P6A.3. THE WSR-88D OBSERVES NON PRECIPITATING CLOUDS

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1. *Introduction*

Cloud studies are important for the understanding of atmospheric processes, the formation of precipitation, and radiation transfer in the atmosphere. For economic reasons and because the backscatter cross-sections of hydrometeors are inversely proportional to the fourth power of the wavelength, remote sensing of clouds is often achieved with millimeter wavelength radars. The Atmospheric Radiation Measurement (ARM) program operates the 8-mm wavelength cloud radar (MMCR) and 3 mm wavelength ARM cloud radar (WACR). These radars are directed vertically and operate at 35 and 95 GHz, respectively (Moran, et al., 1998; Widener and Mead, 2004). Cloud parameters retrieval using mm-wavelength radars can be found also in Kropfli and Kelly 1996, Clothiaux et al. 1995, Kollias et al. 2000, 2001, Matrosov et al. 1992, 2002, and Reinking et al. 2002 among others. The use of high operating frequencies makes it possible to achieve very high spatial resolution (45 m range resolution and a beamwidth of 0.2°) and provide good detectability of non-precipitating clouds. The main disadvantages of theses radars are severe attenuation and their inability to scan. The ARM Program is considering, however, adding scanning capabilities to the cloud radars in the future.

In April 2006, the Cloud Profiling Radar (CPR) was put into orbit as part of the CloudSat Mission. The CPR is a 94-GHz radar developed in order to collect global data from clouds. In the next section, parameters of cloud radars are compared with those from the WSR-88D. X-band radars have also been used in cloud studies (e.g., Hendry and Antar 1984, Iwanami et al. 2001, Martner et al. 2001). S-band radars are usually used for precipitation measurements (Doviak and Zrnic, 2006). We demonstrate herein that the S-band WSR-88D network radar detects non-precipitating clouds and it can be used as a tool in remote sensing of clouds at distances up to 100 km.

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2. *The WSR-88D as cloud radar*

The WSR-88D S-band radar network in the US is used to monitor severe weather and to measure precipitation. Existing radar volume coverage patterns, VCPs, have been designed to meet these requirements. The maximum elevation angle of the VCPs is about 20° and the signal to noise (SNR) threshold to display reflectivity is typically set to 2 dB. Although there is a “clear air mode” whereby a long pulse is transmitted to increase the SNR, it is seldom used. The vast majority of meteorological products is derived from radar data in the boundary layer and is obtained at the lowest elevation angles. All these factors constructively combine to inhibit the display of echoes from non precipitating clouds. This is demonstrated in Fig.1a, b, where a visible satellite image and reflectivity field from the WSR-88D KTLX (Oklahoma City) network radar are shown for May 25, 2007; the time of the satellite image is 1345 UTC and the time of KTLX image is 1351 UTC. From the satellite image, it is seen that almost all of Oklahoma was covered with clouds, whereas KTLX detects only very light precipitation in the South-East and North-East directions from the radar. No precipitation is detected with the radar in the North and South directions from the radar. Echoes near the radar are from insects typical for this season. Figs. 1c-f present images from NSSL’s R&D WSR-88D KOUN collected at 1318 UTC with a “cloud” VCP. In the figure, one can see a layer of nonprecipitating clouds with the top at about 11 km (KOUN is located about 25 km to the SOUTH of KTLX). The maximum reflectivity of the clouds is about 3 dBZ, which is sufficient for detection with the WSR-88D.

