

MountainZebra: Visualization of Radar Data Over Complex Terrain

Curtis N. James¹

Stacy R. Brodzik

Harry Edmon

Robert A. Houze, Jr.

Sandra E. Yuter

Department of Atmospheric Sciences
University of Washington

Submitted
Weather and Forecasting

March 1999

1. Corresponding author: Curtis N. James, Atmospheric Sciences, Box 351640, University of Washington, Seattle, WA 98195-1640. email: curt@atmos.washington.edu

Abstract

MountainZebra is a dataflow configuration that processes and displays radar data over complex terrain. The system includes 3-D topographical information in the NCAR Zebra data visualization and integration software. MountainZebra operates routinely on a 3-D data stream from the National Weather Service WSR-88D (Weather Surveillance Radar-88D) at Camano Island, Washington (near Seattle). The WSR-88D data are continuously acquired, archived, formatted, and interpolated for multi-dimensional display. The three-dimensional topographical information in MountainZebra can be superimposed with any horizontal or vertical display of the radar data. This system allows radar data and other geophysical fields to be analyzed in precise relation to the underlying terrain.

Terrain-based visualization in MountainZebra facilitates radar data analysis by identifying terrain clutter and shadowing and by identifying orographic precipitation mechanisms. We illustrate the utility of MountainZebra in the investigation of stable orographic enhancement over the windward slopes of the Cascade Mountains of the Pacific Northwest and an orogenic squall line to the lee of the Swiss Alps.

1. Introduction

Mountainous terrain affects radar echo patterns by interfering with the radar beam and modifying precipitation processes and patterns. When the radar beam is intercepted by terrain, clutter and shadowing result (Joss and Lee 1995; Lin and Reilly 1997). Terrain modification of the airflow affects precipitation (Smith 1979; Houze 1993, Chapter 12). The spatial coverage and severity of clutter and shadowing depend on the radar characteristics, the geometry of the terrain, and the refractive characteristics of the atmosphere, which vary with low-level stability and moisture stratification (Doviak and Zrnic 1993). In orographic regimes, the variability of the index of refraction is often greater than over flat terrain as a result of frequent low-level inversions (e.g. Gustavsson et al. 1998; Bell and Bosart 1988).

Lin and Reilly (1997) developed a technique that simulates terrain backscatter for given radar characteristics, location, and refractivity environment. They were able to reproduce clutter patterns observed by shipboard radars near coastal mountains. However, for the purpose of identifying terrain clutter and shadowing operationally, it is not necessary to quantify terrain backscatter. One needs only to overlay the 3-D terrain on the 3-D echo pattern at comparable spatial resolution.

Overlaying the high-resolution terrain field and the radar data (accurately located in both the horizontal and vertical) also greatly aids the physical interpretation of the radar echoes. Modification of the airflow and precipitation pattern by the topography occurs on scales ranging from individual peaks and valleys to the gross scale of the whole mountain range. Without being able to visualize precisely how the echo patterns in horizontal and vertical cross sections are juxtaposed with the topography, the analyst is handicapped.

To address these needs, we have developed MountainZebra, a data processing and visualiza-

tion system which displays radar data and terrain simultaneously. This system is built around Zebra, a software package developed by NCAR's Research Data Program (Corbet et al. 1994) which has the ability to ingest and overlay multiple real-time data sets. MountainZebra operates routinely on a data stream from the National Weather Service WSR-88D (Weather Surveillance Radar-88D) at Camano Island, located approximately 50 km north-northwest of Seattle, Washington. The purpose of this paper is to describe the MountainZebra system and show how the incorporation of the terrain-height field into a radar-data visualization system aids the interpretation of the radar data. We first present an overview of the automated WSR-88D data flow as configured for the University of Washington. Then, we illustrate the utility of MountainZebra in the analysis of two examples of orographic precipitation.

2. The automated data flow

Figure 1 contains a schematic of MountainZebra's automated data flow for the Camano Island radar. Raw analog radar returns (or Level I data) obtained by the WSR-88D propagate through the wave guide to the radar processor at the Radar Data Acquisition (RDA) site. The processor converts raw data to reflectivity, radial velocity, and spectral width in polar coordinates and archives these data to exabyte tape. The polar data format is hereafter referred to as "Level II" (Crum and Alberty 1993). The Level II data are then transmitted to the Radar Product Generator (RPG) at the National Weather Service Forecast Office (NWSFO), where various graphical (Level III) products are produced for display at the Principal User Processor (PUP) and disseminated to commercial data providers via the NEXRAD Information Dissemination System (NIDS). The Radar Interface and Data Distribution System (RIDDS, Rhue and Jain 1995) accesses the Level II data in parallel with Level III product generation within the RPG.

Via RIDDS, Level II data from Camano Island go to an on-site workstation where each ray is stored in a circular buffer. Once 100 rays (i.e. 5/18 of a radar sweep) are received, they are packaged, compressed, and queued for transmission to the Department of Atmospheric Sciences at the University of Washington. The data are sent via a nondedicated communication link to the department server at rates of up to 70 kbps. The rays are then uncompressed and reassembled into full Level II volumes. Each volume contains anywhere from 5 to 14 radar sweeps, depending on the volume coverage pattern (or scan strategy) used by the radar at that time. The Level II volumes are written to disk, where they remain for about a week before they are archived to tape. Meanwhile, a workstation dedicated to MountainZebra processing and display immediately reads each reassembled Level II volume and converts it to Universal Format (UF; Barnes 1980; this process not shown in Fig. 1). Then, algorithms are applied to the UF file to remove nonprecipitation echoes and correct aliased radial velocity. Finally, the data are bilinearly interpolated to a Cartesian grid using NCAR's SPRINT software (Mohr and Vaughan 1979).

Data storage limitations constrain us to use a $150 \text{ km} \times 150 \text{ km} \times 10.5 \text{ km}$ interpolation grid with $2 \text{ km} \times 2 \text{ km}$ resolution in the horizontal and 0.5 km resolution in the vertical. Figure 2 shows a vertical cross section of the elevation angle sequence typically employed by the Camano Island WSR-88D in precipitation mode. Figure 3 projects a small portion of the 0.5° elevation base scan onto a horizontal plane. In these figures, a $4/3$ earth radius assumption¹ is used to approximate standard atmospheric refraction (Doviak and Zrnic 1993), and the Cartesian grid-point locations after interpolation are indicated by '+'. At low levels ($< 2 \text{ km MSL}$) and close range ($< 20 \text{ km}$), the interpolation grid reduces the vertical resolution of the tilt sequence (Fig. 2). Elsewhere, the

1. The current version of SPRINT makes this assumption during interpolation to approximate ray propagation. For the purpose of visually identifying terrain clutter, shadowing, and anomalous propagation, this assumption may not be adequate. Ideally, the interpolation routine should use a nearby sounding to better approximate ray propagation.

interpolation grid is comparable to or at a finer resolution than the vertical resolution of the tilt sequence. The WSR-88D provides 1 km resolution in reflectivity and 0.5 km resolution in radial velocity along each radial. Thus, the along-radial resolution is reduced by the 2 km horizontal interpolation everywhere in the domain. The azimuthal resolution is reduced at ranges less than 120 km, and especially at ranges less than 40 km (Fig. 3). The loss of resolution could easily be remedied by interpolating on a finer grid with the side effects of larger volume size, longer computation time for the interpolation, and greater oversampling of the grid versus the polar radar data at farther ranges. Another problem is that many of the grid points are located in data-void regions (i.e. between 4.3°, 6.0°, 9.9°, 14.6°, and 19.5° elevation scans in Fig. 2). This limitation of the scan strategy can produce concentric rings of missing data in horizontal cross sections.

Interpolating the data to a Cartesian grid facilitates the computation and display of arbitrary horizontal and vertical cross sections and makes analysis more intuitive, without the “saw tooth” effect seen in Constant Altitude Plan Position Indicator (CAPPI)² displays. The Cartesian-interpolated fields further facilitate statistical and diagnostic computations with the data, especially those that involve spatial derivatives.

