Improved Detection Using Negative Elevation Angles for Mountaintop WSR-88Ds. Part III: Simulations of Shallow Convective Activity over and around Lake Ontario

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ABSTRACT

During the winter, lake-effect snowstorms that form over Lake Ontario represent a significant weather hazard for the populace around the lake. These storms, which typically are only 2 km deep, frequently can produce narrow swaths (20–50 km wide) of heavy snowfall (2–5 cm h$^{-1}$ or more) that extend 50–75 km inland over populated areas. Subtle changes in the low-altitude flow direction can mean the difference between accumulations that last for 1–2 h and accumulations that last 24 h or more at a given location. Therefore, it is vital that radars surrounding the lake are able to detect the presence and strength of these shallow storms. Starting in 2002, the Canadian operational radars on the northern side of the lake at King City, Ontario, and Franktown, Ontario, began using elevation angles of as low as $-0.1^\circ$ and $0.0^\circ$, respectively, during the winter to more accurately estimate snowfall rates at the surface. Meanwhile, Weather Surveillance Radars-1988 Doppler in New York State on the southern and eastern sides of the lake—Buffalo (KBUF), Binghamton (KBGM), and Montague (KTYX)—all operate at 0.5° and above. KTYX is located on a plateau that overlooks the lake from the east at a height of 0.5 km. With its upward-pointing radar beams, KTYX’s detection of shallow lake-effect snowstorms is limited to the eastern quarter of the lake and surrounding terrain. The purpose of this paper is to show—through simulations—the dramatic increase in snowstorm coverage that would be possible if KTYX were able to scan downward toward the lake’s surface. Furthermore, if KBUF and KBGM were to scan as low as $0.2^\circ$, detection of at least the upper portions of lake-effect storms over Lake Ontario and all of the surrounding land area by the five radars would be complete. Overlake coverage in the lower half (0–1 km) of the typical lake-effect snowstorm would increase from about 40% to about 85%, resulting in better estimates of snowfall rates in landfalling snowbands over a much broader area.

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1. Introduction

When Weather Surveillance Radar-1988 Doppler (WSR-88D) systems were installed throughout the United States and at selected overseas sites during the early and mid-1990s, all of the radars had—and still have—scanning strategies with 0.5° as the lowest elevation angle. For a radar located on the top of a mountain, the lowest elevation angle overshoots much of the hazardous weather conditions near the ground in the surrounding area. National Weather Service (NWS) forecasters who depend on detections from mountaintop radars for issuing warnings and short-term forecast products could benefit from the additional information provided by lowered elevation angles.

The first two papers in this series point out the advantages of utilizing negative elevation angles at mountaintop sites in the western United States. By using negative elevation angles with the Missoula, Montana, WSR-88D, forecasters at the local NWS office would be able to detect, among other things, the onset of arctic blizzards in the surrounding valleys and the presence of shallow warm-season severe storms triggered by the flow of cold air over a large lake 100 km from the radar. In addition, measurements at lower elevation angles would greatly improve the accuracy of quantitative precipitation estimates throughout the radar coverage area (Brown et al. 2002). Based on a draft of the Brown et al. (2002) paper and a routine inspection of the Missoula forecast office during March 2001, the Office of the Inspector General of the U.S. Department of Commerce recommends that the NWS conduct “appropriate environmental impact and engineering studies on radar radiation and the feasibility of lowering the angle of the Missoula radar” (USDC 2001). Though radiation studies need to be conducted for political reasons, it is well established that there is no radiation hazard to the public outside the WSR-88D radar enclosure (see references cited by Brown et al. 2002).

The second paper investigates the three mountaintop radars that cover Utah and western Colorado (Wood et al. 2003). If elevation angles of those radars were lowered, forecasters at the Salt Lake City, Utah, and Grand Junction, Colorado, NWS offices would be able to better detect, among other things, flash flood situations that catch hikers by surprise in the canyons of southeastern Utah, low-altitude lake-breeze fronts that adversely affect flight operations at Salt Lake City International Airport, and shallow snowstorms that impact the major surface transportation arteries in the region.