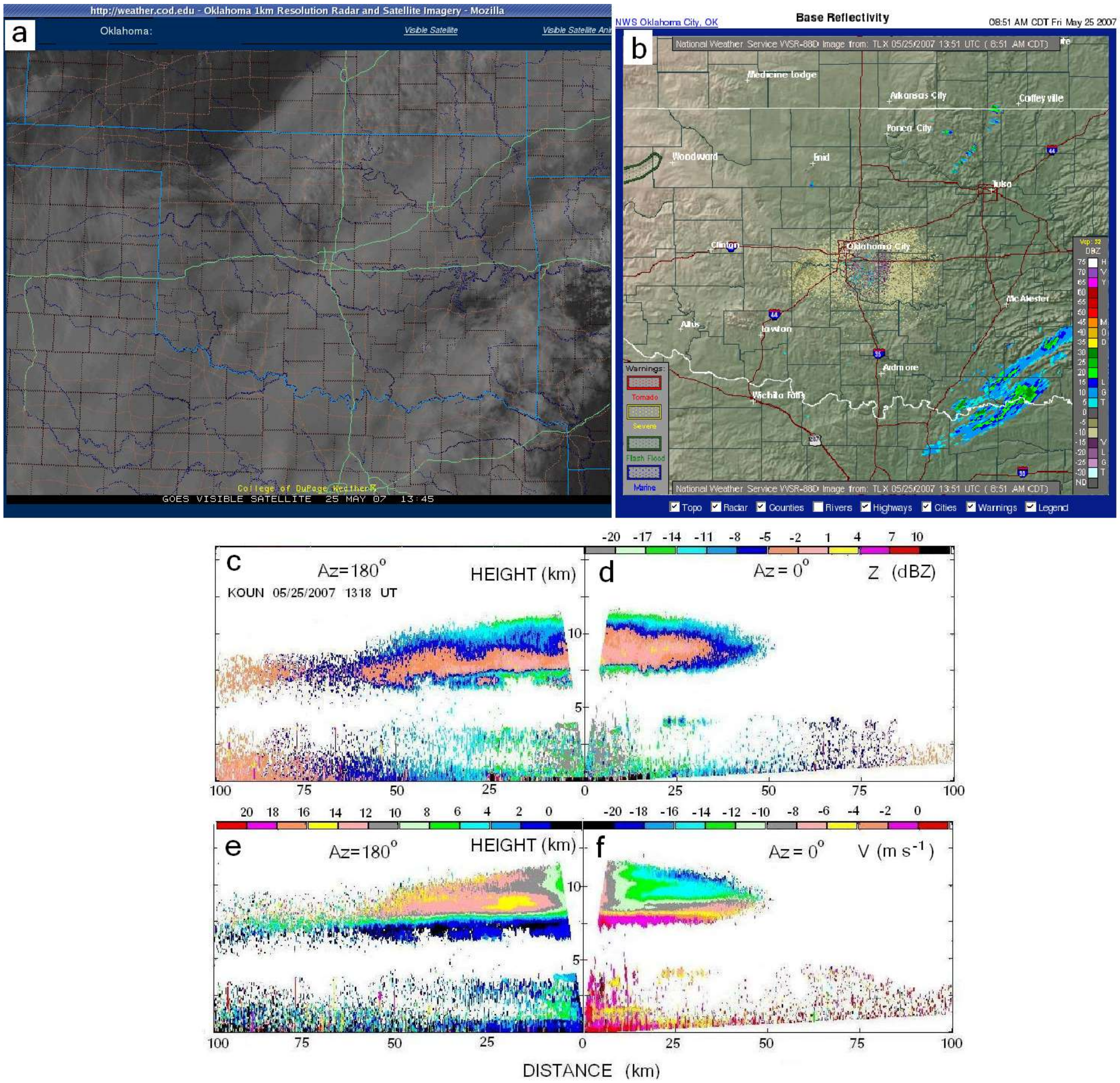

Fig.1. May 25th, 2007. (a): GOES visible satellite image of clouds over Oklahoma taken at 1341 UTC; (b): reflectivity field of WSR-88D KTLX at 1351 UTC; (c): vertical cross-section of reflectivity collected with WSR-88D KOUN at 1318 UTC at azimuth 180º (South); (d): same as in (c) but at azimuth 0º (North); (e) and (f): the Doppler velocity fields.

