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WSR-88D MONITORING OF SHALLOW LAKE-EFFECT SNOWSTORMS OVER AND AROUND LAKE ONTARIO: SIMULATIONS OF IMPROVEMENTS USING LOWER ELEVATION ANGLES

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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^{o} 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 forecasts would like to have lowered elevation angles.

There are two simulation studies that 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 lake-effect severe storms 100 km from the radar (Brown et al. 2002). In addition, measurements at lower elevation angles would greatly improve the accuracy of quantitative precipitation estimates throughout the radar coverage area. 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 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).

A 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 detect, among other things, flash flood situations that catch hikers unawares 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—which referenced the Brown et al. (2002) and Wood et al. (2003) papers—recommends that "The National Weather Service should improve nationwide 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

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radar, which is 0.52 km above the lake's surface, is in a prime position for detecting convective activity over and around the lake.

Since the Montague WSR-88D overshoots much of the lake-effect snow activity and other convective activity, the use of negative elevation angles would improve the range of detection of shallow storms. Likewise, if the lowest elevation angle of the Buffalo and Binghamton WSR-88Ds was lowered from 0.5^o to 0.2^o, 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 slightly lowered angles for the Buffalo and Binghamton radars, and to thereby demonstrate how detection of 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 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 narrow part of the lake, there is a broad area of snowfall over the downstream shore. On the other hand, when the flow is along the major axis of the lake, a single snowband occurs that produces heavy snowfall in the narrow zone.

From its elevated location, the Montague WSR-88D currently overshoots much of the lake-effect snow activity and other 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 convective activity over portions of both Lake Ontario and Lake Erie. KTYX and KBUF are two of five radars that detect convective activity over 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 two Ontario radars are $–0.1^o$ and 0.0^o, respectively, during the winter and 0.3^o during the summer. In comparison, the lowest angle for the three New York radars is 0.5^o. The lower elevation angles are separated by 0.2^o for the Canadian radars, while they are separated by either $0.4–0.5^o$ or 0.95^o for the WSR-88Ds.

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 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 lake shore.

b. Forecasting challenges

Operational forecasters are continually working toward improving short-term (less than 6 hours) 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 to detect severe winter weather conditions and provide 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 are associated with shallow lake breeze boundaries (King et al. 2003). 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 scale of convective mesoscale snowstorms is often less than 2 km and can be limited to around 1 km at times (Waldstreicher 2002). Summertime lake breeze circulations on the Great Lakes are generally on the order of 1 to 2 km. (Keen and Lyons 1978). For current operational scan strategies that the WSR-88D network provides, detection of these types of shallow weather features is limited.

3. OPTIMIZED SCANNING STRATEGIES

a. WSR-88D radars

The technique for computing the scanning strategy or Volume Coverage Pattern (VCP) for a mountaintop WSR-88D is shown in Fig. 2 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^o 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^o above a flat surface. In this study, we use the lower value of 0.2^o. Using standard conditions for the index of refraction (e.g., Battan 1973) and the height of the radar above the surrounding terrain (0.5 km for KTYX), one can determine (by trial and error) that the elevation angle of the radar beam center that grazes the surface is –0.6^o for KTYX. Applying Smith's results to mountaintop radar KTYX, the lowest elevation angle then is –0.4^o (0.2^o 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. 2. Having selected the lowest elevation angle φ_1, a midaltitude 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 φ_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 desired elevation angle difference is achieved (this procedure is illustrated between φ_1 and φ_2 in Fig. 2). Then the process of decreasing range at 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^o and 19.5^o (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%.

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^o. For a VCP consisting of 14 elevation angles ranging from 0.2^o to 19.5^o, the $\Delta H_{\%}$ value was 20.33% (see resulting VCP 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^o minimum elevation angle restriction is relaxed). For KTYX, KBUF, and KBGM, the lower elevation angles are separated by about one-half beamwidth (0.4–0.5^o) instead of a separation angle of 0.95^o that is common for the WSR-88D precipitation scanning strategies, except for new VCP 12 that also uses one-half beamwidth separation.

The elevation angles determined in this manner are separated by the same vertical distance at a given height above the ground. Since the vertical distance is a percentage of height, the distance between elevation angles at a given range decreases with decreasing height. This approach, which was also used to create VCP 12 (e.g., Brown et al. 2005), 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.

b. 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 2002–2003, an experiment was conducted where the lowest elevation angles for the other radars in the network were set between –0.1^o and +0.1^o (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. Forecasters across Canada were uniformly positive about results obtained during the experiment. They reported an increased ability to monitor localized snow, especially at midranges.

Following the winter experiment, the results were evaluated to determine whether some of the elevation angles needed to be adjusted. Reasoning similar to that of Smith (1998) was used as part of the evaluation. Long-term statistics of radar measurements at the various sites suggested that the computed horizons at some of them were not correct, owing to the coarseness of the digital terrain map used and to the fact that trees are not included as part of the Digital Elevation Model 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.

Unfortunately detailed analysis of the impact of the lower elevation angles on quantitative precipitation estimates (QPE) during the winter has not been done for the Canadian radars, primarily because of a lack of widely distributed trustworthy snow measurements for verification. For mountain-top 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. In the absence of an operational correction for the vertical profile of reflectivity (VPR), precipitation rate estimates based directly on measurements in snow aloft will give low values, so any increased partial blockage at lower angles is partially balanced by lesser VPR effects. Improved detection was considered a success independently of any impact on QPE.

The Canadian experience has shown some consequences of using lower elevation angles. The most significant issue was 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 were based on the spatial distribution of long-term statistics of radar measurements. Blockage was 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 was the appearance of gaps in the data that resulted where the lower elevation angles led to increased ground clutter relative to weather signals. The Doppler clutter filters removed weak precipitation echoes along with the clutter echoes. This resulted in light snow showers intermittently disappearing as they moved over terrain features.