The National Research Council (NRC) recently assessed the capabilities of the WSR-88D on the top of Sulphur Mountain in California to detect flash-flood-producing situations in the Los Angeles area. The ensuing report (NRC 2005) indicates that the Sulphur Mountain WSR-88D is well located for detecting heavy precipitation events that lead to flash floods. In addition, the report recommends that “The National Weather Service should improve nationwide Next Generation Doppler Radar (NEXRAD) coverage of low-level precipitation and wind, especially for elevated radar sites in complex terrain, through the adoption of a modified scan strategy that will allow scanning at lower elevation angles.”

Though most mountaintop radars are in the western United States (including Alaska and Hawaii), there are a few WSR-88Ds in the eastern United States that also are on the tops of “mountains.” One of these is radar KTYX in the town of Montague, New York, on the top of the Tug Hill Plateau to the east of Lake Ontario. The radar, which is 0.52 km above the lake’s surface, is in a prime location for detecting convective activity over and around the lake.

Many of the heavy snow situations that affect commerce and transportation in the Great Lakes region are due to lake-effect snowstorms that are only 2 km deep. Since the lowest elevation angles of the Montague WSR-88D overshoot much of the lake-effect snow activity and other shallow convective activity, the use of negative elevation angles would improve the range of detection of such storms. Likewise, if the lowest elevation angle of the Buffalo and Binghamton WSR-88Ds was lowered from 0.5° to 0.2°, the detection capabilities of those radars would increase. Consequently, the purpose of this paper is to simulate negative elevation angles for the Montague radar and to simulate slightly lowered angles for the Buffalo and Binghamton radars, and to thereby demonstrate how detection of shallow convective storms, in conjunction with two Canadian radars on the north side of Lake Ontario, could be improved using these lower elevation angles.

2. The situation

a. Radar coverage

The most notable wintertime convective activity in the vicinity of Lake Ontario occurs in the form of lake-effect snowstorms that typically are only 2 km deep. These snowstorms occur during the late fall and winter when cold air flows over a relatively warm lake (e.g., Peace and Sykes 1966; Reinking et al. 1993; Niziol et al. 1995; Lackmann 2001). When low-altitude flow is across the short axis of the lake, there is a broad area of snowfall over the downstream shore. On the other hand, when the flow is along the long axis of the lake,
a single snowband occurs that produces heavy snowfall in the narrow zone.

From its elevated vantage point, the Montague WSR-88D currently overshoots much of the lake-effect snow activity and other shallow convective activity in the surrounding area. The Buffalo WSR-88D (KBUF) at the other end of the lake is in an ideal location to monitor shallow activity over portions of both Lake Ontario and Lake Erie. KTYX and KBUF are two of five radars that cover Lake Ontario and the surrounding terrain (Fig. 1a). The other radars include the Binghamton, New York, WSR-88D (KBGM) and two radars in the province of Ontario on the north side of the lake—WKR in King City and XFT in Franktown. The lowest elevation angles for the Ontario radars are $-0.1^\circ$ and $0.0^\circ$, respectively, during the winter and $0.3^\circ$ during the summer. In comparison, the lowest angle for the three New York State radars is $0.5^\circ$. Successive lower elevation angles are separated by $0.2^\circ$ for the Canadian radars, while they are separated by either $0.4^\circ$–$0.5^\circ$ or $0.95^\circ$ for the WSR-88Ds. The half-power beamwidths of the two Canadian radars are $0.65^\circ$ and those for the three WSR-88Ds are $0.85^\circ$–$0.88^\circ$.

Current coverage by the five radars within 2 km of the surface of Lake Ontario and the surrounding terrain is indicated in Fig. 1b; red shading indicates where the radars are scanning more than 2 km above the surface at the lowest unblocked elevation angle. There is a gap (red area) in the east-central portion of the lake and adjacent southern shore where 2-km-deep snowstorms are not detected. Details of storm structure within the lower half of a storm ($0$–$1$ km) are limited to the western 40% of the lake and the eastern lakeshore.

### b. Forecasting challenges

Operational forecasters are continually working toward improving short-term (less than 6 h) forecasts of weather that has the potential to adversely affect the public. Severe winter weather in the Great Lakes region often creates tremendous impacts on commerce and transportation, literally bringing an area to a standstill in a very short period of time (Niziol 1982). Therefore, any improvements in short-term forecasts should increase the warning lead times for the affected communities and potentially decrease the impacts of these events.