Figs. 1c-f demonstrate that a “cloud” VCP can be designed for the WSR-88D to observe non-precipitating clouds. The main features of the cloud-VCP are 1) an increased dwell time (0.1 s) in comparison with the legacy dwell time (about 0.04 s) typically used to observe storms, 2) an elevation scan up to 60º (19º for most VCPs for weather observations), and 3) dense elevation sampling (0.25º ; 1º and larger is used to observe weather). Feature 1) allows a significant increase in sensitivity. In Figs. 1c-f one can see the cone of silence for the WSR-88D (i.e., the elevations larger than 60º). Preliminary radar observations conducted with the WSR-88D KOUN using the “cloud” VCP coupled with photographic images of the sky confirm that most all types of non-precipitating clouds, which can be seen by the naked eye, are detected with the radar.

Typically, one does not associate the WSR-88D with observations of clouds because of its long wavelength and the decrease of signal with the inverse fourth power of wavelength. But the radar injects a powerful pulse and has a sensitive receiver so that a reflectivity factor of -23 dBZ at 10 km produces returned power equal to receiver noise. The main radar parameters are listed in Table 1. It is well known that 0.9-cm wavelength radars such as the ARM MMCR are capable of resolving many of the structures found within clouds of varying optical thickness. Furthermore, 3-mm wavelength radars such as the ARM WACR and the CloudSat CPR are well suited for cloud observations, although attenuation becomes more of an issue at these wavelengths.

Table 1. Radar parameters

	MMCR	**WACR**	**CPR**	**WSR-88D**
Wavelength (mm)	8.7	3	3	109
Pulse power (kW)	0.1	1.7	Not available	800
Pulse width (us)	0.3 / 0.6	0.3	3.3	1.5
Antenna diameter (m)	3	0.6	1.95	8.4
Radial resolution (m)	45 / 90	45	500	250
Two-way transversal resolution (m)	17@10 km	29@10 km	1400 (cross-track) 2500 (along-track)	82@10 km; 410@50km
Minimum detectable reflectivity (dBZ)	-30- -37	-40 @ 2 km	-26	-23 @10 km
Scanning capability	No	No	No	Yes
Doppler capability	Yes	Yes	No	Yes
Unambiguous velocity (m s^{-1})	3.2	7.9	N/A	27… 35
Polarization diversity	Yes for the SGP	Yes	No	Yes for KOUN. Yes for WSR-88Ds in the near future.
Attenuation	Severe	Severe	Severe	No

The minimum detectable reflectivity, Zmin (defined as the one producing an SNR=0dB at a given range) and spatial resolution of a radar are critically important parameters for cloud observations. Moran at al. (1998) estimate Zmin for the MMCR to be in the range of -47 to -30 dBZ at 10 km for different modes of operations. Inspection of the radar images found at the MMCR's web page (http://www.arm.gov) suggests that a practical range of radar reflectivities detectable by the MMCR fall within the -30 to -35 dBZ range. The minimum detectable reflectivity of the WSR-88D is "only" -23 dBZ; however, this sensitivity is adequate to detect many types of clouds. Note that Zmin for KOUN is 3 dBZ less than that of the network WSR-88D, because it uses a power splitter for polarimetric operations. As can be seen in the figure, even with the 3 dB loss, KOUN is able to resolve many features of the cloud. To increase radar sensitivity, modified threshold schemes can be utilized (Ivic and Zrnic 2007 this preprint).

The WSR-88D produces three variables from each range gate; these are reflectivity factor Z, Doppler velocity V, and spectrum width W. In Fig. 2, data examples of these spectral moments are presented in the form of vertical cross-sections, RHI (range-height indicator). It is seen that layer structures, the tops and bottoms of clouds, and Doppler velocities in clouds can be obtained with the WSR-88D; this collection of the parameters cannot be obtained from satellites. The WSR-88Ds are scanning radars so that Fig.2 is an "instant" image of the clouds. The vertically pointing mm-wavelength radars produce only vertical profiles of the radar parameters.