Another consequence of the lower angles was an increase in reports of sea (lake) clutter. Sea clutter is not removed by Doppler clutter filters, but 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 presence of clutter associated with large water surfaces. Lowering the angles produced increased sea clutter in the side lobes, especially during temperature inversions. Sea clutter might be anticipated at KTYX and potentially to a small degree at KBUF when lower elevation angles are adopted. Despite these limitations, the overall conclusion in Canada was that the move to lower elevation angles during the winter was worthwhile once forecasters were trained to understand the new phenomena that were introduced.

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 the Flatland VCP are shown in Fig. 3. 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. 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. 4 and 5, respectively. Over Lake Ontario, the maximum range of detection of a 2-km-deep snowstorm increases from 115 km to 145 km with the Flatland VCP. Over Lake Erie, the maximum range increases from about 120 km to about 150 km.

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 can produce narrow swaths (20–50 km wide) of heavy snowfall (2–5 cm hr^{-1}) 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 make the difference between accumulations that last for 1–2 hr and accumulations that last 24 hr 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. 6. 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^{o} over the lake is shown in Fig. 7.

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. 8. 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^{o} (Fig. 8a) to –0.4^{o} (Fig. 8b), 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^{o} scan is blocked by nearby terrain from northeast through south-southwest of the radar, so the blocked portion is covered by the next elevation angle (0.0^{o}). Within that portion there is a narrow region to the southeast where the lowest unblocked elevation angle is 0.4^{o}. Though portions of the coverage region are blocked by intervening terrain, there is radar coverage closer to the ground at all azimuths with the Mountaintop VCP than with the current VCPs. Brown et al. (2002) discuss the procedure for computing the amount of radar beam blockage.

Comparisons of vertical cross-sections to the west of the radar over the lake using VCP 12 and the Mountaintop VCP are shown in Fig. 9. 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 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 10 shows coverage of Lake Ontario snowstorms using the two Canadian radars and optimum lower elevation angles for the three New York radars. Compared with the current configuration shown in Fig. 1b, there is a marked improvement resulting from the lowered elevation angles. The main improvement comes from KTYX scanning at –0.4^{o}, but there also is some improvement from KBUF and KBGM scanning at the lower elevation angle of +0.2^{o}

Rather than having no detections over the east-central portion of the lake and adjacent land areas, Fig. 10 shows that detections are possible over the entire lake and over all of the surrounding land area. Over-lake 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.

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 overall storm evolution as well as what is developing near the surface of the earth. Unfortunately, those WSR-88Ds placed at elevated locations have been constrained to operate with the lowest elevation angle being +0.5^{o} like 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 at 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 airflow is down the long axis of the lake, a long single snowband forms. Where it crosses the shoreline, snow accumulates at rates of 2–5 cm hr^{-1} or more. In order to adequately warn the public, it is vital for forecasters to know where the snowband is located, the strength of the low-altitude reflectivity, and whether it is moving or stationary. Like all WSR-88Ds, KTYX's lowest elevation angle is 0.5^{o}. 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^{o}, 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^{o} to 0.2^{o}, the detection range of 2-km-deep snowstorms would increase from 115 km to 145 km over Lake Ontario and from about 120 km to about 150 km 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 improved coverage of hazardous weather conditions.

Since the 2002–2003 winter, flatland Canadian radars have been scanning as low as -0.1^{o} to $+0.1^{o}$ in order to monitor snowstorms. Mountaintop radars scan even lower. Forecasters find that, with the lower elevation angles, they have increased their ability to monitor evolving snowfall events. Those at mountaintop sites perceive that precipitation rates are much closer to surface values than before scanning angles were lowered. The Canadian experience also revealed that the lower angles can increase the amount of ground clutter with clutter filters removing some weak precipitation echoes along with the ground clutter. Radars near bodies of water find that sea (lake) clutter—not being stationary—is not removed by the clutter filter. However, though there are some inconveniences that can arise with lower elevation angles, they are far outweighed by the increased ability of the radars to detect stronger precipitation events and obtain more accurate quantitative precipitation estimates. Therefore, if NOAA's National Weather Service were to lower the elevation angles of their WSR-88D radars, forecasters would be able to take better advantage of the warning and short-term forecasting capabilities of the radars.

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TABLE 1. Comparisons of elevation angles for WSR-88D Volume Coverage Pattern (VCP) 12, Flatland VCP (KBUF and KBGM), and Mountaintop VCP (KTYX).

VCP 12	Flatland VCP	KTYX VCP
0.5	0.2	-0.4
0.9	0.6	0.0
1.3	1.1	0.4
1.8	1.6	0.9
2.4	2.2	1.5
3.1	2.9	2.1
4.0	3.7	2.9
5.1	4.7	3.9
6.4	6.0	5.1
8.0	7.6	6.7
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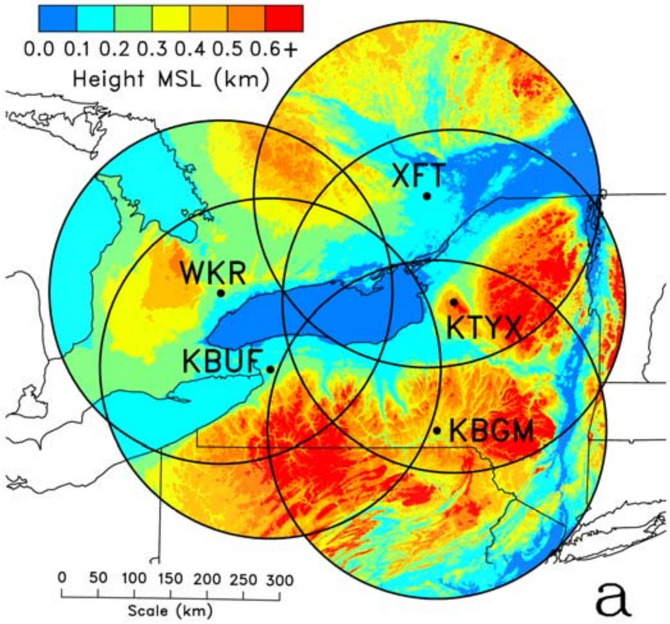
12.5	12.2	11.5
15.6	15.4	15.0
19.5	19.5	19.5