For the operational forecaster, the challenge of monitoring and predicting weather conditions in the short-term time frame is often hindered by inadequate observational capabilities. Lake-effect snowstorms occur on such a small spatial scale that the entire storm may not even be reflected in the standard surface observing network. In addition, during the winter, most observational data buoys are removed from the Great Lakes due to issues with winter weather conditions and ice cover in particular (Niziol 2003). Therefore, weather radar becomes even more valuable for detecting severe
winter weather conditions and providing the information necessary to predict changes in those conditions over the short term.

During the summer months, it has been shown that severe thunderstorms and tornadoes in the Great Lakes region can be associated with shallow lake-breeze boundaries (King et al. 2003). Experience indicates that the WSR-88D is capable of detecting these boundaries and therefore can provide additional information about the potential for convective development in the short term.

The vertical extent of convective mesoscale snowstorms is often less than 2 km and can be limited to around 1 km at times (Waldstreicher 2002). Vertical circulations of summertime lake breezes on the Great Lakes are generally on the order of 1–2 km (e.g., Keen and Lyons 1978). For current operational scanning strategies that the WSR-88D network provides, detection of these types of shallow weather features is limited.

3. Optimized scanning strategies

a. Canadian Weather Radar Network

The network of operational Doppler radars maintained by the Meteorological Service of Canada is located primarily in southern Canada (e.g., Lapczak et al. 1999). Some mountaintop radars, particularly those that are more than 500 m above surrounding terrain, use negative angles year-round. During the winter of 2002/03, an experiment was conducted where the lowest elevation angles for the other radars in the network were set between $-0.1^\circ$ and $+0.1^\circ$ (Donaldson et al. 2003). Prior to the introduction of these very low winter angles, forecasters commonly complained of unseen snow events, especially shallow snowstorms caused by cold-air advection over warm water. Consequently, forecasters across Canada were uniformly positive about results obtained during the experiment. They found that they were better able to monitor localized snow, especially at midranges (i.e., 60–120 km).

The displays from WKR in Fig. 2 exemplify the types of improvements that are seen using lower elevation angles for the detection of shallow snow events. The displays on the left contain ground return because Doppler velocity data (needed for the Doppler velocity clutter filter) were not available at that elevation angle; the clutter filter was applied to those on the right. The top-right panel display at $-0.11^\circ$ elevation angle shows convective snowbands forming over Lake Ontario and crossing the downstream shoreline. At the $0.53^\circ$ elevation angle (top-left panel in Fig. 2), the radar beam overshoots all of the shallow convective activity (located as close as 75 km to the radar). The bottom panels show a well-organized single snowband over Lake Ontario. When the elevation angle is lowered from $0.53^\circ$ to $-0.24^\circ$, the reflectivity values within the eastern portion of the band increase by 10–20 dBZ—thereby providing much more accurate quantitative precipitation estimates. Thus, the use of lower elevation angles permits the detection of otherwise undetectable precipitation events, as well as providing more accurate estimates of precipitation amounts occurring at the surface.

Following the 2002/03 experiment, the results were evaluated to determine whether some of the elevation angles needed to be adjusted. As part of the evaluation process, the lowest elevation angle was permitted to be within about 0.25–0.35 beamwidths of the ground (e.g., Smith 1998). Long-term statistics of radar reflectivity measurements at the various sites suggested that the computed horizons used for determining the lowest elevation angle at some of them were not correct, owing to the coarseness of the Digital Elevation Model (DEM) map used and to the fact that trees are not included as part of the DEM data. The evaluation resulted in the elevation angles at some sites being raised above those used during the previous winter; the revised elevation angles are now used every winter.

Because of a lack of widely distributed trustworthy snow measurements for verification, detailed analyses of the impact of the lower elevation angles on quantitative precipitation estimates (QPEs) during the winter have not been performed for the Canadian radars. In the absence of an operational correction for the vertical profile of reflectivity, precipitation rate estimates based directly on measurements in snow aloft will be underestimated. For mountaintop radars, the perception of some forecasters is that the radar rain-rate estimates are closer to surface observations than before, presumably because the radar measurements are now closer to the surface. Improved detection using lower elevation angles is considered a success independently of any impact on QPE.