After interpolation by Sprint is complete, each volume is converted to Unidata’s Network Common Data Format (NetCDF) for display. The NetCDF files are written to disk and remote copied back to the NWSFO (Fig. 1). Once the files are available on disk, dedicated workstations at both the Department of Atmospheric Sciences and the NWSFO automatically ingest the data for display. Within one to two weeks, each NetCDF volume that is deemed meteorologically significant is moved to mass storage for future reference. Radar volumes in UF format are UNIX

2. CAPPI displays are traditionally produced by assigning the value of the nearest data bin in the polar-coordinate tilt sequence to each grid point of a Cartesian array. Interpolation schemes use multiple data bins in the vicinity of each Cartesian grid point to estimate its value.

compressed, copied to exabyte tape, and deleted from disk.

3. Terrain-based visualization in Zebra

The automated data flow, which includes the acquisition, processing, and archival of each radar volume, is finished within 5 to 8 min of the completion of a volume scan. MountainZebra then provides terrain-based visualization. Dedicated MountainZebra displays are located at both the NWSFO and the Department of Atmospheric Sciences. The displays update automatically when the processing of each new volume is complete. As described by Corbet et al. (1994), Zebra is highly interactive, allowing the user to synthesize multiple real-time data sets, overlay diverse fields, zoom in and out, specify any arbitrary horizontal or vertical cross section, change contouring options, and make time-lapse movies. MountainZebra includes topographical information on less than 1-km horizontal resolution, which can be displayed along with radar fields or other data sets in any arbitrary horizontal or vertical cross section selected by the user. Thus, four-dimensional interpretation of precipitation system structure and dynamics in relation to terrain geometry can be achieved with MountainZebra.

There have been other attempts to overlay radar data and topography. Doick and Holt (1995) created three-dimensional displays of radar and terrain and suggested, as we do, that this would improve radar data interpretation and lead to new observational insights. MountainZebra accomplishes this goal particularly well by interpolating radar fields to a three-dimensional Cartesian grid (as opposed to vertically stacking CAPPI displays) and automatically updating. MountainZebra also allows the user to overlay any other relevant field (e.g., satellite data, mesoscale model fields, station data, etc.) with the radar data and terrain.

Archived radar data from other sources can also be converted to UF format, interpolated,

and converted to NetCDF for analysis and display in customized versions of MountainZebra containing the appropriate topographic data. This method has been used to analyze data sets from several other radars in mountainous regions, including WSR-88D Level II archives from Eureka, CA, and encoded Graphical Image Format (GIF) archives from the Monte Lema radar of the Swiss Meteorological Institute, near Locarno, Switzerland. The latter is part of a MountainZebra system customized for the Swiss Alps which is a prototype for a near-real-time system to be used in the Mesoscale Alpine Programme (MAP; Binder and Schär 1996).

The sample terrain-based displays that follow illustrate the utility of terrain-based radar data visualization for investigating orographic precipitation. The samples include stable orographic precipitation in western Washington and an orogenic squall line to the lee of the Swiss Alps.

a. Orographic precipitation in western Washington

At 0931 UTC 23 January 1998, widespread precipitation fell over western Washington in the moist, stable flow ahead of an approaching trough. The 12Z sounding taken from the coastal town of Quillayute (UIL) exhibited a lifted index of 7, a freezing level of 2.3 km MSL, and a Brunt-Väisälä frequency at 3 km MSL of roughly 0.009 s^{-1} . MountainZebra horizontal cross sections of Camano Island radar reflectivity (Fig. 4a) and radial velocity (Fig. 4b) at 1.5 km MSL altitude show widespread precipitation and south-southwesterly flow. In the horizontal cross section of reflectivity, precipitation is suppressed between 80 km west and 40 km southeast of the radar site as a result of subsidence to the lee of the Olympic Mountains. Just to the northeast of the rain shadow, upslope enhancement is occurring over the windward slopes of the Cascade Mountains, as evidenced by higher reflectivity in this region.

A vertical cross section of reflectivity (Fig. 5a) taken from the radar toward the northeast

(indicated by the red line segment in Fig. 4a and 4b) reveals the enhanced precipitation over the windward slopes of the Cascades. As evidenced by the horizontal alignment of the reflectivity contours and the enhanced reflectivity associated with a bright band located between 1.5 and 3 km altitude MSL, the precipitation was stratiform in nature. Orographic lifting was not destabilizing the thermodynamic profile enough to produce convection. The height of the bright band, though not well resolved by the 0.5 km vertical resolution of the interpolation grid, roughly corresponded to the freezing level of 2.3 km MSL measured by the upstream sounding at UIL 2.5 hours later. The heaviest precipitation was occurring between 50 km and 65 km range from the radar, where the reflectivity approached 40 dBZ. The radial velocity field along the same cross section (Fig. 5b) exhibited strong radial convergence in this region of maximum enhancement. Assuming that there is little divergence in the cross-radial direction, one would expect relatively strong vertical velocities in this region. Thus, the radial velocity and the reflectivity data are consistent with the topographical forcing. Overlaying radar fields with the topography in vertical cross sections allows the user to identify readily where orographic enhancement is occurring. The orographic enhancement seems to be greatest on the lower slopes—not at the crest of the Cascade Range. This characteristic was noted by Hobbs et al. (1975) in a case study of a front passing over the Cascades. Collection of a large sample of Camano Island radar data with MountainZebra will allow us to determine statistically whether the enhancement is favored on the lower slopes.

Overlaying radar volumes with topography is also advantageous when assessing data quality. In this example, we note in both Fig. 5a and 5b that the lowest scan is partially blocked by Mt. Baker (the tallest peak in the terrain profile). In this region, clutter suppression has removed data where mountain slopes are exposed to the radar signals. In Mt. Baker's shadow ($x=80$ to 100 km), the returned power is less than immediately upstream.

Also of interest in this example is the apparent gravity wave structure in the radial velocity field between 2 and 7 km height (Fig. 5b). At 3 km altitude, we note a layer of maximum radial velocity (~ 25 m/s) that spans most of the cross section. In this layer, the radial velocity field oscillates with an horizontal wavelength of about 15 km. In order to investigate the presence of gravity waves, we use the dispersion relation for linear, 2-D gravity waves in irrotational, Boussinesq flow,

$$\nu - \bar{u}k = \pm N \frac{k}{\sqrt{k^2 + m^2}},$$

where ν is the ground-relative frequency of the waves, N is the Brunt-Väisälä frequency, and k and m are the horizontal and vertical wave numbers, respectively (Holton 1992). Assuming stationary hydrostatic waves, $\nu = 0$ and $m \ll k$, we estimate that the value of N necessary to produce a horizontal wavelength of 15 km with a mean wind of 25 m s^{-1} is 0.0105 s^{-1} . This corresponds roughly to the Brunt-Väisälä frequency estimated using the UIL sounding.

b. An orogenic squall line to the lee of the Swiss Alps

On 7-8 July 1996, a squall line formed to the lee of the Swiss Alps and was well sampled by the new Swiss operational C-band Doppler radar at Monte Lema in Southern Switzerland (Fig. 6). Joss et al. (1998) describe this radar system in detail. Full-volume reflectivity and radial velocity data were obtained for analysis, and the data were processed and interpolated to a Cartesian grid for terrain-based display. The squall line was associated with a surface mesocyclone that formed to the lee of the Swiss Alps and then moved eastward across Northern Italy under the influence of an upper-level trough. An analysis of the 14 km resolution Swiss Model (SM; Majewski 1991) simulation of this case indicates that the mesocyclone was similar to one simulated by Aebischer

and Schär (1998), in terms of its location of development, horizontal scale, and propagation. Such lee cyclones in Northern Italy are known to occur in two stages (Buzzi and Tibaldi 1978; McGinley 1982). In the first stage, the progression of a surface cold front is slowed by the terrain. Cold air invades the Mediterranean region and low-level vorticity is rapidly generated over the Gulf of Genoa and northwestern Italy. During the second stage, the rate of cyclone development decreases to that of typical baroclinic systems as the upper-level trough interacts with the orogenic low.

Figure 6 shows the SM sea level pressure field, initialized at 12Z July 7 and valid at 00Z July 8, indicating the approximate location and strength of the mesocyclone (central pressure ≈ 995 mb). SM forecasts initialized at 00Z predicted the development of northerly downslope flow by 06Z that intensified to speeds of over 30 m s^{-1} by 12Z (Fig. 7c).