MM-wavelength radars experience strong attenuation in dense clouds and precipitation: ground based radars would produce erroneous reflectivities for the upper layer in left column of Fig.2 and the clouds aloft in the right column of the figure. For space-borne mm-wavelength radars, the lower layer clouds in the left column and precipitation in the right column would be masked by the upper cloud layers. S-band radiation of the WSR-88D has negligible attenuation in clouds and in moderate precipitation.

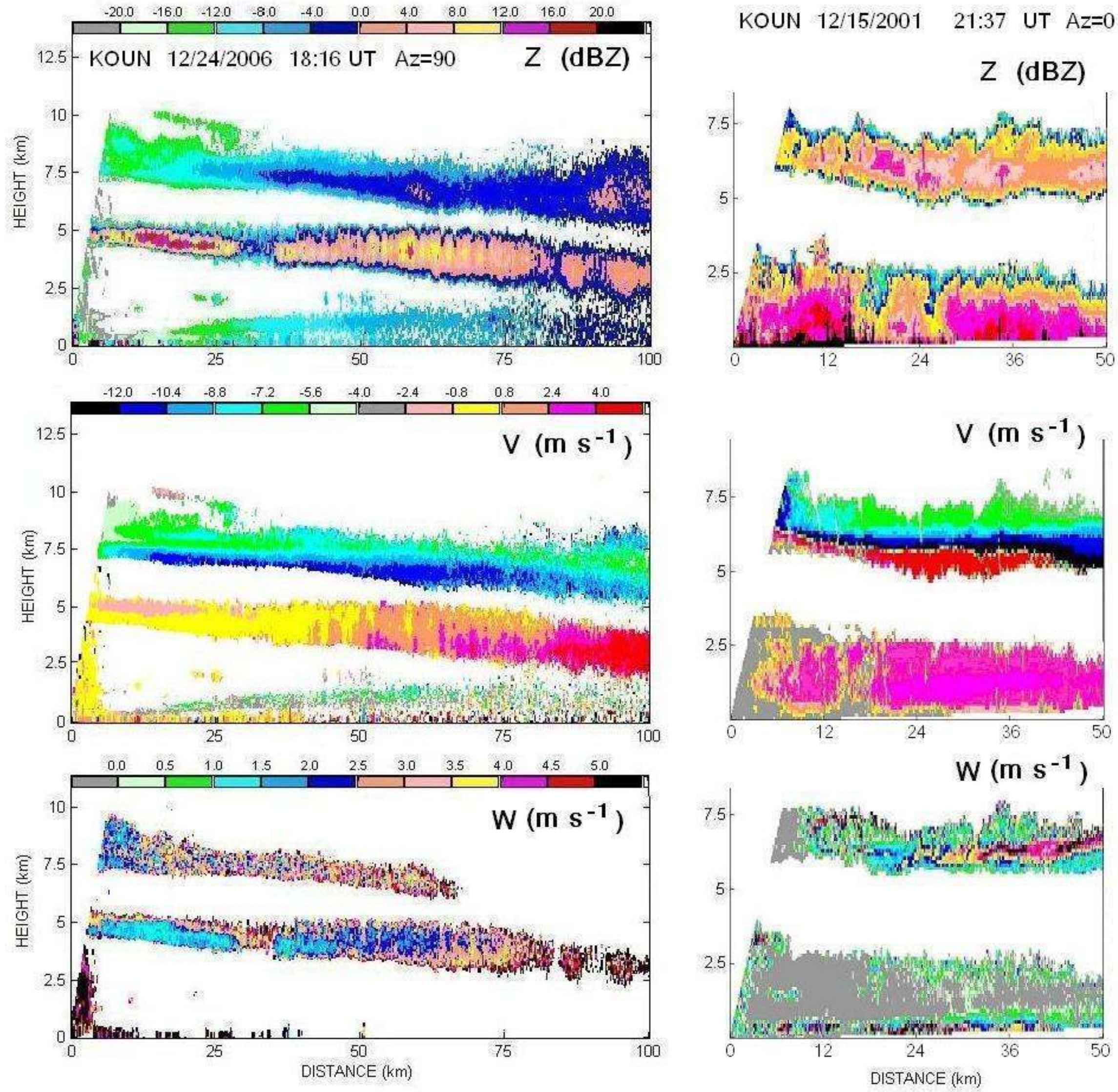

Fig. 2. Vertical cross-sections of three spectral moments (left column) on 24 Dec. 2006, non-precipitating clouds; (right column): 15 Dec. 2001, non-precipitating clouds above precipitation.