The Canadian experience shows some of the consequences of using lower elevation angles. The most significant issue is that the radar horizon is rarely level, so compromises needed to be made similar to those discussed in the next section for KTYX. Assessments of blockage are based on the spatial distribution of the long-term statistics of radar measurements. Blockage is accepted in some sectors for the lowest elevation angles in order to achieve low-altitude coverage in other critical sectors. Regional offices were consulted in order to understand local issues and balance the compromises.
Coverage for most blocked sectors can still be achieved using higher elevation angles. Partial blockage is harder to assess and is still being investigated. Another consequence seen in the Canadian network is the appearance of gaps in the data where the lower elevation angles lead to increased ground clutter relative to weather signals. The Doppler clutter filters remove weak precipitation echoes along with the clutter echoes. This results in light snow showers intermittently disappearing as they move over terrain features.

Another consequence of the lower angles is an increase in reports of sea (lake) clutter. Sea clutter, which is not removed by Doppler velocity clutter filters, was regularly seen at only one radar before introduction of the low elevation angles. After the introduction of the lower angles, several offices reported the

Fig. 2. Comparisons of WKR detections of shallow snowbands over Lake Ontario during Jan 2005 at (left) 0.53° and (right) negative elevation angles [(top right) −0.11° and (bottom right) −0.24°]. The Doppler velocity clutter filter was not applied to the left panels because no Doppler velocity data were collected at 0.53°, but the clutter filter was applied to the right panels (with some residual clutter evident). Range circles are at 20-km intervals from the radar.
presence of clutter associated with large water surfaces. Lowering the angles produces increased sea clutter in the sidelobes, especially during temperature inversions. Despite these limitations, the overall conclusion in Canada is that the move to lower elevation angles during the winter is worthwhile once forecasters are trained to understand the new phenomena that are introduced.

b. WSR-88D radars

The technique for computing the scanning strategy or volume coverage pattern (VCP) for a mountaintop WSR-88D is shown in Fig. 3 and discussed in detail by Brown et al. (2002); the basic concepts for this technique were developed by Brown et al. (2000). Briefly, the procedure involves two steps: (a) determining the lowest elevation angle and (b) given the lowest elevation angle, determining the other elevation angles of the VCP. Based on a theoretical study, Smith (1998) found that when the center of the lowest beam is about 0.25–0.35 beamwidths (or 0.2°–0.3° for a WSR-88D) above a flat surface, there is an acceptable balance between the loss of power received from low-altitude features and the increase in ground clutter. In our previous studies (Brown et al. 2002; Wood et al. 2003), we assumed that the center of the lowest beam was 0.3° above a flat surface. In this study, we use the lower value of 0.2°. Using standard conditions for the index of refraction (e.g., Battan 1973) and radar height above Lake Ontario and the surrounding terrain (0.5 km for KTYX), one can determine (by trial and error) that the elevation angle of the KTYX radar beam center that grazes the surface of the lake is −0.6°. Applying Smith’s results to mountaintop radar KTYX, the lowest elevation angle would be −0.4° (0.2° above the grazing angle).

The rest of the elevation angles in this VCP (called a “mountaintop VCP”) were determined using the procedure illustrated in Fig. 3. Having selected the lowest elevation angle, \( \phi_1 \), an arbitrary midlatitude height, \( Z_t \), is specified and the corresponding distance from the radar is computed. The procedure is to decrease the range at that elevation angle until the height has decreased by an amount equal to a specified percentage \( \Delta H_{\%} \) (usually 15%–30%) of the initial height. At that range, the next elevation angle, \( \phi_2 \), is computed at the original height \( Z_t \). If the difference between the two adjacent elevation angles is less than a specified amount (one-half vertical beamwidth in this study), the range is decreased at constant height until the specified elevation angle difference is achieved (this procedure is illustrated between \( \phi_1 \) and \( \phi_2 \) in Fig. 3). Then, the process of decreasing the range at a constant elevation angle is repeated until the percentage height difference is met, etc. For the mountaintop VCP, we wanted 14 elevation angles between −0.4° and 19.5° (see Table 1). Therefore, a series of computations were made using different \( \Delta H_{\%} \) values until the particular \( \Delta H_{\%} \) value was found that produced the specified conditions; for KTYX, the value was 22.80%. This approach produces a set of elevation angles that are closest together at low elevation angles (providing improved vertical resolution at all ranges) and that become systematically farther apart with height.