Analysis of Monte Lema volumes using MountainZebra indicates that prior to the development of downslope flow, thunderstorms were initiated by the upslope flow of moist, conditionally unstable air in the northeast quadrant of the mesocyclone. The convective activity extended from near the center of the mesocyclone toward the northeast, but exhibited very little convective organization in its weakly sheared environment. However, under the forcing of downslope flow between 01Z and 02Z, the reflectivity of the convective cells intensified, and the convection organized into a squall line (Fig. 8a). It propagated slowly to the southeast for approximately three hours, then asymmetries developed, with the southern side of the convective line moving rapidly southeastward. Behind the leading convective line, a comma-shaped precipitation pattern was observed in the reflectivity field (Fig. 9), and the radial velocity field indicated the presence of rotation. Thus, the evolution of this squall line was apparently similar to that of long-lived squalls over flat terrain, in which the southern side of the convective line accelerates and a mesoscale convective vortex (MCV) forms in the trailing stratiform region (Skamarock et al. 1994).

Vertical cross sections of radial velocity and reflectivity through the Alpine squall line also exhibit structures that are common to midlatitude squalls. A leading convective line is observed between $x=120$ and $x=140$ km (Fig. 10a), characterized by high reflectivity and deep vertical development. A trailing stratiform region is identified between $x=40$ and $x=120$ km, characterized by weaker reflectivity and horizontally aligned reflectivity contours. In the radial velocity field (Fig. 8b), there is evidence of strong low-level convergence at the base of the convective line over the foothills of the Alps ($x=140$ km; see Fig. 10b). Other structures that can be identified are front-to-rear flow at altitudes above 6 km in the trailing stratiform region, low-level rear inflow, and evidence of strong storm-top divergence.

Despite its prototypical structure, the MountainZebra displays, together with forecast model output suggest that the squall line was influenced by orographic forcing. Analysis of the evolution of the radial velocity field indicates that between 01Z and 02Z, a surge of downslope flow converged with the upslope flow around the lee cyclone. It was during this time that the convection became organized into a squall line. This downslope flow was observed by radar, in radial velocity cross sections in Fig. 8b and 10b, with the most intense radial inflow immediately above the Alpine slopes. It is believed that the downslope flow enhanced the rear inflow into the squall line, contributing to its development and organization.

4. Conclusions

Terrain-based visualization improves radar data analysis over complex terrain, both in the identification of topographically induced errors and the investigation of orographic precipitation mechanisms. For this purpose, MountainZebra has been developed to acquire, process, archive, and display radar data in precise relation to the underlying terrain. Real-time WSR-88D level II

data from Camano Island, Washington, are accessed via the National Severe Storm Laboratory's RIDDS system and used as input to a chain of programs that reformats and interpolates radar data for display in Zebra. We have generated high-resolution topographical information that can be superimposed on the radar data in any arbitrary horizontal or vertical cross section.

The sample displays provided in this paper demonstrate the utility of terrain-based radar data visualization. In a stable precipitation event over western Washington, this technique aided in the identification of a rain shadow to the lee of the Olympic Mountains and stable orographic enhancement over the windward slopes of the Cascade Range. Evidence of gravity waves was also found in vertical cross sections through the radial velocity field.

Radar data from a squall line on the southern side of the Swiss Alps were also examined in relation to the terrain. Although the squall line contained flow structures that are common to mid-latitude squall lines, there is evidence to suggest that the structures were orogenic and orographically enhanced. It appears that a lee mesocyclone produced upslope flow that initiated convection and later evolved into an MCV structure behind the leading convective line. It is also evident that downslope flow, converging with upslope flow around the mesocyclone, contributed to squall line development and organization.

Thus, by interpolating radar volumes to a Cartesian grid and overlaying them with the terrain in any horizontal or vertical cross section, effective terrain-based visualization is achieved. Since MountainZebra can display any regularly or irregularly gridded geophysical field, this visualization technique can be expanded to include mesoscale model fields, satellite imagery, and other geophysical fields, and can be applied to both operational applications and research in mountain meteorology.

Acknowledgments. The authors appreciate the collaboration of Brad Colman and Chris Hill of the Seattle National Weather Service Forecast Office. The high-resolution terrain elevation data were provided by NCAR's Scientific Computing Division and the MAP Data Centre. Monte Lema radar data and SM fields were provided by Jürg Joss, Gianmario Galli, and Peter Binder of the Swiss Meteorological Institute. This research was supported in part by National Science Foundation Grant ATM-9409988, Office of Naval Research Grant N00014-97-0717, National Aeronautics and Space Administration Grant NAG5-1599, and by JISAO Cooperative Agreement NA67RJ0155 (JISAO contribution number 672).

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Figures

Figure 1. Schematic of the Camano Island WSR-88D data flow. Enclosed in rectangles are the Radar Data Acquisition (RDA) site (top left), the Seattle National Weather Service Forecast Office (NWSFO; top right), and the University of Washington Department of Atmospheric Sciences (bottom). Workstations equipped with the Zebra software are indicated with a “Z”. Conversion to universal format not shown.

Figure 2. WSR-88D tilt sequence using Volume Coverage Pattern 21 and assuming standard atmospheric refraction. The location of the radar dish is indicated by the open circle at 0.0 km horizontal range, and the Cartesian grid-point locations are indicated by ‘+’.

Figure 3. The bin geometry of the northeast quadrant of the WSR-88D base reflectivity scan (0.5°) at close range, projected onto a horizontal plane. The Cartesian grid-point locations are indicated by ‘+’. The bins at range less than 10 km are too small to be distinctly plotted

and are not shown.

Figure 4. MountainZebra constant altitude cross sections at 1.5 km MSL using Camano Island WSR-88D (a) reflectivity and (b) radial velocity data from 0931 UTC 23 January 1998. The background topography is shown in grayscale increments of 0.4 km MSL, with altitudes ≤ 0.0 km highlighted in steelblue. Range ring spacing is 20 km. Negative radial velocity is used to indicate inbound wind.

Figure 5. MountainZebra vertical cross sections of (a) reflectivity and (b) radial velocity from southwest to northeast along the red line segment in Fig. 4. The vertical profile of the underlying topography is shown in gray.

Figure 6. The 12 hour SM forecast of sea level pressure (contours) and 950 mb wind (vectors) valid 00Z 8 July 1996. The approximate locations of the Monte Lema radar and Milan, Italy, are shown. Dashed line indicates vertical cross section of SM-simulated meridional wind.

Figure 7. Vertical cross section of the SM-simulated meridional wind along the dashed line in Fig. 6. Forecasts are valid (a) 00Z (initialized 12Z July 7, 1996), (b) 06Z (initialized 00Z July 8, 1996), and (c) 12Z July 8, 1996 (initialized 00Z July 8, 1996).

Figure 8. MountainZebra horizontal cross sections of (a) reflectivity at 3.0 km MSL and (b) radial velocity at 1.5 km MSL from Monte Lema at 0450 UTC 8 July 1996. The red segment

indicates the location of the vertical cross sections in Fig. 10 (range ring spacing is 10 km).

Figure 9. MountainZebra horizontal cross section of reflectivity at 3.0 km MSL, 0750 UTC 8 July 1996, indicating the size and position of the MCV in the context of the Alpine topography.

Figure 10. MountainZebra vertical cross sections from northwest to southeast of (a) reflectivity and (b) radial velocity obtained from an interpolated 20 tilt volume scan from Monte Lema at 0452 UTC 8 July 1996.