3. *Polarimetric WSR-88D for cloud studies*

The US National Weather Service is planning to upgrade the WSR-88D network with polarimetric capabilities in the near future (Saffle et al. 2007). More radar variables can be measured with polarimetric radar, which is important in light of the desired retrieval of cloud properties. Recently the WSR-88D KOUN has been upgraded with polarimetric capabilities. KOUN can operate in two polarimetric modes: Simultaneous transmission and reception of Horizontally and Vertically polarized waves (SHV mode) and the Linear Depolarization Ratio (LDR) mode. In the latter mode, a horizontally polarized wave is transmitted and both horizontally and vertically polarized waves are received. In the SHV mode, the measurable parameters are reflectivity Z, Doppler velocity V, spectrum width W, differential reflectivity ZDR, differential phase φ_{dp}, and correlation coefficient between the two returns ρ_{hv},. Examples of the radar fields are shown in Figs. 3-5. In the LDR mode, instead of ZDR the linear depolarization ratio (LDR) is measured and ρ_{xh} is obtained instead of ρ_{hv}. Combining SHV and LDR modes, all polarimetric parameters but one can be inferred. In polarimetric modes, the one-lag estimators are utilized to mitigate noise influences (Melnikov 2006, Melnikov and Zrnic 2007). Dense sampling in elevation, longer dwell time, and lag one estimators of polarimetric variables have been applied for SNR values as low as -10 dB for observations of clouds at distances up to 100 km.