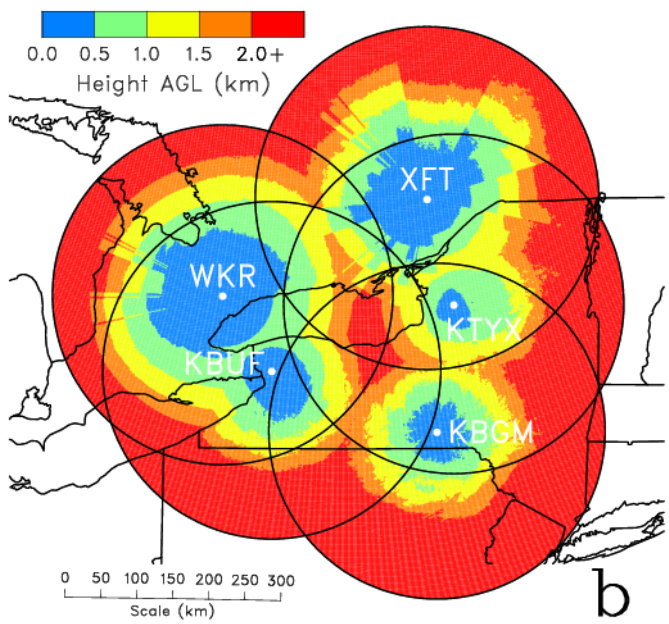


Fig. 1. (a) Topography within 230 km of the five radars surrounding Lake Ontario (center of figure): WKR - King City, Ontario; XFT - Franktown, Ontario; KBUF - Buffalo, New York; KBGM – Binghamton, New York; KTYX - Montague, New York. Topographic data courtesy of the WSR-88D Radar Operations Center. (b) Coverage within 2 km of the surface of Lake Ontario and adjacent terrain at the lowest elevation angles for the surrounding radars; the red area is more than 2 km above the surface. The lowest elevation angle for WKR is -0.1^{o}, for XFT is 0.0^{o}, and for the New York State radars is 0.5^{o}. Where the radar beam for WKR or XFT is blocked, the height of the next elevation angle (separated by 0.2^{o}) is used.

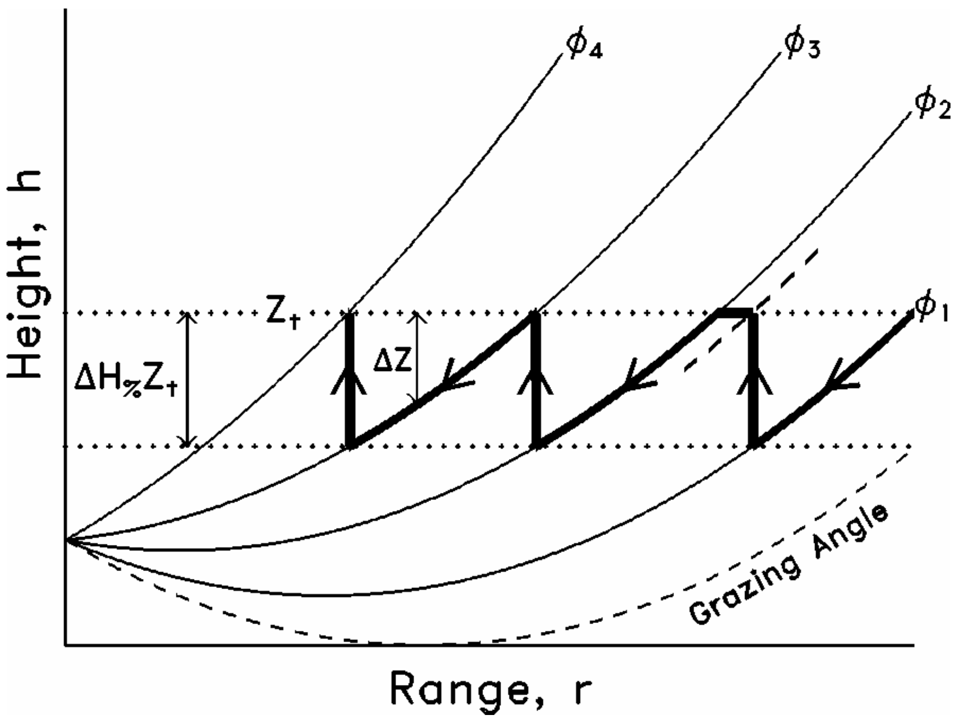
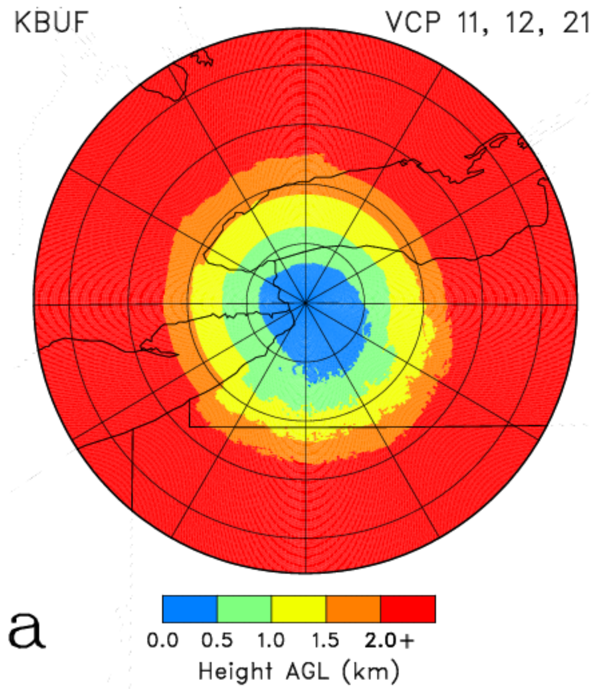