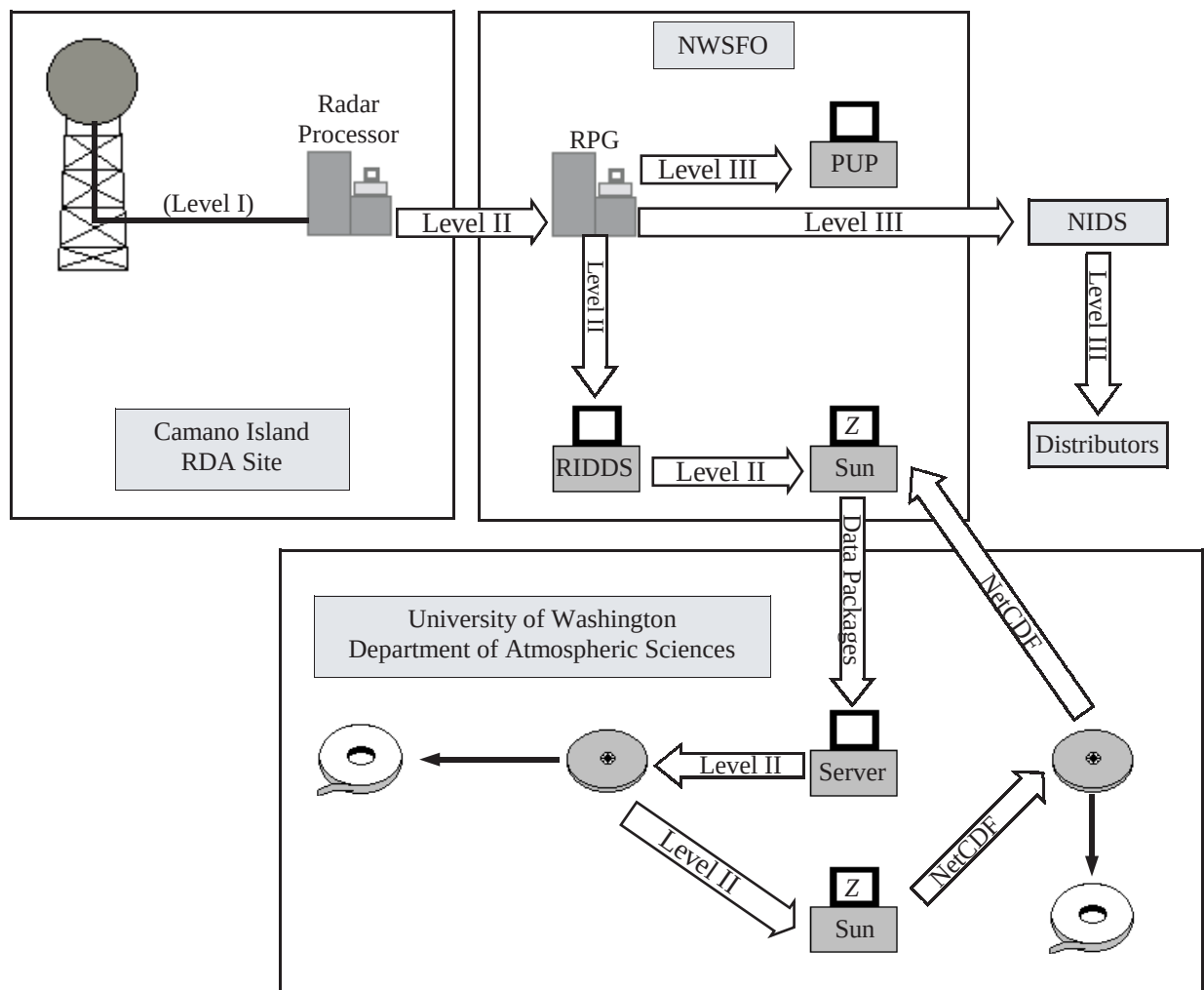


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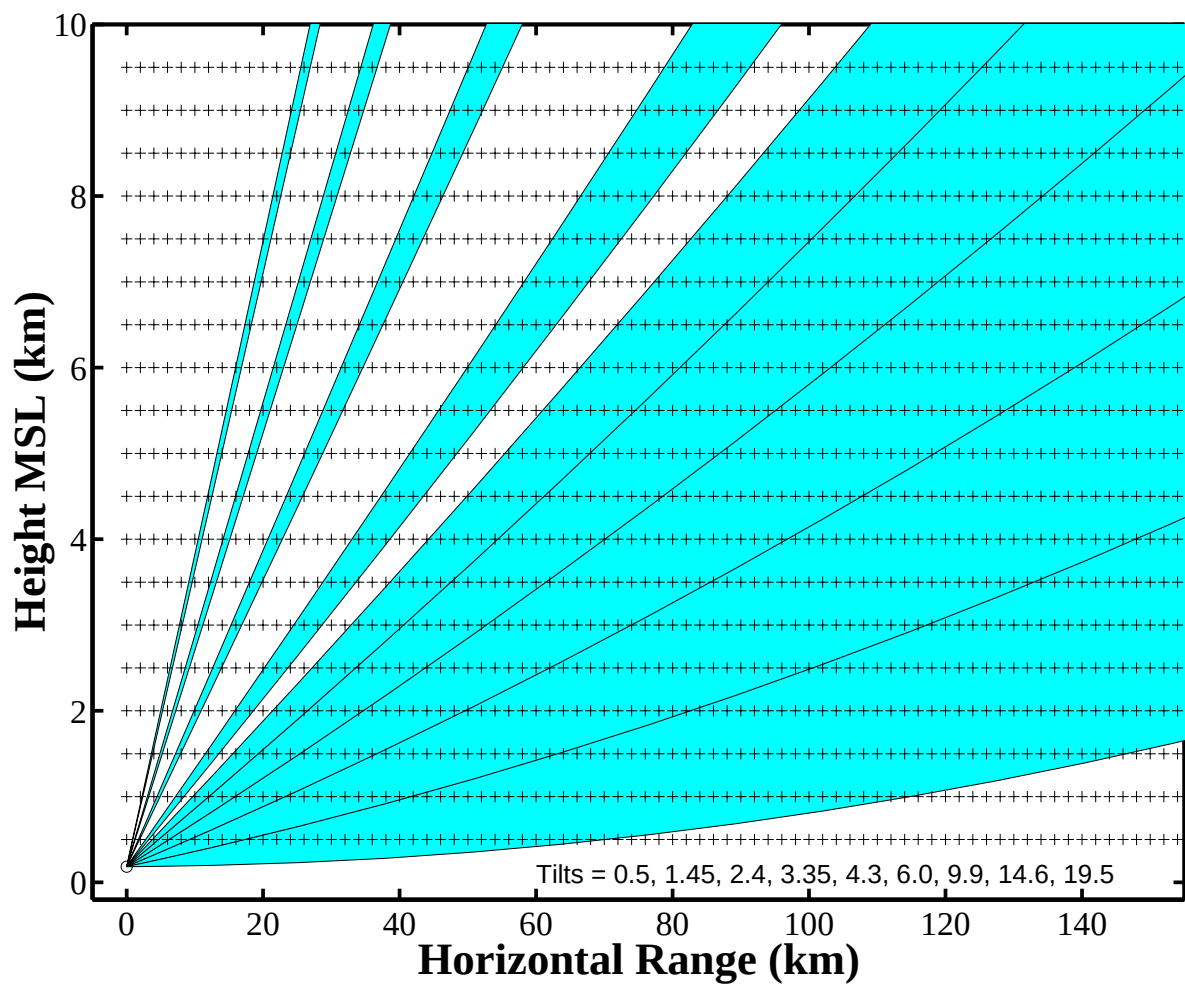


Figure 2. WSR-88D tilt sequence using volume coverage pattern 21 and assuming standard atmospheric refraction. The location of the radar dish is indicated by the open circle at 0.0 km horizontal range, and the Cartesian grid-point locations are indicated by the “+”.