The same approach was used to compute a “flatland VCP” for the Buffalo and Binghamton WSR-88Ds, where the grazing angle was assumed to be 0.0°. For a VCP consisting of 14 elevation angles ranging from 0.2° to 19.5°, the \( \Delta H_{\%} \) value was 20.33% (see resulting VCP

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**Table 1. Comparisons of elevation angles for the WSR-88D VCP 11, the flatland VCP (KBUF and KBGM), and the mountaintop VCP (KTYX).**

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<thead>
<tr>
<th>VCP</th>
<th>Flatland VCP</th>
<th>Mountaintop VCP</th>
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<tbody>
<tr>
<td>0.5</td>
<td>0.2</td>
<td>−0.4</td>
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<tr>
<td>1.45</td>
<td>0.6</td>
<td>0.0</td>
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<tr>
<td>2.4</td>
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<td>19.5</td>
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in Table 1). This VCP can be used as a first guess for any WSR-88D that is surrounded by relatively flat terrain (if and when the 0.5° minimum elevation angle restriction is relaxed). For KTYX, KBUF, and KBGM, the lower elevation angles are separated by about one-half of a vertical beamwidth (0.4°–0.5°) instead of a separation angle of 0.95° that is common for the WSR-88D precipitation scanning strategies, except for the new VCP 12, which also uses a one-half beamwidth separation (e.g., Brown et al. 2005).

One might anticipate that when WSR-88D elevation angles are lowered, regions of ground clutter will increase around the three WSR-88Ds and that sea (lake) clutter would be detected by KTYX and potentially by KBUF. Fortunately, an advanced ground clutter canceling technique based on Gaussian model adaptive processing (GMAP) is being implemented on WSR-88Ds (e.g., Siggia and Passarelli 2004; Ice et al. 2005). The procedure is to remove a narrow portion of the Doppler velocity spectrum centered on 0 m s\(^{-1}\) that is associated with essentially stationary ground clutter; the portion removed is variable, depending on the radar and clutter characteristics. Then the portion of the Doppler velocity spectrum that was removed is replaced by values obtained by fitting the remaining weather portion of the spectrum (above the noise level) with a Gaussian function. Because radar return from ground clutter is eliminated, the resulting estimates of reflectivity, mean Doppler velocity, and spectrum width are based solely on meteorological targets.

The presence of sea clutter poses a different problem. Since sea clutter can be moving, a more sophisticated approach is required over water (e.g., Steiner and Smith 2002; Kessinger et al. 2005). A sea clutter detection algorithm (SCDA) was developed at the National Center for Atmospheric Research that measures the “roughness” of the reflectivity field (using a couple of different parameters) and the rate at which reflectivity decreases with height above the water surface. The algorithm has been used quite successfully on coastal radars in the United Arab Emirates (Kessinger et al. 2005). However, it is not known how well the SCDA would be able to separate weak, shallow precipitation from sea clutter. Before lower elevation angles are used with KTYX, and possibly KBUF, a WSR-88D version of SCDA needs to be prepared and tested.

4. WSR-88D detection improvements with lowered elevation angles

a. Buffalo radar (KBUF)

The heights of the lowest KBUF elevation angle above the surface using current VCPs 11, 12, and 21 and

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**Fig. 4.** Heights of lowest elevation angles above Lakes Erie (west-southwest) and Ontario (north) and adjacent terrain for KBUF using (a) VCPs 11, 12, and 21 (0.5°) and (b) the flatland VCP (0.2°, 0.6°). The black area is more than 2 km above the surface. The distance to which there are detections 2 km or less above the surface is slightly greater over Lake Erie than over Lake Ontario because Lake Erie is 100 m higher. Range rings are at 50-km intervals.
the flatland VCP are shown in Fig. 4. Over most of the coverage area, the detection range of 2-km-deep phenomena increases by 30 km with the flatland VCP—representing a 55%–60% increase in coverage area. Coverage by the flatland VCP, however, is slightly less than that for the current VCPs in a few narrow wedges to the southeast of the radar, where the lowest angle (0.2°) is blocked by terrain and the next-higher elevation angle (0.6°) is used.