Fig. 2. Schematic of the process used to compute elevation angles for a simulated mountaintop VCP. See text for details. From Brown et al. (2002).



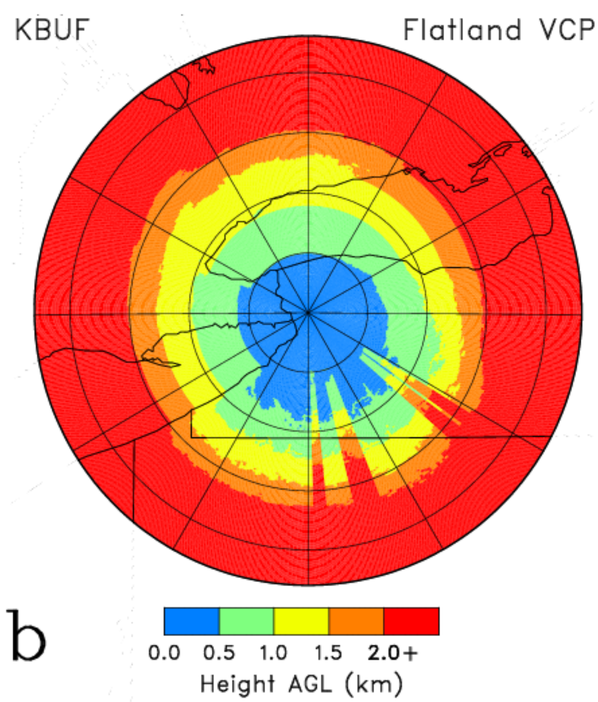


Fig. 3. Height of lowest elevation angles above Lakes Erie and Ontario and adjacent terrain for KBUF using (a) VCPs 11, 12, and 21 (0.5°) and (b) Flatland VCP (0.2°, 0.6°). The red area is more than 2 km above the surface. Range rings are at 50 km intervals.