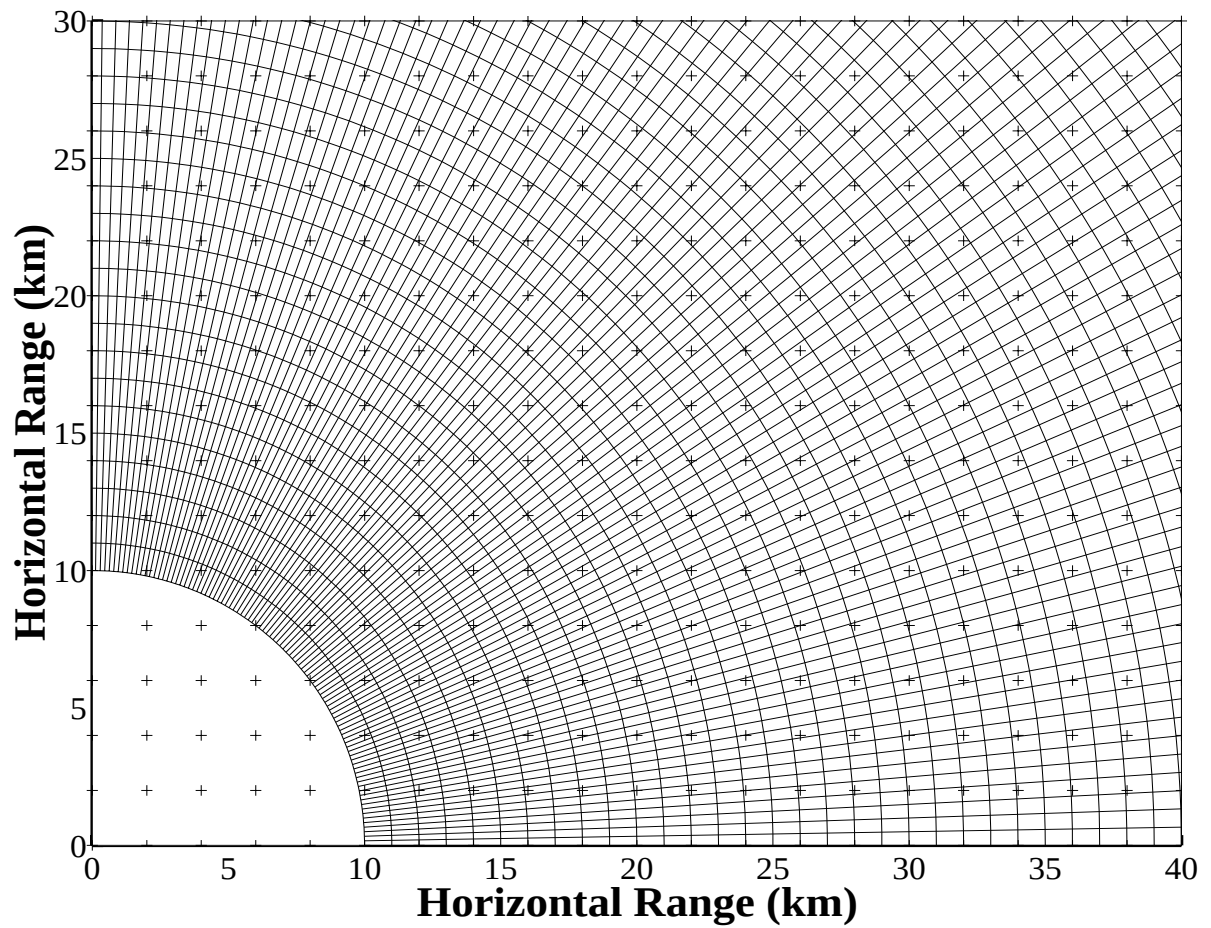


Figure 3. The bin geometry of the northeast quadrant of the WSR-88D base reflectivity scan (0.5 deg) at close range, projected onto a horizontal plane. The Cartesian grid point locations are indicated by a “+”. The bins at range less than 10 km are too small to be distinctly plotted and are not shown.