Vertical cross sections for both the current and flatland VCPs to the northeast over Lake Ontario and to the southwest over Lake Erie are shown in Figs. 5 and 6, respectively. Over Lake Ontario, the maximum range of detection of a 2-km-deep snowstorm increases from 115 to 145 km with the flatland VCP. Over Lake Erie, the maximum range increases from about 120 to about 150 km. With the flatland VCP, there is significantly greater vertical resolution within the lower portions of snowstorms—leading to improved quantitative precipitation estimates.

During lake-effect snow situations where low-altitude flow is down the length of Lake Erie (from west-southwest toward east-northeast), a single snowband forms that frequently can produce narrow swaths (20–50 km wide) of heavy snowfall (2–5 cm h\(^{-1}\) or more) that extend 50–75 km inland over the metropolitan areas at the downwind end of the lake (e.g., Niziol 1987). Similar situations are found at the downwind end of Lake Ontario. Subtle changes in the low-altitude flow direction can mean the difference between accumulations that last for 1–2 h and accumulations that last 24 h or more at a given location. With the larger monitoring area provided by the flatland VCP, changes in snowband orientation can be detected earlier.

**b. Binghamton radar (KBGM)**

The heights of the lowest KBGM radar beams above the surrounding terrain using current VCPs 11, 12, and 21 and the flatland VCP are shown in Fig. 7. With the flatland VCP, 2-km-deep snowstorms are detectable to within about 5 km of the Lake Ontario shoreline, instead of about 35 km with the current VCPs. There is about a 60% increase in the coverage area within 2 km of the surface with the flatland VCP and there is no terrain blockage. A comparison of vertical cross sections toward 330° over the lake is shown in Fig. 8.
c. Montague radar (KTYX)

The heights of the lowest KTYX radar beams above the terrain/lake using current VCPs 11, 12, and 21 and the mountaintop VCP are shown in Fig. 9. With the current VCPs, the center height of the lowest beam is within 2 km of the lake’s surface and surrounding terrain only within 100 km of the radar at the extreme eastern end of the lake. With the lowest elevation angle of the mountaintop VCP decreased from $0.5^\circ$ (Fig. 9a) to $0.4^\circ$ (Fig. 9b), the detection range for a 2-km-deep storm over the lake and surrounding terrain more than doubles from about 100 km to about 220 km. This means that detection using the mountaintop VCP increases from the eastern quarter of the lake and surrounding terrain to the eastern two-thirds. Part of the $0.4^\circ$ scan is blocked by nearby terrain from the northeast through south-southwest of the radar, so that the blocked portion is covered by the next elevation angle ($0.0^\circ$). Within that portion there is a narrow region to the southeast where the lowest unblocked elevation angle is $0.4^\circ$. Though portions of the coverage region are blocked by intervening terrain, there is radar coverage closer to the ground at all azimuths.

**Fig. 7.** Heights of lowest elevation angles above Lake Ontario and adjacent terrain for KBGM using (a) VCPs 11, 12, and 21 ($0.5^\circ$) and (b) the flatland VCP ($0.2^\circ$). The black area is more than 2 km above the surface. Range rings are at 50-km intervals.

**Fig. 8.** Vertical cross sections of (a) VCP 11 and (b) flatland VCP elevation angles along the $330^\circ$ azimuth from KBGM. The dashed line is 2 km above the surface of Lake Ontario.
Comparisons of vertical cross sections to the west of the radar over the lake using VCP 11 and the mountaintop VCP are shown in Fig. 10. In addition to more than doubling the coverage range of shallow lake-effect snowstorms, the mountaintop VCP provides much more information about the vertical reflectivity structure of the storms. Detection of the structure in the lower half of a storm (within 1 km of the surface), which provides the best estimates of snowfall rate over the lake and surrounding coastal regions, increases from about 45 km to about 160 km from the radar.

**d. Composite coverage**

Figure 11 shows the coverage of Lake Ontario snowstorms using optimum lower elevation angles for the two Canadian and three New York State radars. Compared with the current configuration shown in Fig. 1b, there is a marked improvement resulting from the lowered WSR-88D elevation angles. The main improvement comes from KTYX scanning at −0.4°, but there

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**Fig. 9.** Heights of lowest elevation angles above Lake Ontario and adjacent terrain for KTYX using (a) VCPs 11, 12, and 21 (0.5°) and (b) the mountaintop VCP (−0.4°, 0.0°, 0.4°). The black area is more than 2 km above the surface. Range rings are at 50-km intervals.