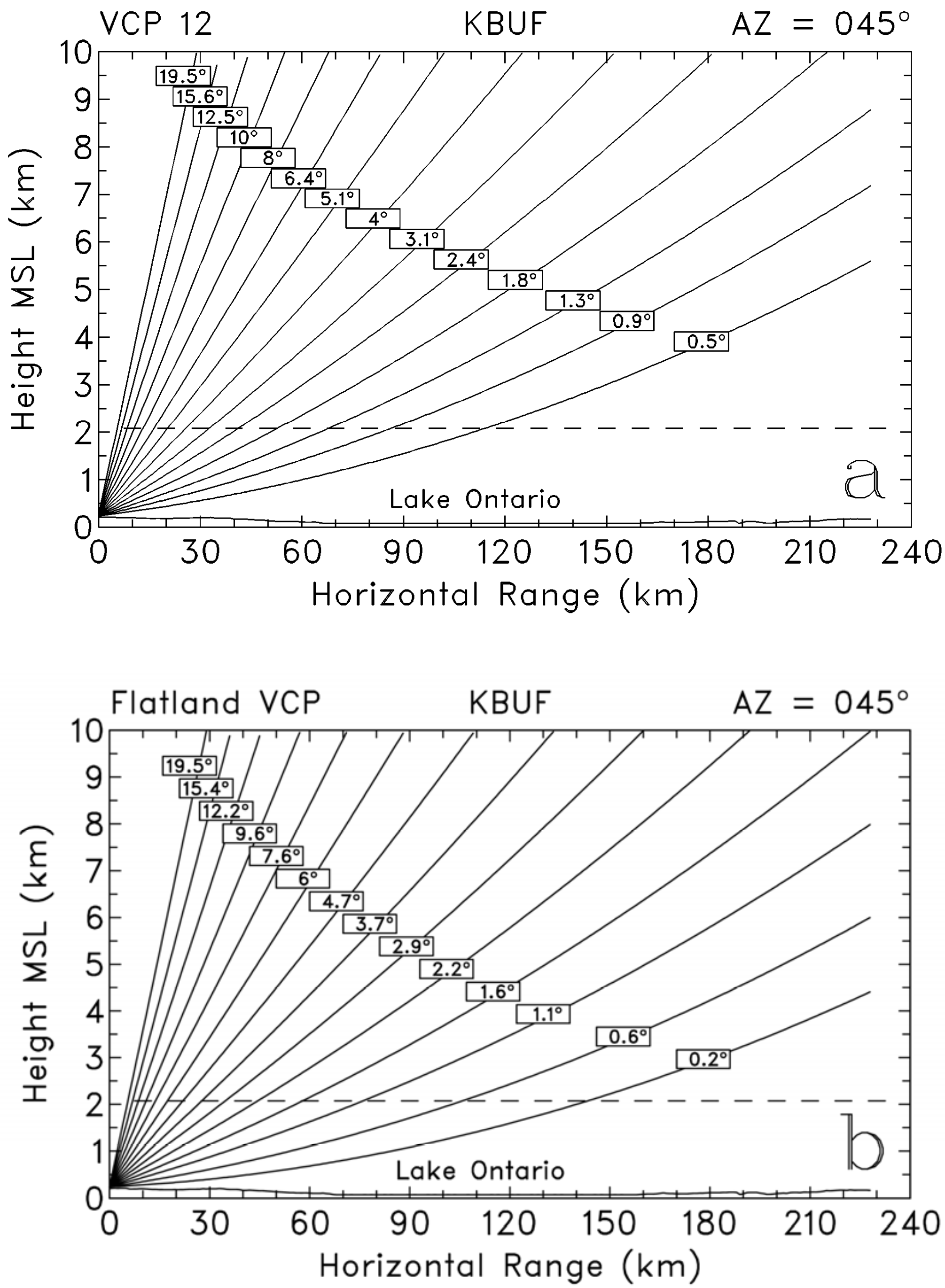


Fig. 4. Vertical cross-section of (a) VCP 12 and (b) Flatland VCP elevation angles along the 045^{o} azimuth from KBUF. The dashed line is 2 km above the surface of Lake Ontario.

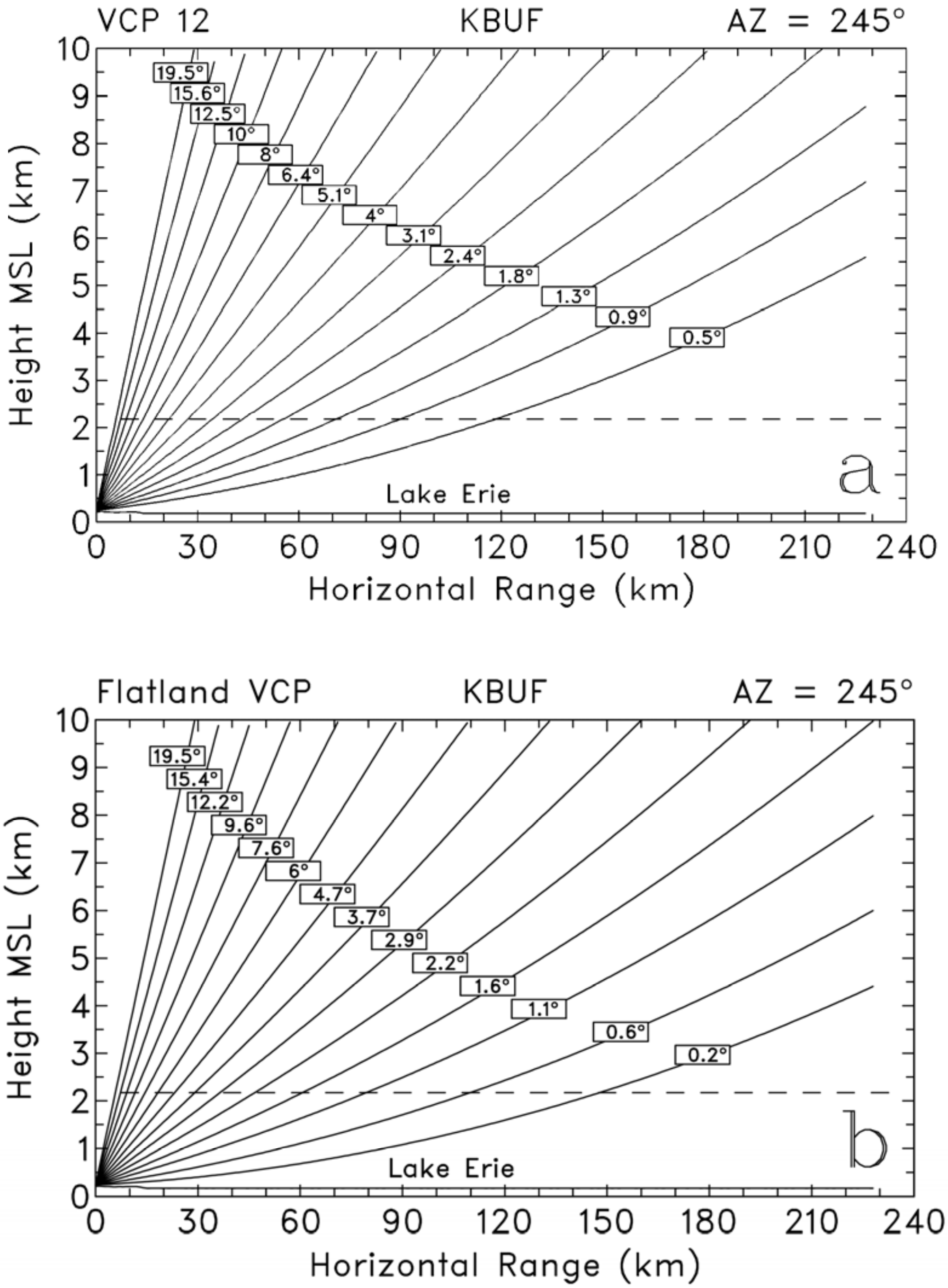


Fig. 5. Vertical cross-section of (a) VCP 12 and (b) Flatland VCP elevation angles along the 245° azimuth from KBUF. The dashed line is 2 km above the surface of Lake Erie.