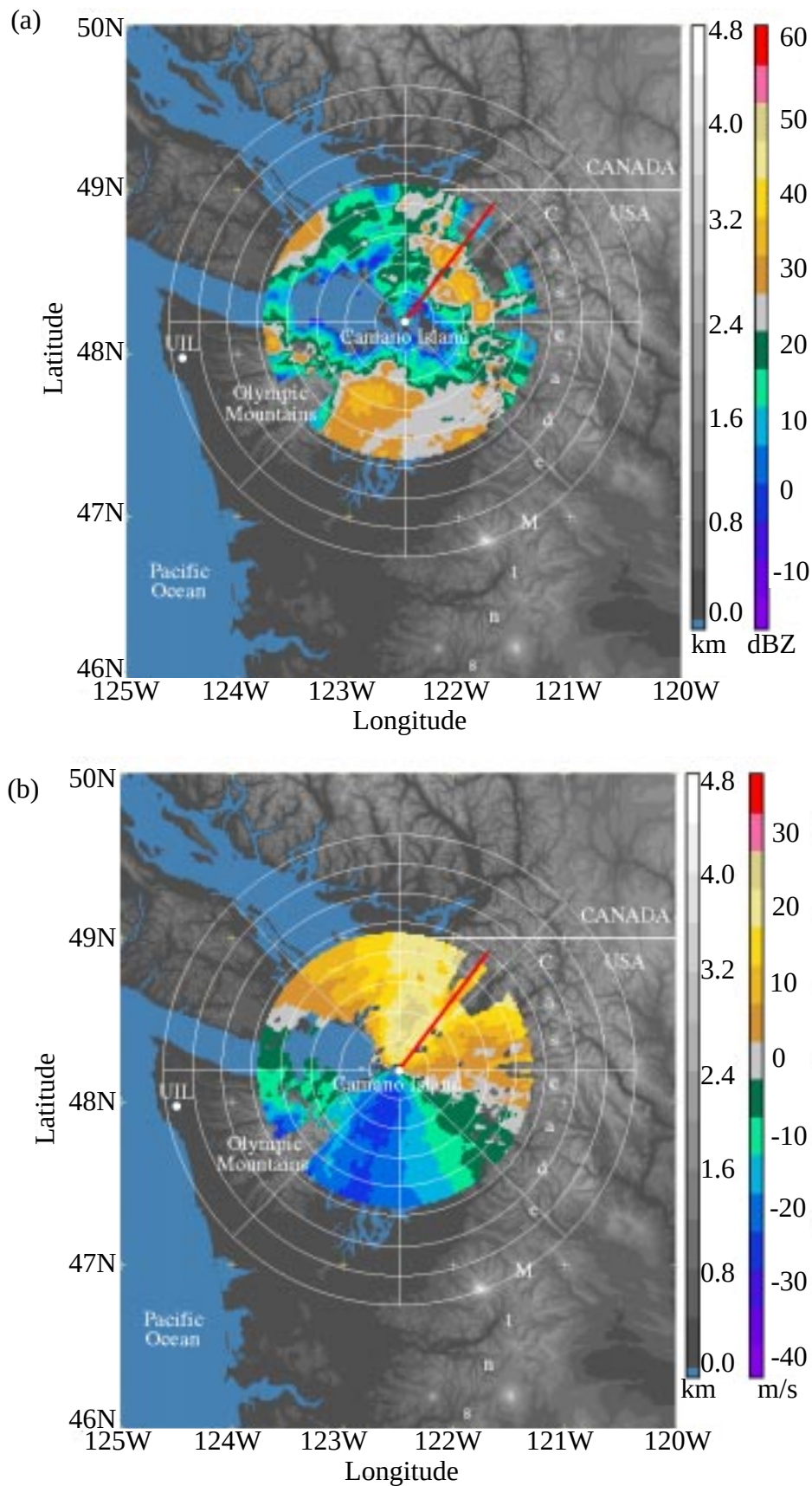


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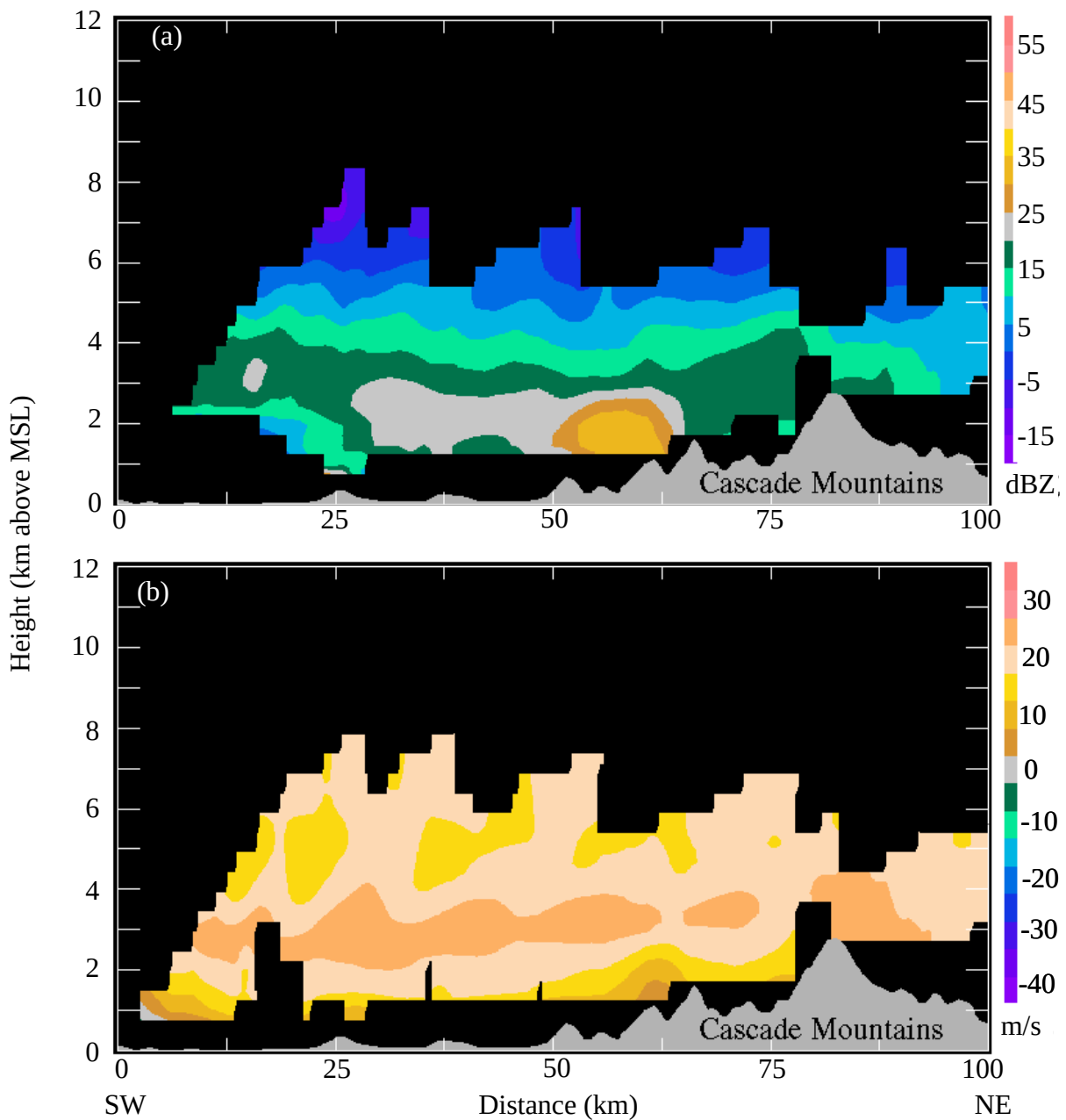


Figure 5. MountainZebra vertical cross sections of (a) reflectivity and (b) radial velocity from southwest to northeast along the red line segment in Fig. 4. The vertical profile of the underlying topography is shown in gray.

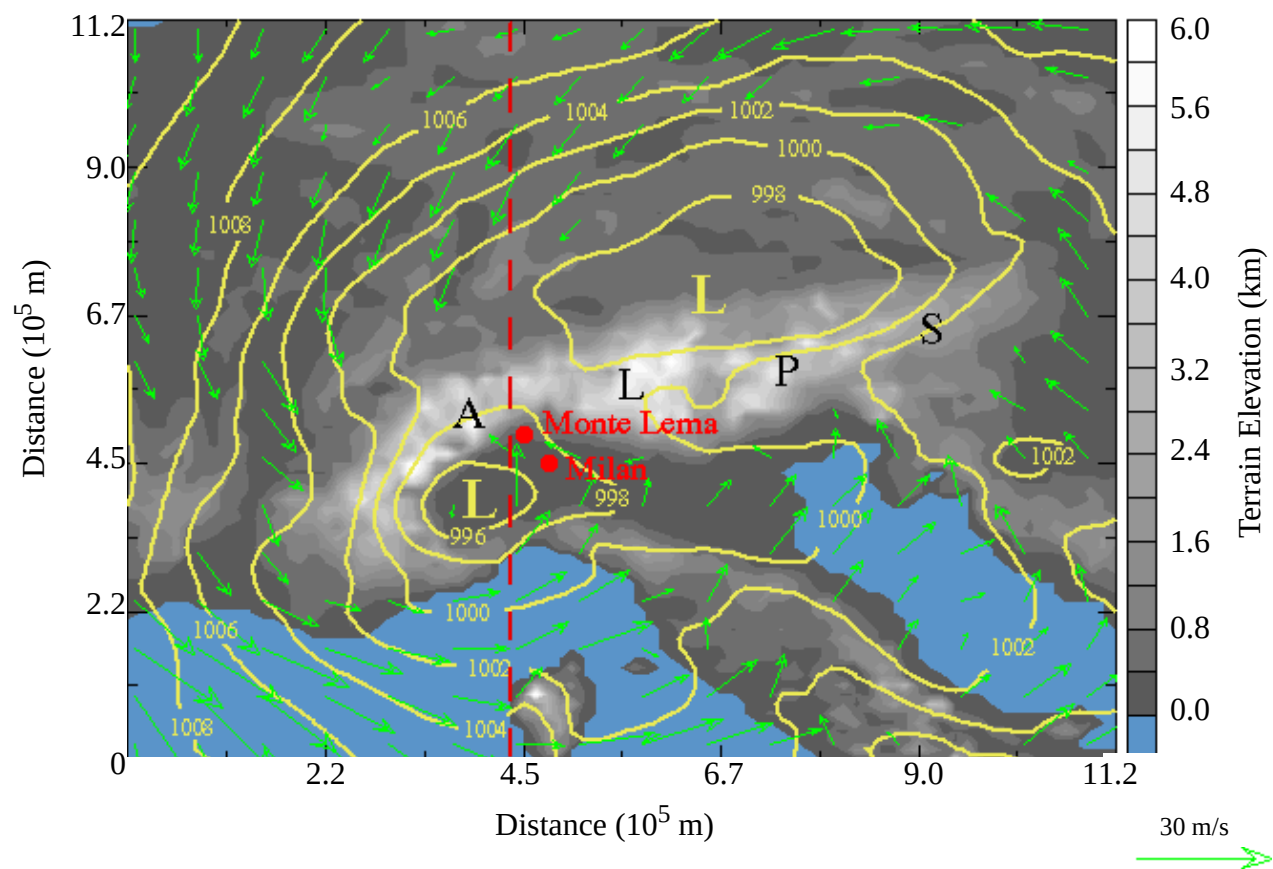


Figure 6. The 12-hour SM forecast of sea level pressure (contours) and 950 mb wind (vectors) valid 00Z 8 July 1996. The approximate locations of the Monte Lema radar and Milan, Italy are shown.