**Fig. 10.** Vertical cross sections of (a) VCP 11 and (b) mountaintop VCP elevation angles along the 270° azimuth from KTYX. The dashed line is 2 km above the surface of Lake Ontario.
also is improvement from KBUF and KBGM scanning at the lower elevation angle of +0.2°.

Rather than not being able to detect shallow lake-effect storms over the east-central portion of the lake and adjacent land areas (Fig. 1b), Fig. 11 shows that detections are possible over the entire lake and over all of the surrounding land area. Overlake coverage in the lower half (0–1 km) of the typical lake-effect snowstorm increases from about 40% to about 85%, resulting in better estimates of snowfall rates in landfalling snowbands over a much larger area.

e. Warm season detections

In addition to improving the detection of cold-season convective activity, the lowered and more closely spaced elevation angles of the mountaintop and flatland VCPs also improve the detection of warm-season phenomena. For example, some low-top supercell storms in the Great Lakes region can be as short as 4 km. The presence of a shallow mesocyclone within a low-top supercell provides some warning that a tornado may be developing aloft. However, tornadoes that form along surface boundaries (e.g., Wakimoto and Wilson 1989) occur with little if any lead time and may go undetected if the radar does not scan low enough.

Shallow boundaries, which can be responsible for triggering convective storms (e.g., Wilson and Schreiber 1986), currently are difficult to detect by a WSR-88D unless they are relatively close to the radar. For example, consider the presence of shallow convergence associated with a gust front or lake-breeze front as denoted by the idealized vertical profile of convergence in Fig. 12a; a mirror-image vertical profile of di-
vergence can be used to represent a microburst. We assume that the radar is located on an infinitesimally narrow mountain peak 0.5 km above a flat plane (representing Lake Ontario and the adjacent flat coastal plain) and that the radar beam propagates under standard atmospheric conditions. The divergence–convergence value measured at the lowest elevation angle can be estimated from the curves in Fig. 12a at the height corresponding to the height of the beam center at a given range. Based on that value and the divergence–convergence value at the surface, one can compute the percentage of surface divergence and convergence that would be detected at the lowest elevation angle as a function of range from the radar to the divergence–convergence feature (Fig. 12b). Since the vertical profiles in Fig. 12a are mirror images of each other, their detections at the lowest elevation angle are combined in Fig. 12b.

Using the current VCPs 11, 12, and 21, the lowest elevation angle of 0.5° would overshoot the presence of divergence–convergence beyond a range of about 72 km (Fig. 12b). However, using the mountaintop VCP, well over 90% of the surface divergence–convergence values would be detected at a range of 72 km at the lowest elevation angle (−0.4°). In fact, the lowest elevation angle of the mountaintop VCP does not overshoot the divergence–convergence features until the radar beam is nearly 190 km from the radar. For a given percentage of detection, the increase in the range of detection for the mountaintop VCP relative to the current VCPs is approximately 105–115 km.

The rainfall rate in convective storms can be simulated by specifying a representative vertical profile of the reflectivity (e.g., Brown and Torgerson 2003) and then computing a vertical profile of the rainfall rate from a realistic relationship between the reflectivity and rainfall rate (Fig. 13a). A 10-km-tall storm, which is typical in the Lake Ontario region, was chosen for this simulation. With the simulated radar located 0.5 km above the lake and coastal plain, one can compute the percentage of the surface rainfall rate detected at the lowest elevation angle as a function of the distance from KTYX for the current VCPs 11, 12, and 21 and for the mountaintop VCP (Fig. 13b). At a range of about 120 km from the radar, the current VCPs detect 50% of the surface rainfall rate, while the mountaintop VCP detects more than 90% of the surface value. At a range of 240 km, essentially no rainfall is detected at the lowest elevation angle with the current VCPs, whereas 50% of the surface rainfall rate is still being detected by the mountaintop VCP. For a given percentage of detection, the increase in the range of detection for the