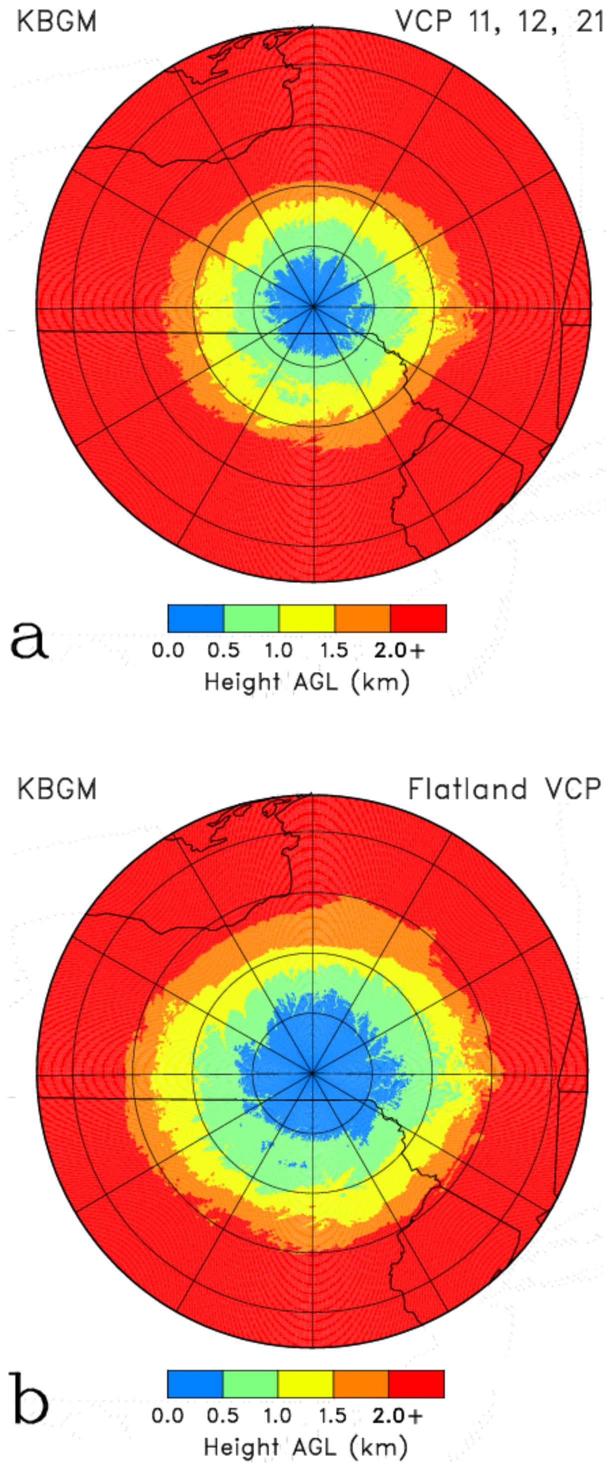


Fig. 6. Height of lowest elevation angle above Lake Ontario and adjacent terrain for KBGM using (a) VCPs 11, 12, and 21 (0.5^{o}) and (b) Flatland VCP (0.2^{o}). The red area is more than 2 km above the surface. Range rings are at 50 km intervals.