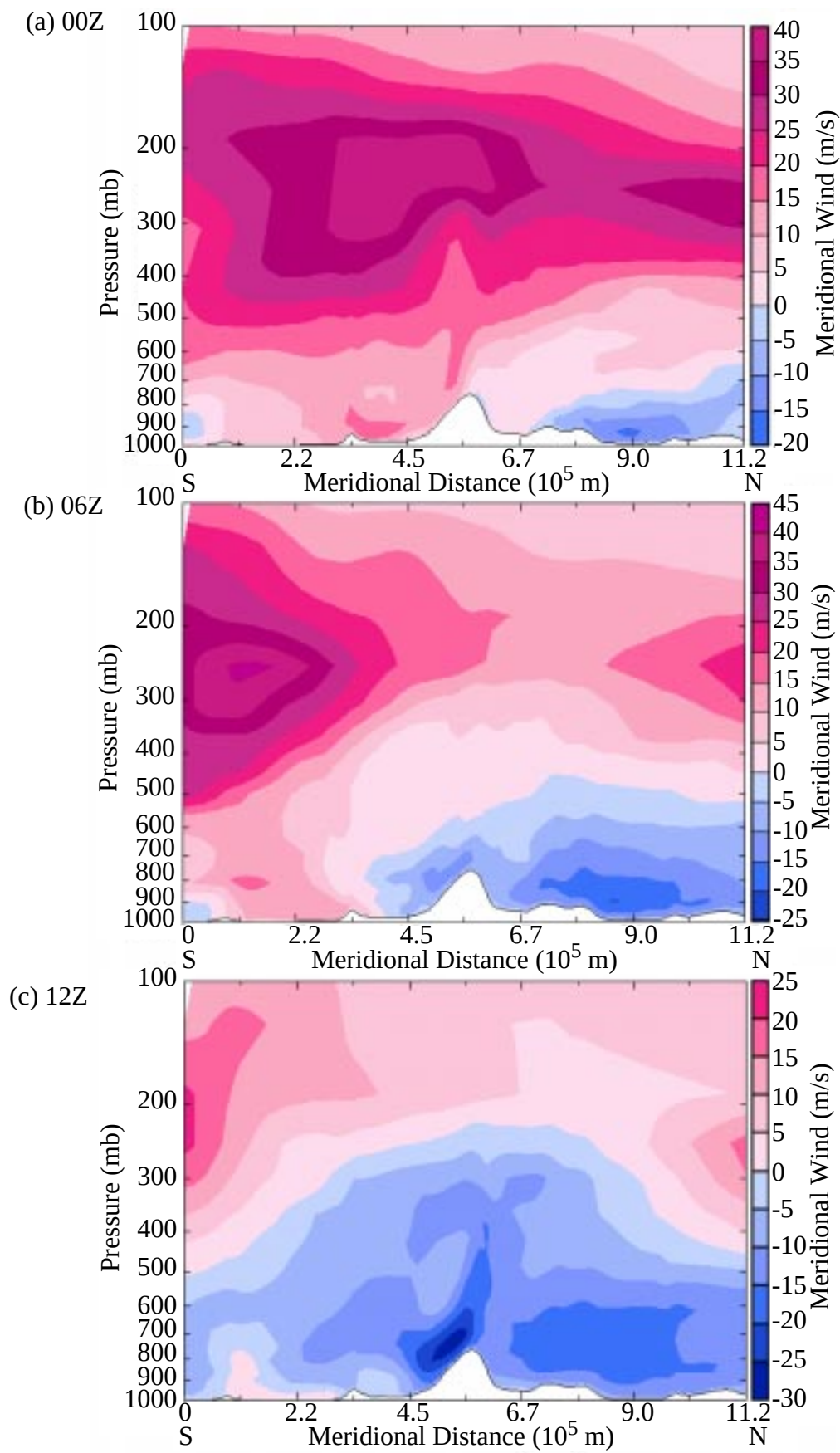


Figure 7. Vertical cross section of the SM-simulated meridional wind along the dashed line in Fig. 6. Forecasts are valid (a) 00Z (initialized 12Z 7 July 1996), (b) 06Z (initialized 00Z 8 July 1996), and (c) 12Z 8 July 1996 (initialized 00Z 8 July 1996).

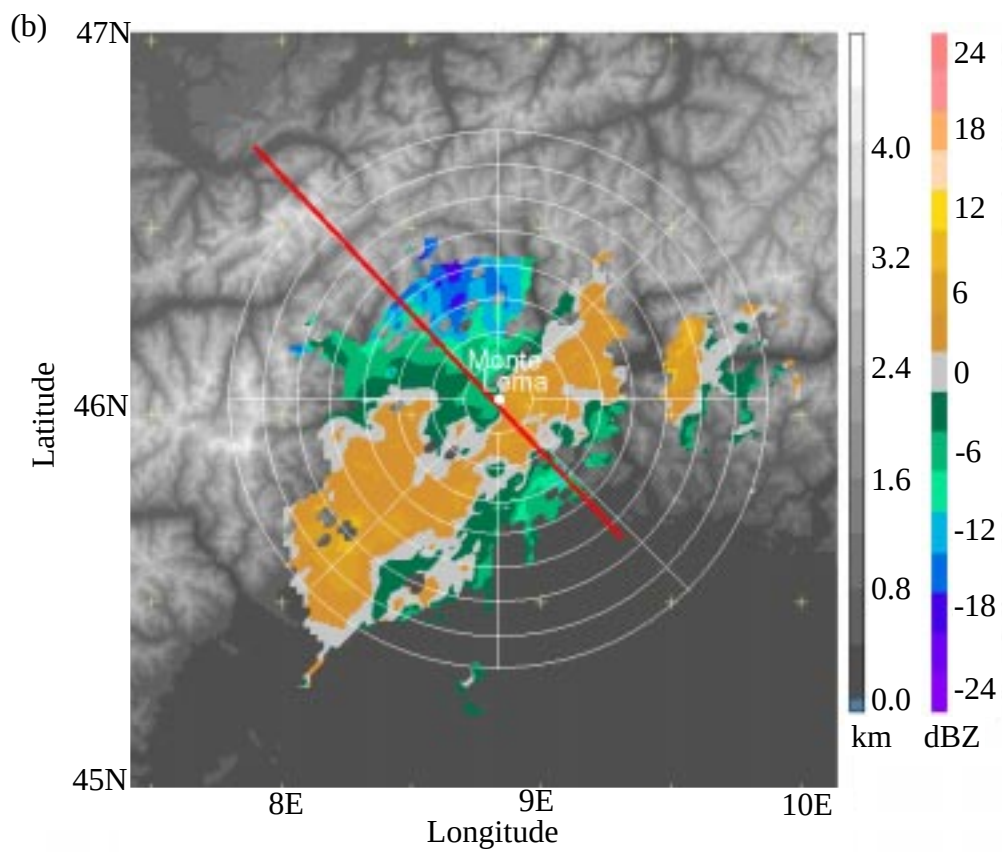
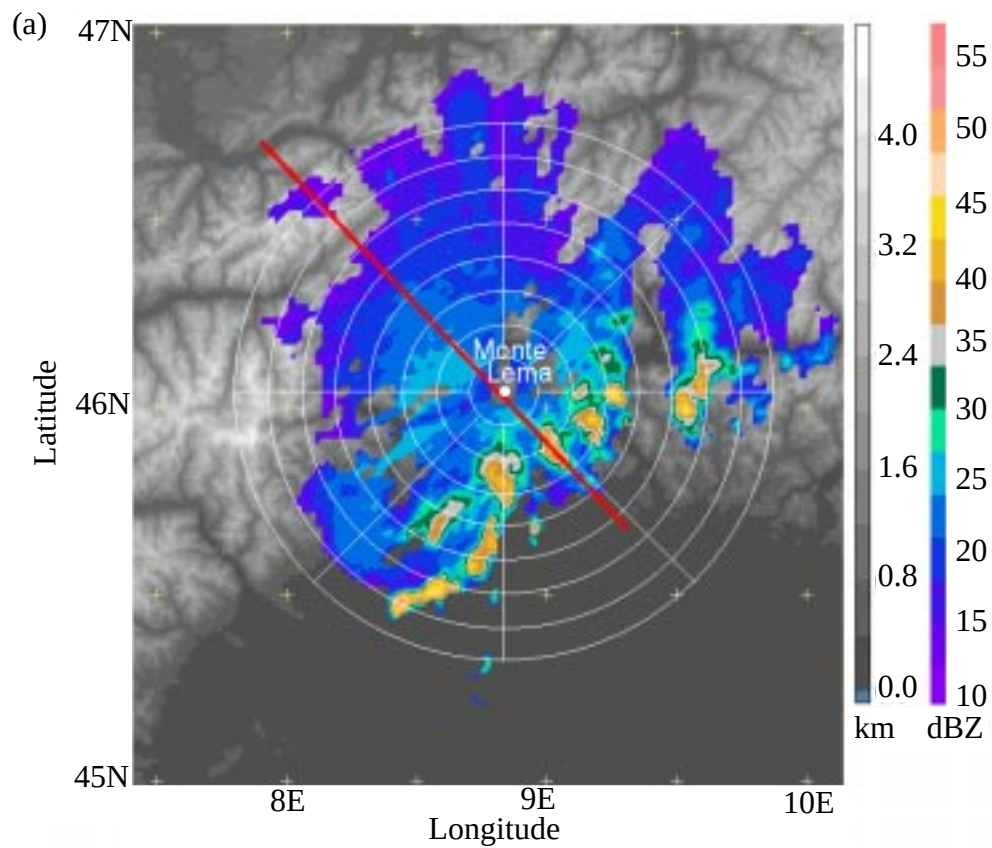


Figure 8. MountainZebra horizontal cross sections of (a) reflectivity at 3.0 km MSL and (b) radial velocity at 1.5 km MSL from Monte Lema at 0450 UTC 8 July 1996. The red segment indicates the location of the vertical cross sections in Fig. 10 (range ring spacing is 10 km).