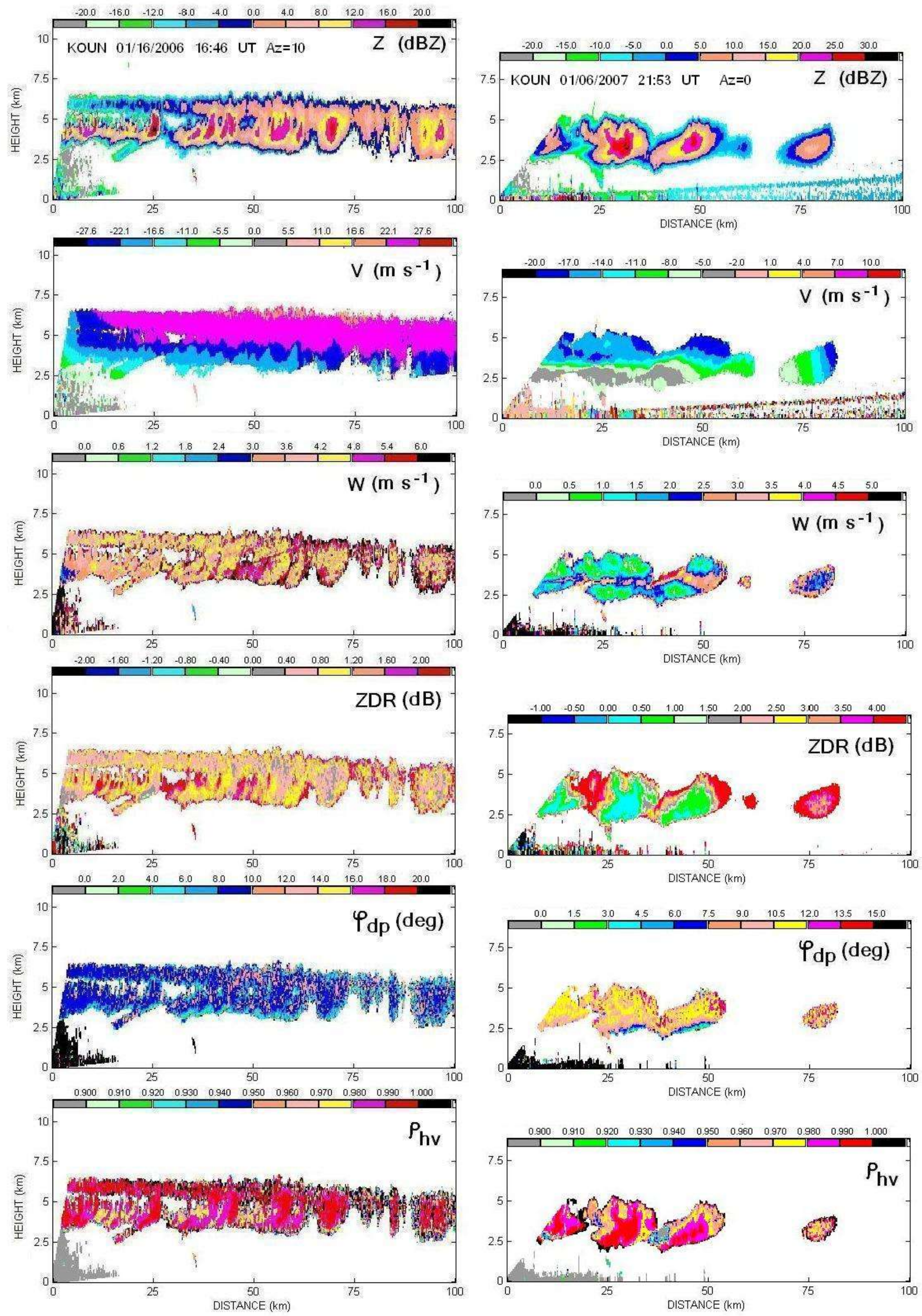

Fig. 3. Vertical cross-section of six radar parameters obtained with the polarimetric WSR-88D. (left column): Jan 16, 2006, 16:46 UT at azimuth 10º. (Right column): Jan. 6, 2007, 21:53 UT at azimuth 0º.

