P2.9

CORRECTIONS TO SCATTEROMETER WIND VECTORS – REMOVING THE EFFECTS OF RAIN

David E. Weissman *
Gregory Apgar
Hofstra University, Hempstead, New York

Jeffrey S. Tongue
NOAA/National Weather Service, Upton, New York

Mark A. Bourassa
Center for Ocean Atmosphere Prediction Studies
Florida State University, Tallahassee, Florida

1. INTRODUCTION

Precipitation affects polar orbiting scatterometer measurements, such as those from QuikSCAT. The presence of precipitation both in the atmosphere and its impacts on the sea surface increases the K_u-band reflectivity in the normalized radar cross section (NRCS). This can result in appreciable errors in derived sea surface wind speed and direction data from the affected scatterometer data. Unfortunately, the erroneous data is commonly in the vicinity of synoptic scale, dynamic atmospheric systems, such as cyclones and frontal boundaries, where measurements of surface winds are most important for scientific investigations.

This project is developing techniques to improve scatterometer derived wind products, when rain occupies a substantial fraction of a remotely sensed region. Our previous study (Weissman et al. 2002) demonstrated that moderate precipitation could result in measured 3 to 10 ms^{-1} wind speeds being erroneously sensed using scatterometers at least twice their true values. This project presents a physically-based approach that corrects the NRCS by the scatterometer. The method utilizes passive radiometric Advanced Microwave Scanning Radiometer (AMSR) measurements collocated with scatterometer measurements when precipitation is present in the atmosphere. The three-dimensional AMSR data are combined with models of the electromagnetic processes associated with propagation and scattering from rain, to remove the effects of volumetric precipitation (backscatter and attenuation). The approach also includes removal of the enhanced sea surface roughness due to precipitation impacts, by developing a new model function for the rain-induced roughness. The surface wind vectors are then recalculated using the corrected scatterometer NRCS. The method is also performed for coastal locations using the three-dimensional data from the network of S band Weather Surveillance Radars, 1988 Doppler (WSR-88D), referred to as NEXRAD, for high resolution atmospheric rain measurements.

* *Corresponding author address:*
David E. Weissman,
Hofstra University, Hempstead, NY 11549-1000;
e-mail: eggdew@hofstra.edu

2. BACKGROUND

Scatterometers are active K_u-band radars measuring the NRCS from wind generated capillary waves on water surfaces. The presence of precipitation in the path between the sea surface and the polar orbiting scatterometer, such as QuikSCAT and SeaWinds on ADEOS-II, can result in erroneously high NRCS measurements and resultant wind vector estimates (high magnitude and wrong directions). Primarily, precipitation concern is rain, though melting snow in the atmosphere can result in "bright banding", which should be considered. Rain creates volumetric backscatter and attenuation, as well as surface rain impacts that add to sea surface roughness. Thus, wind vectors derived from scatterometer measured NRCS in the presence of rainfall are often seriously erroneous.

Important scientific advances and knowledge have been impeded by the presence of rain-contaminated wind vector estimated data products. For example, these deficiencies can erroneously indicate intense low pressure systems which have serious impacts on estimates of wind driven ocean circulations and climatic studies. The results obtained during studies of high-wave number surface wind forcing, have been shown to contain significant biases and discrepancies (Milliff et al. 2004; Chelton 2004). These studies document the problems associated with the acceptance or rejection of erroneous data, during the analysis of small scale wind features and wind stress curl. Similar problems occur in a wide range of user applications. It is widely accepted that the status-quo of "flagging" data suspected of contamination from rain using statistical methods is unsatisfactory, and that improved, rain-corrected winds are necessary for the oceanographic and meteorological community in the future. This project presents one of several possible methods intended to suppress the rain-induced error.

3. METHODOLOGY

The underlying principle for the methods and results being presented here is the removal, from each scatterometer NRCS measurement, of backscatter and attenuation effects by atmospheric precipitation within the volume through which the radar beam passes, and of the increase in surface roughness from the impact of the precipitation. Over the open ocean, we have used the three-dimensional estimates of liquid water from either coincident Tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI) (for QuikSCAT) or from the AMSR (for SeaWinds on ADEOS-II). In near coastal areas, NEXRAD can provide volume reflectivity (S-band). The volumetric S-band NRCS can be converted into K_u-band NRCS using a mathematical model that was developed to represent the principal electromagnetic mechanisms of attenuation and scattering, using the polarization and illumination details for the scatterometer.

In contrast to most of the literature in radar meteorology concerned with S-band measurements and applications, the dual polarized K_u-band scatterometer requires a different method of electromagnetic calculations. The three commonly used assumptions for S-band radar, namely, spherical raindrops, Rayleigh electromagnetic scattering and the Marshall-Palmer drop size distribution (DSD) are not suitable for the K_u-band radar beam with high incidence angles. Like many in the research community who use radar at this frequency, the more elaborate DSD of Haddad et al. (1997) is favored. Detailed electromagnetic backscattering and extinction coefficients for raindrops were calculated as a function of their sizes, shapes (oblateness), and incidence angle in this study. The K_u-band NRCS and attenuation can be derived from the NEXRAD S-band NRCS data values using fundamental principles (Bringi and Chandrasekhar 2001) and the calculated DSD's and extinction coefficients (S.L. Durden 2003, personal communication).