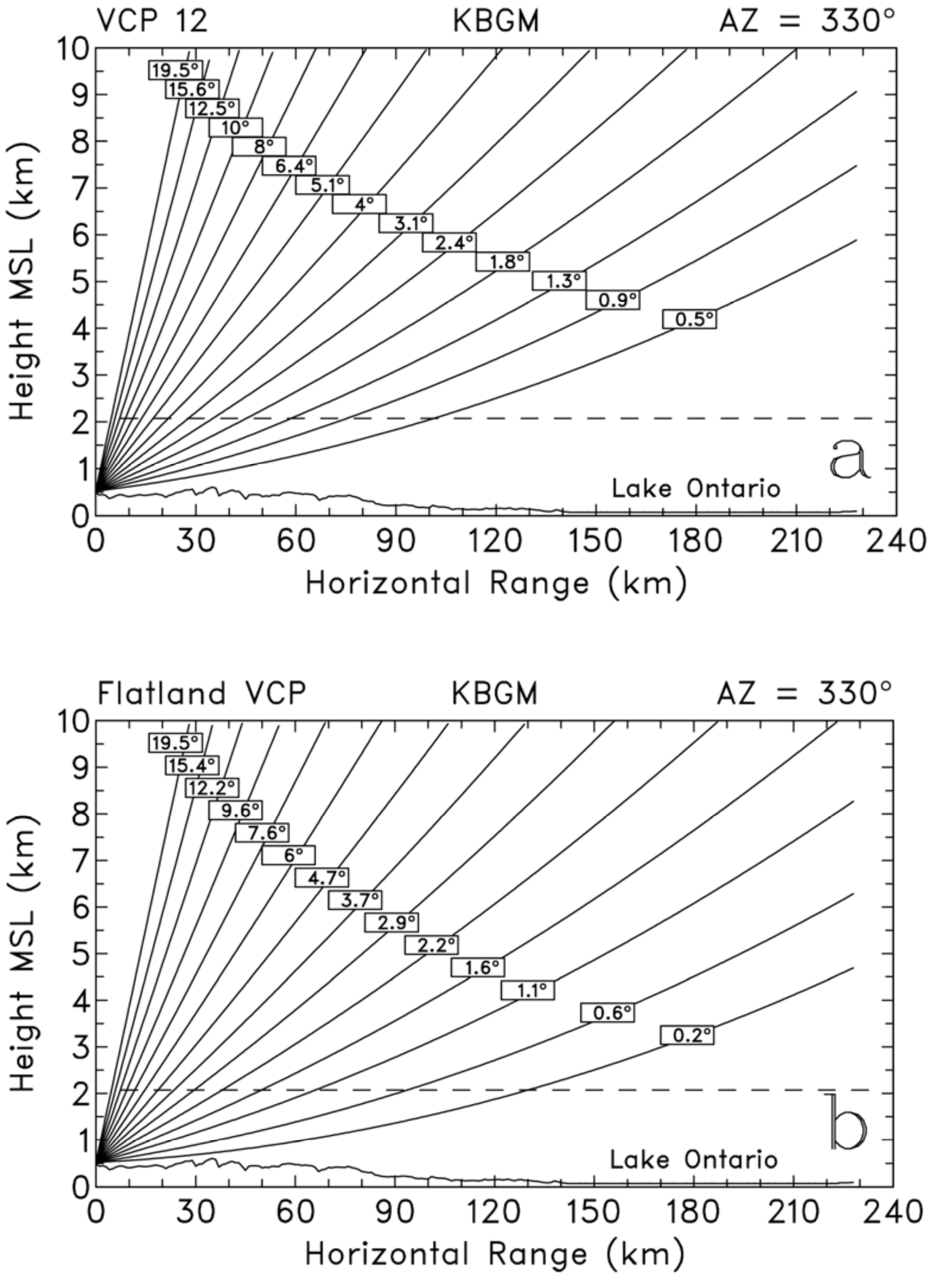


Fig. 7. Vertical cross-section of (a) VCP 12 and (b) Flatland VCP elevation angles along the 330^{o} azimuth from KBGM. The dashed line is 2 km above the surface of Lake Ontario.

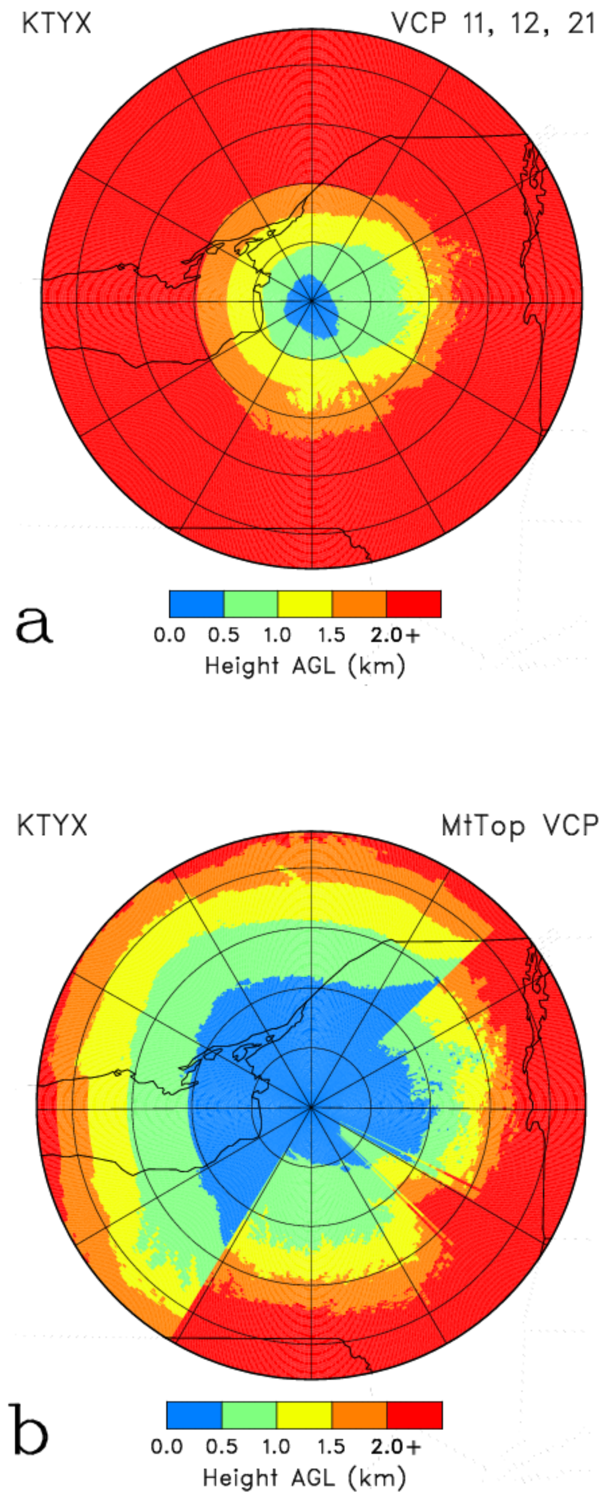
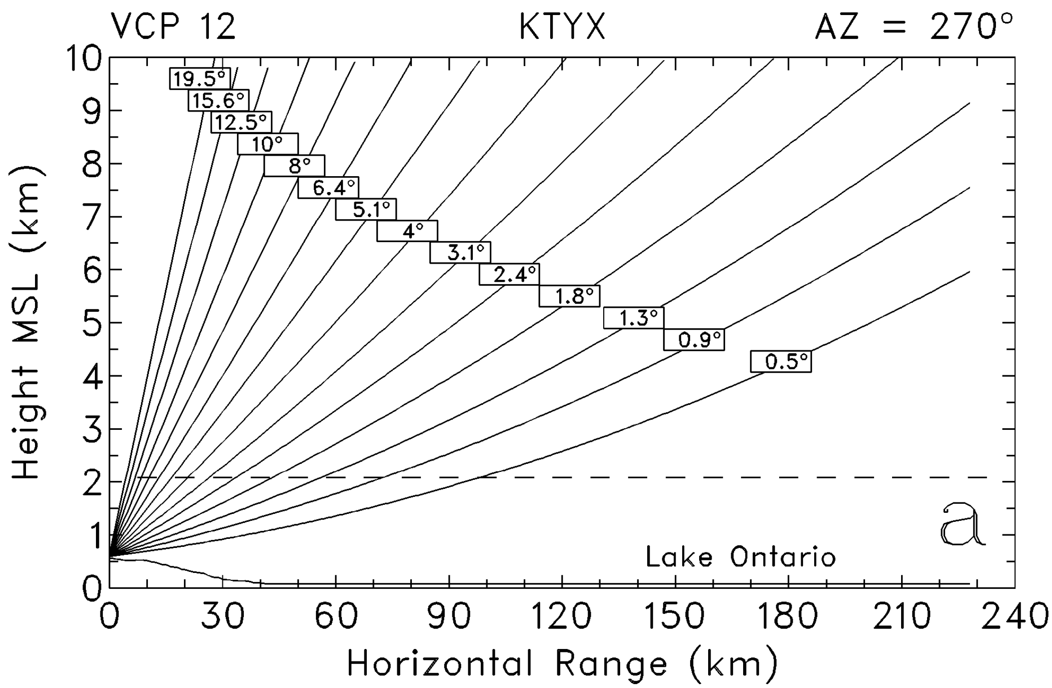


