered the traditional southern Michigan "snow belt". Across southeast Michigan, these bands can sometimes result in localized snow accumulations of 50 to 150 mm (2 to 6 in.), with the area most frequently affected being the region from Flint south to Ann Arbor and Detroit. The results of this study indicate that these snow bands develop under typical conditions known to be favorable for lake-effect snow occurrence. In particular, in a limited sampling, conditions for the occurrence of these types of bands across southeast Michigan were found to have the following characteristics:

- a strong westerly wind with speeds ≥ 20 knots at 925-mb through 850-mb
- CBL depths > 1 km, but more commonly > 1.5 km
- relative humidity of ≥ 80 percent at 850-mb
- relative humidity of ≥ 80 percent at 700-mb if the CBL depth >2.5 km
- lapse rates > 4.0 °C km^{-1} within the CBL
- estimated ΔT between 850 mb and the lake surface >16 °C
- limited shear through the CBL.

However, this study has shown that additional elements are also very important in the formation of intense west-east oriented bands that extend into southeast Michigan. A case study examination of one of these events indicates that such a snow band evolved in response to the development of a strong lower-tropospheric convergence zone across southern lower Michigan. More specifically, an intense band formed when west to southwesterly flow over the south end of the lake initiated a lake-induced frontogenetic process, with significant convergence developing along a boundary between a shallow, cold airmass southeast of the lake, and a warmer, more well-mixed airmass induced by, and directly downstream of, Lake Michigan. Enhanced convergence and frontogenetic forcing resulted in part from the development of a frictionally-induced, northward-directed ageostrophic component of the surface wind in the shallow, stable, strongly-sheared cold airmass southeast of Lake Michigan and in part to the development of a northward-directed isallobaric contribution to the surface ageostrophic wind that naturally occurs across southern Michigan whenever a cold westerly flow crosses Lake Michigan.

Lastly, examination of NCAR/Penn State MM5 model forecasts for this event indicates that the model was able to simulate the relatively narrow convergence zone that resulted in the intense snow band. However, model difficulties with the details of the forecast thermal structure in the lower-troposphere resulted in the forecast convergence zone being significantly too far south. Nonetheless, this study suggests that there is much potential value to be gained from a local model in predicting the development and trends of certain features that may be critical to formation of significant weather phenomena.

Acknowledgments

The authors thank Bruce Smith and Bill Marino for their observations and suggestions that were used as starting points for this study. Also, thanks to Dr. Greg Mann for his help obtaining model and observational data for the event on 10-11 January 1997, and for his very helpful discussions on his modifications to the MM5 model.

Authors

Michael Evans is a lead forecaster at the NWS Forecast Office in State College, Pennsylvania. His principal research interests include lake-effect snow forecasting, quantitative precipitation forecasting and forecasting precipitation type. He received his Bachelor of Science Degree in Meteorology from The Pennsylvania State University in 1985, and his Master of Science Degree in Atmospheric Science from the State University of New York at Albany in 1992. Since then, he has worked for the National Weather Service at Charleston, West Virginia, Detroit, Michigan, and now at State College.

Dick Wagenmaker is currently the Science and Operations Officer at the National Weather Service Forecast Office in Detroit, Michigan. Upon graduating from the University of Michigan, he joined the National Weather Service in 1983 as a Meteorologist Intern in Little Rock, Arkansas. He subsequently held Journeyman and Lead Forecaster positions at the National Weather Service Forecast Offices in Ann Arbor/Detroit, Michigan, before becoming Science and Operations Officer in 1993. His primary research interests include lake-effect snow forecasting and radar detection of severe weather phenomena.

References

Anthes, R.A., E.-Y. Hsie, and Y.-F. Li, 1987: Description of the Penn State / NCAR mesoscale model version 4 (MM4). NCAR Tech. Note: NCAR / TN-282+STR, 66pp.

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

Dockus, D.A., 1985: Lake-effect snow forecasting in the computer age. *Natl. Wea. Dig.*, 10:4, 5-19.

Evans, M.S., 1996: A method for forecasting lake-effect snow using synoptic-scale model forecasts of 850-mb and 700-mb vertical velocity and relative humidity. NWS Central Region Technical Attachment 96-09, NOAA/NWS, Kansas City, MO.

Grell, G., J. Dudhia, and D. Stauffer, 1995: A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5), NCAR Tech. Note: NCAR/TN-398+STR.

Holton, J.R., 1992: *An Introduction to Dynamic Meteorology*, Academic Press Inc., 511pp.

Holroyd, E.W., 1971: Lake-effect cloud bands as seen from weather satellites. *J. Atmos. Sci.*, 28, 1165-1170.

Kain, J.S., and J.M. Fritsch, 1990: A one-dimensional entraining-detraining plume model and its application in convective parameterization. *J. Atmos. Sci.*, 47, 2784-2802.

Mann. G.E., 1999: Great Lakes Collective Influences Upon the Evolution of Lake-Effect Storms in the Western Great Lakes. Ph.D. Thesis, University of Michigan, Ann Arbor MI, 285pp.

Niziol, T.A., 1987: Operational forecasting of lake-effect snowfall in western and central New York. *Wea. Forecasting*, 2, 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, 61-67.

Rothrock, H.J., 1969: An Aid in Forecasting Significant Lake Snows: ESSA Tech. Memo.WBTM CR-30, NOAA/NWS, Kansas City MO, 18 pp.

Miner, T.J., P.J. Sousounis, J. Wallman, and G.E. Mann, 2000: Hurricane Huron. *Bull. Amer. Meteor. Soc.*, 81, 223-236.

Wagenmaker R.B. and B.S. Smith, 1995: A preliminary case study of a persistent lake-effect snow band in south lower Michigan on 3-4 January 1995. A Review of the 1994-1995 Lake-Effect Snow Project in the National Weather Service Central Region, NOAA/NWS, Kansas City MO.

CALL FOR PAPERS — THE NWA METEOROLOGICAL SATELLITE APPLICATIONS AWARD

The Meteorological Satellite Applications Award has been established by the National Weather Association (NWA) to stimulate interest and foster the study and use of satellite remote sensing data in weather analysis and forecasting. **Undergraduate students are invited to write an original paper on meteorological satellite applications.** Themes of the papers may include original research, case studies, or a survey of applications. The recipient of the award will receive a stipend of $500 and be invited to present their paper at the NWA Annual Meeting. Frances C. Parmenter-Holt, Chairperson of the NWA Remote Sensing Committee, sponsors this award.

The student must be enrolled as an undergraduate at the time the paper is written and be in good academic standing at the college or university attending. The student also must be a U.S. citizen or hold permanent resident status.

DEADLINE: 15 JUNE 2001

Submission of Papers: Student papers should not exceed ten (10) pages including photographs and appendices. Candidate authors should submit:

- an original and three copies of their paper
- a letter of application with the paper title, university affiliation, and contact information including mailing address, phone, fax, and e-mail address if available
- a letter from their Department Head or other faculty member that confirms the student author was an undergraduate when the paper was written and that the student is in good academic standing at the college or university. Additionally this letter should highlight the original research or contributions the student has made to this paper.

Submissions should be sent by 15 June 2001 to:

National Weather Association
Attn: MetSat Applications Award
6704 Wolke Court
Montgomery, AL 36116-2134.

Announcement of the recipient of the award will be made in October 2001. For additional information contact the NWA office. ***All members — please help spread the word about this award/grant initiative.***