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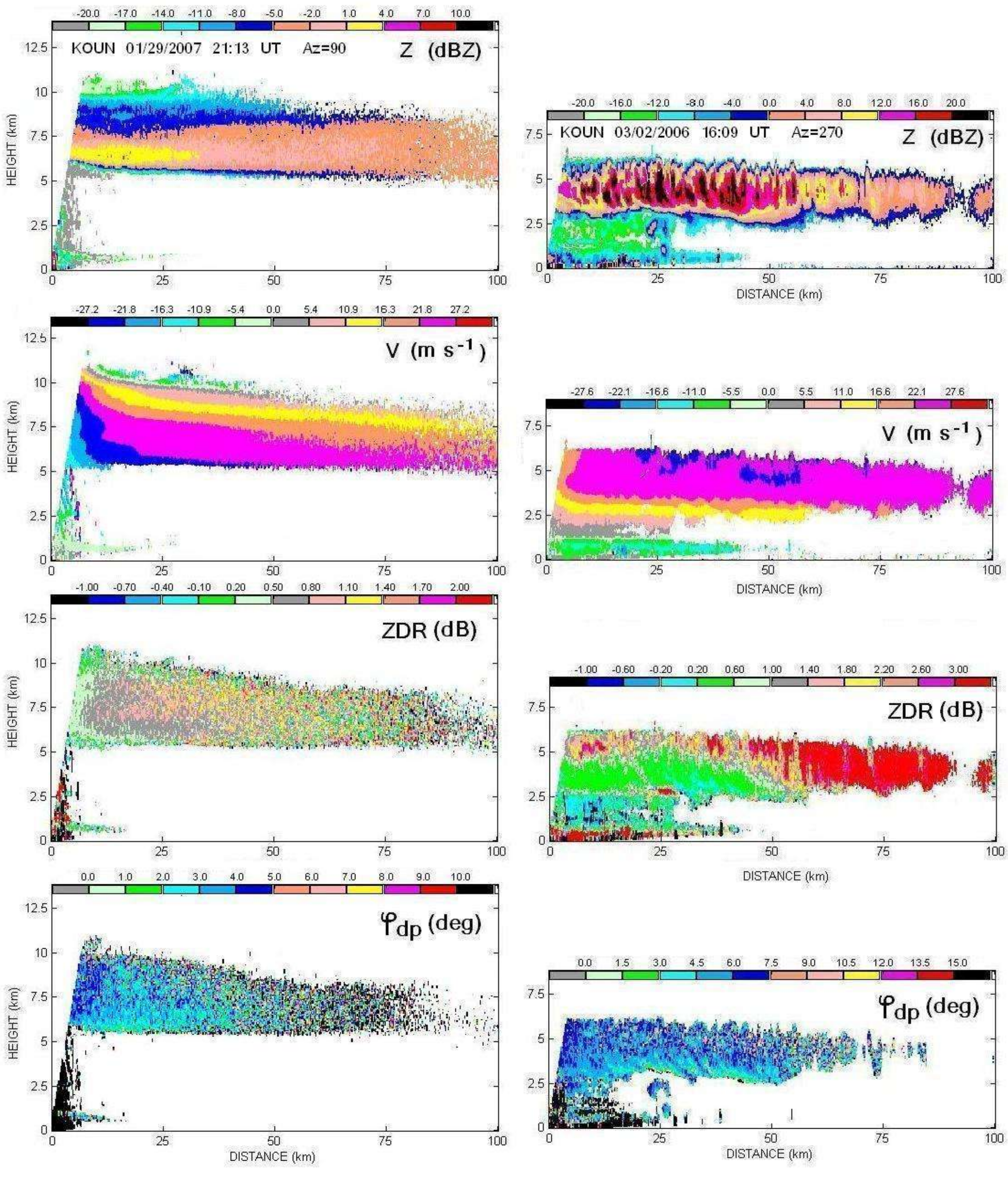

Fig. 4. Vertical cross-sections of non-precipitating clouds collected with the WSR-88D KOUN on (left column) Jan. 29, 2007 and (right column) March 2, 2006.