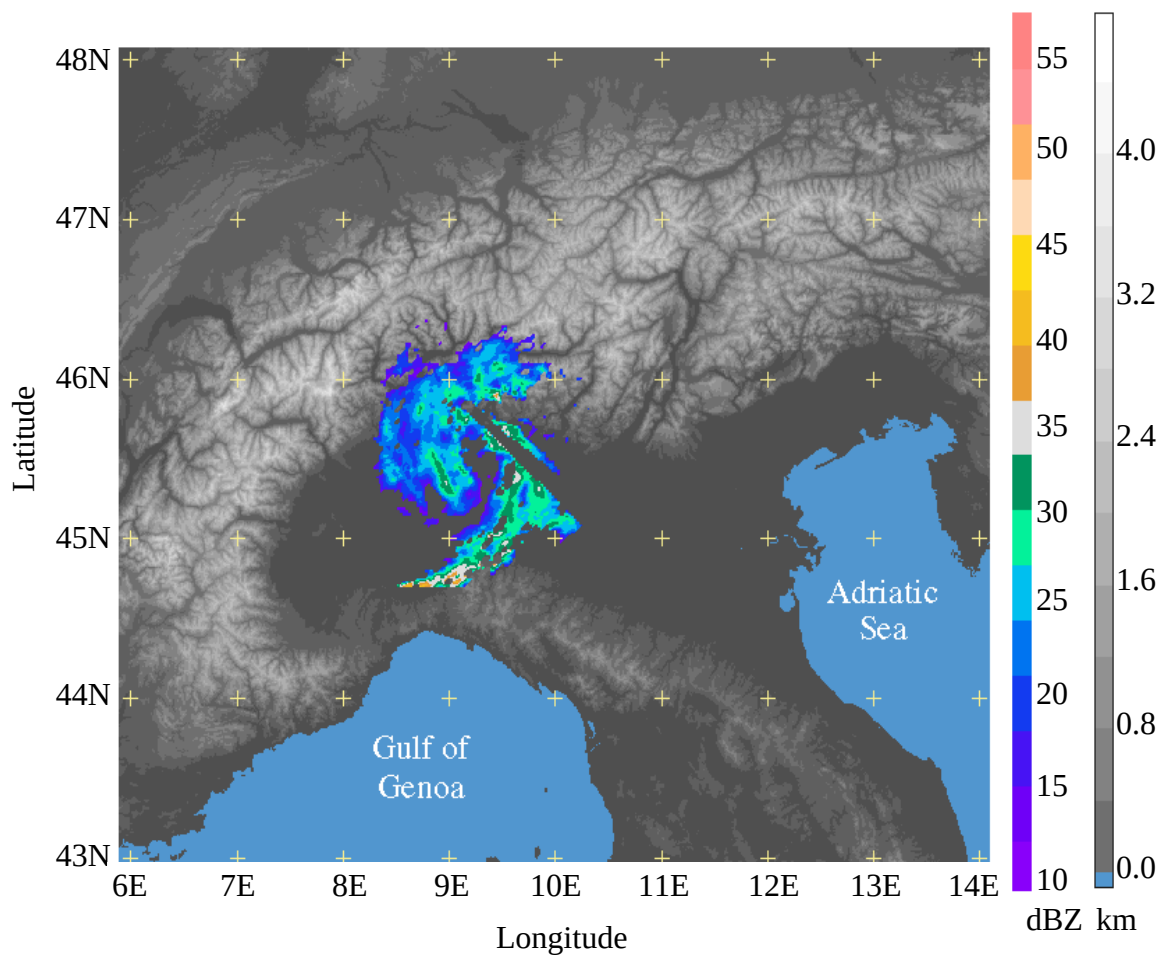


Figure 9. MountainZebra horizontal cross section of reflectivity at 3.0 MSL, 0750 UTC 8 July 1996, indicating the size and position of the MCV in the context of the Alpine topography.

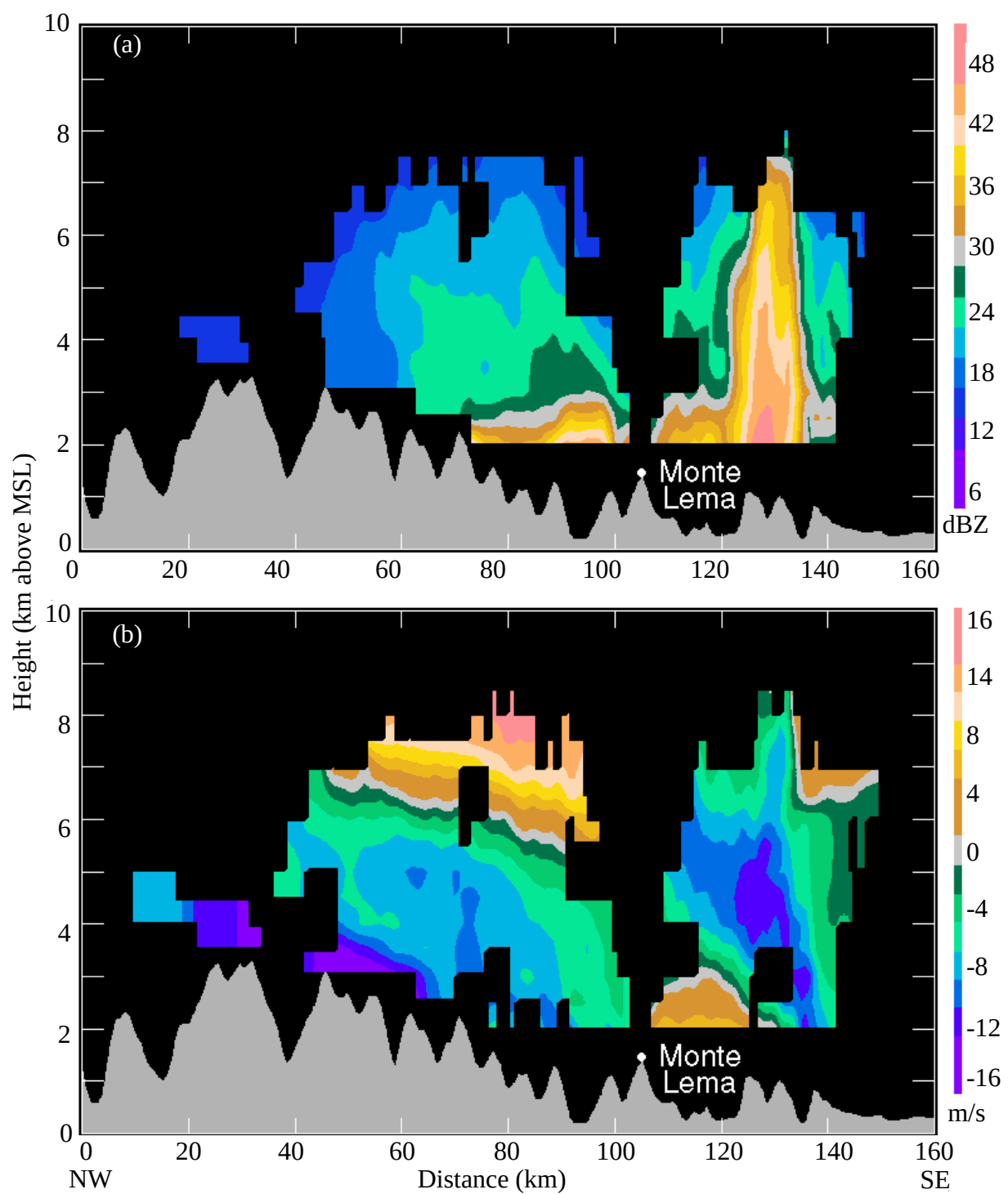


Figure 10. MountainZebra vertical cross sections from northwest to southeast of (a) reflectivity and (b) radial velocity obtained from an interpolated 20 tilt volume scan from Monte Lema at 0452 UTC 8 July 1996.