Fig. 8. Height of lowest elevation angles above the lake and adjacent terrain for KTYX using (a) VCPs 11, 12, and 21 (0.5°) and (b) Mountaintop VCP (–0.4°, 0.0°, 0.4°) . The red area is more than 2 km above the surface. Range rings are at 50 km intervals.



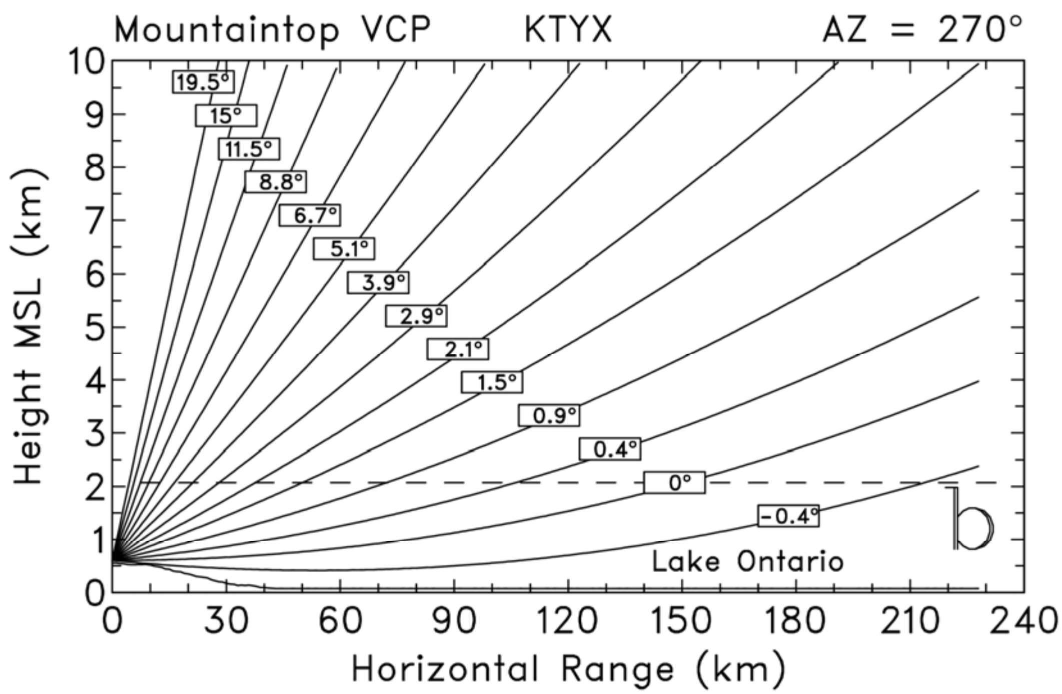


Fig. 9. Vertical cross-section of (a) VCP 12 and (b) Mountaintop VCP elevation angles along the 270° azimuth from KTYX. The dashed line is 2 km above the surface of Lake Ontario.

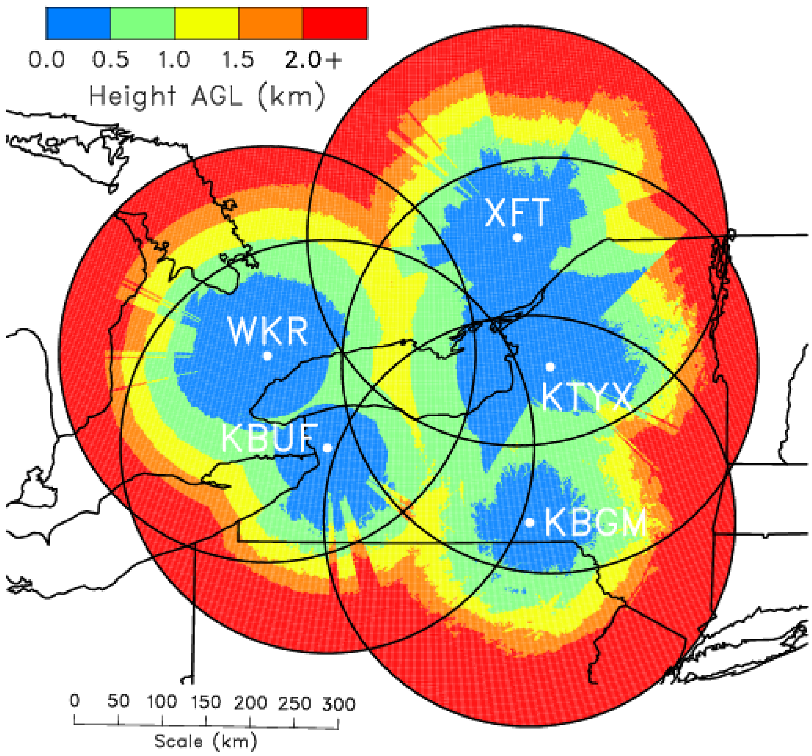


Fig. 10. Coverage within 2 km above Lake Ontario and adjacent terrain by the two Ontario radars using current elevation angles and the three New York WSR-88Ds using lowered elevation angles; the red area is more than 2 km above the surface.