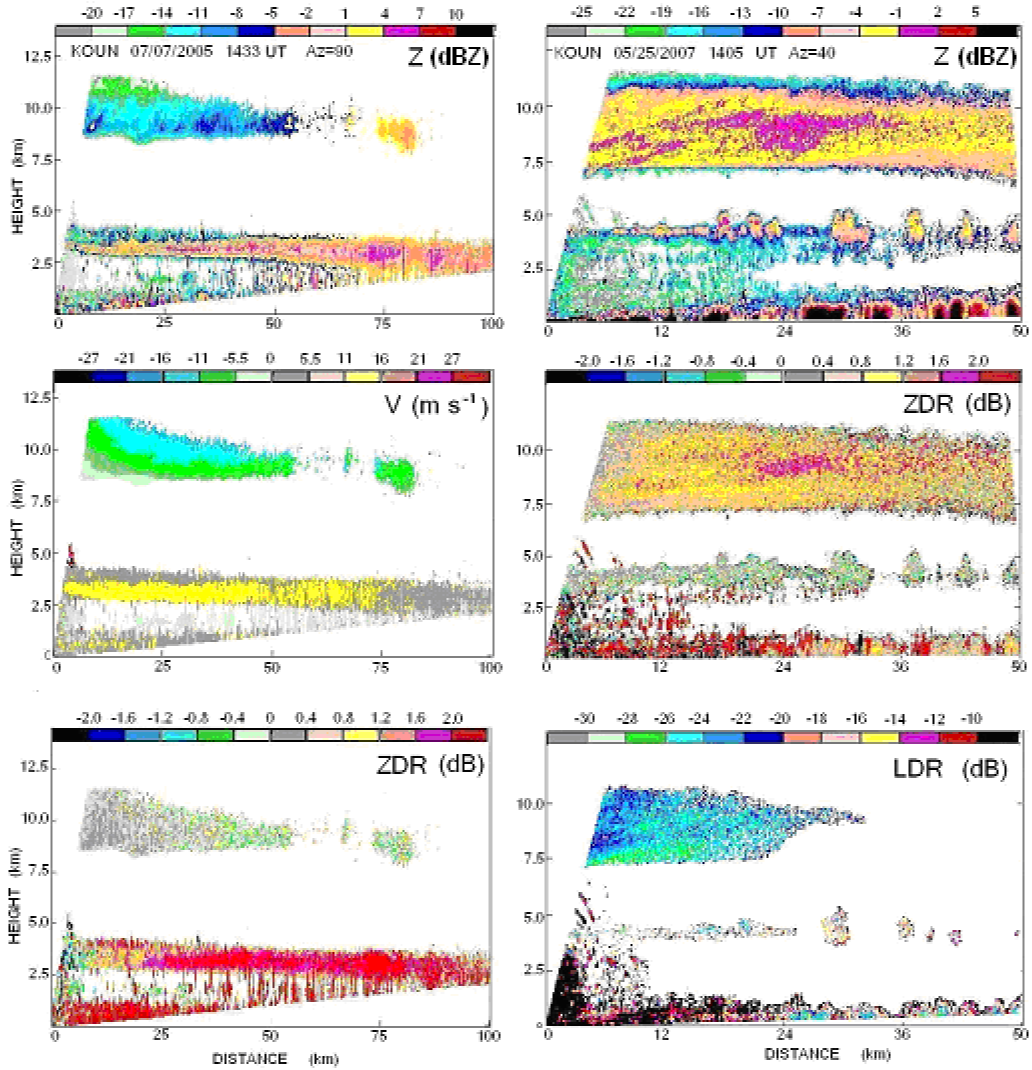

Fig. 5. Vertical cross-section obtained with the polarimetric WSR-88D (left column) in the SHV mode on July 7, 2005 at azimuth 90º and (right column) in the SHV and LDR modes on May 25, 2007 at azimuth 40º.

A tremendous variety in spatial structure of polarimetric variables have been observed in non-precipitating clouds conducted with the research polarimetric WSR-88D KOUN. In some clouds, fields of differential reflectivity are uniform; see ZDR panels in Figs. 4 (left column) and Fig. 5 (left column) in the cloud aloft. More frequently, ZDR spans an interval of 0 to 5 dB and exhibits patterns with "pockets" of high and low values (Fig. 3, Fig. 4 right column) that suggests formation and evolution of hydrometeors. Fields of the copolar correlation coefficients also exhibit an abundance of information that could be useful to characterize clouds. In the LDR mode, the linear depolarization ratio can be measured at distances up to 20-30 km (Fig. 5 right column). The polarimetric functionality of KOUN offers additional opportunities for recognizing types of scatterers. For example, from the ZDR data in Fig. 5 (left column), we can ascertain that the lower layer is due to insects.

4. *Conclusions*

Preliminary observations made with the WSR-88D show sufficient sensitivity of the radar to measure parameters of non-precipitating clouds. Cloud characteristics can be obtained with the WSR-88D in scanning mode, i.e., to generate "instant" fields of spectral moments. Special volume coverage patterns suited to map cloud properties can be designed with update times from 2 to 6 minutes. Such observations can be implemented on the existing radar network.

Polarimetric properties of clouds obtained with the proof of concept polarimetric WSR-88D show high spatial and temporal variability of the parameters clearly demonstrating the values of scanning capabilities. Optimum volume scanning strategies will enable three-dimensional cloud volume sampling, results from which are important for validation of cloud overlap assumptions used in large scale models.

Cloud observations with the WSR-88Ds can be used in studies related to the development and evolution of clouds and precipitation, cloud model parameterization, application to climate effects, and radiation transfer in the atmosphere.

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