![Fig. 13. Simulated convective rainfall rate. (a) Vertical profile of the simulated rainfall rate (R) and the associated reflectivity (Z) profile. The reflectivity profile is based on vertical profiles of the maximum reflectivity observed in convective storms at the time that the maximum reflectivity is reaching the surface (e.g., Brown and Torgerson 2003). The rainfall rate value at a given height was computed from the reflectivity value at the same height using the indicated Z–R relationship. (b) Percentage of simulated surface rainfall rate detected at the height of the center of the lowest radar beam for VCPs 11, 12, and 21 (dotted line) and the mountaintop VCP (solid line) as a function of range from the radar to the rainfall area. KTYX is assumed to be 0.5 km above a flat surface that represents Lake Ontario and the surrounding coastal plain.](image-url)
5. Concluding discussion

The WSR-88D radar network was established to enable forecasters to issue more timely and accurate warnings of severe thunderstorms, tornadoes, threatening wind conditions, and devastating floods (e.g., Crum and Alberty 1993). To accomplish this, the radars need to monitor storm evolution aloft as well as near the surface. Unfortunately, those WSR-88Ds placed at elevated locations have been constrained to operate with the lowest elevation angle being +0.5°, as is the case with flatland radars, thereby making it difficult for forecasters to use the radars to achieve many of the stated objectives (e.g., Brown et al. 2002; Wood et al. 2003).

One of those elevated WSR-88Ds is KTYX located in the town of Montague on top of the Tug Hill Plateau beyond the eastern end of Lake Ontario in upper New York State. Among the hazardous conditions that occur within the coverage area of KTYX are shallow lake-effect snowstorms. When low-altitude cold air flows over a warm lake, the resulting convective snowbands can produce snowfall that accumulates at rates of 2–5 cm h⁻¹ or more. To adequately warn the public, it is vital for forecasters to know where the snowbands are located, the strength of the low-altitude reflectivity, and whether the bands are moving or stationary. Like all WSR-88Ds, KTYX’s lowest elevation angle is 0.5°. With the typical lake-effect snowstorm being only 2 km deep, KTYX can detect the presence of the storm only to a range of 100 km over the lake and surrounding terrain. Range is limited to only 45 km for reflectivity data in the lowest 1 km that can be used to make fairly accurate estimates of snowfall accumulations. If the lowest elevation angle was decreased to ~0.4°, the detection range would more than double to 220 km and the range of accurate snowfall accumulations would more than triple to 160 km.

Near the other end of Lake Ontario is the Buffalo WSR-88D (KBUF), which is a typical flatland radar. We have shown that if the lowest elevation angle for KBUF were lowered from 0.5° to 0.2°, the detection range of 2-km-deep snowstorms would increase from 115 to 145 km from the radar over Lake Ontario and from about 120 to about 150 km from the radar over Lake Erie. The Binghamton WSR-88D (KBGM) shows comparable improvements in the detection of shallow snowstorms that affect the populated areas to the southeast of Lake Ontario. Though these are relatively small increases compared with KTYX, they represent increases in overall radar coverage areas of 55%–60%.

Beginning during the 2002/03 winter, Canadian weather radars have been scanning at lowered elevation angles that permit the optimum detection of shallow snowstorms. Flatland radars scan as low as ~0.1° to +0.1°. Forecasters have found that, with the lower elevation angles, they have increased their ability to monitor evolving snowfall events. Those who use radars at mountaintop sites sense that the precipitation rates detected at negative elevation angles are much closer to the surface values than before the scanning angles were lowered.

Based on the Canadian experience, WSR-88Ds can expect to encounter increased ground clutter and detect sea (lake) clutter for the first time after lowered elevation angles become operational. The increased ground clutter should be effectively eliminated through use of the newly installed Gaussian model adaptive processor (GMAP). Most of the sea clutter problem would be eliminated when the currently operational sea clutter detection algorithm (SCDA) is adapted for WSR-88D use. With these potential problem areas being satisfactorily eliminated, lowered elevation angles would increase the ability of the radars to detect hazardous low-altitude phenomena and to obtain more accurate quantitative precipitation estimates. In addition, it is well established that there is no radiation hazard to the public outside the WSR-88D radar enclosure (see references cited by Brown et al. 2002). Therefore, lower elevation scan angles on WSR-88D radars will provide the critical additional information that will lead to improved warnings and short-term forecasts.

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