This study's data products include QuikSCAT or ADEOS-II level 2A scatterometer NRCS data, AMSR or TMI volumetric profiles for the precipitation water and the NEXRAD archive level II Z data products. The AMSR and TMI products provide both stratiform and convective rain fractions, which allows for the matching of the raindrop size distribution for each condition. Instead of using published reflectivity/rain-rate relationships (Z/R) derived from different configurations and circumstances, an individual analysis for the scatterometer parameters was performed.

The AMSR data product (provided by the Colorado State University, courtesy of Dr. Chris Kummerow) for each event will estimate the relative fractions of convective and stratiform rain in each resolution cell. These fractions are then used to compute the total volume reflectivity (Z) from the stratiform and convective parts calculated with separate DSD's. This enables the computation of the attenuation profiles and total volume radar cross section, leading to the corrected scatterometer NRCS, for the wind driven sea surface from which more accurate wind vectors can be calculated.

a *NEXRAD Studies of Precipitation Volume In 3-D With AMSR*

Past experience with the application of NEXRAD rain measurements (Klazura and Imy 1993) demonstrated that the higher spatial and time resolution that is available is very useful for studying the interactions of the scatterometer radar beam with the atmosphere. NEXRAD data collected at coastal locations has been used previously, by identifying times coincidence with QuikSCAT overpasses. Several studies and findings have emerged from that effort (Weissman et al. 2002, 2003). However, these studies used archive "Level III" NEXRAD 4-bit base reflectivity (Z) products which could only provide a horizontal, two dimensional scan. The "Level III" data has insufficient detail for this new application. In order to extend our investigation to three dimensions, archive "Level-II" NEXRAD products are used. These allow for a volumetric examination of the atmosphere using 8-bit Z data from the several elevation angles.

To access the archive "Level-II" NEXRAD, a new LINUX version of the Open Radar Product Generator in Common Operations and Development Environment (ORPG CODE) (Istok et al. 2002) was used. Z from individual elevation scans were converted ASCII format and analyzed using the commercially available “MATLAB” software. This facilitated interpolations between the elevation angles and coordinate transformations into a 3-dimensional volume of Z with approximately half kilometer resolution. A sample of the volumetric NEXRAD Z product is shown in Fig. 1. This data is from the WSR-88D in Wilmington, NC. It displays the event that was studied previously in Weissman et al. (2003) their figure 2. Figure 1 also demonstrates that vertical structure of precipitation varies considerably over short distances. It would be ill-advised to depend on climatological data to assume a rain-height dimension, for a detailed physical research analysis.

The NEXRAD (S-band) Z is converted to Z for K_u-band (for both polarizations), using the electromagnetic techniques discussed in section 3a. This capability is also being applied to evaluate the accuracy of the products containing the vertical profile of precipitable water content from AMSR and TMI. Using these products allows for the determination of backscatter and attenuation in the atmospheric to the surface signal for scatterometer data. This new capability can have many applications to the study of how both atmospheric, as well as surface impact-rain affects the scatterometer’s NRCS.

b. *Rain-Impact Roughness On Sea Surface*

A critical factor in the affects of rain on scatterometer data is rain-impacts (“splash effects”) on the sea surface. The usefulness of collocated NEXRAD and QuikSCAT for detecting and estimating rain impact roughness is seen in Figure 3 (not shown) of Weissman et al. (2003). These are QuikSCAT vs. NEXRAD derived rain rates (representing averages over each 25 km ^{2} QuikSCAT cells). From this study, one can conclude that for rain rates below 2 mm hr^{-1}, the affect of rain are negligible below this level. Above 2mm hr^{-1}, the rain impact affect becomes increasingly important.

There have been numerous pioneering studies of the effect of rain (usually including a variable wind) on the NRCS (Moore et al. 1979; Bliven and Giovanangelli 1993; Bliven et al. 1997). However these were conducted in laboratory wave tanks, and while providing critical fundamental knowledge, they do not meet all the needs associated with satellite based observations. A recent field experiment from a National Oceanic and Atmospheric Administration (NOAA) research vessel, intended to support scatterometer observations, was conducted in the Pacific Ocean during the Kwajalein Experiment (Contreras et al. 2003). Some results are applicable to the needs of this project, primarily the relative intensity of the rain-impact NRCS can be effectively addressed by their results. However, because of the small antenna footprint and limited resolution in both rain rate conditions and beam angles, they do not provide sufficient information to answer many questions raised by this study.

The ground-based NEXRAD locations provide a higher resolution and more accurate estimate of the volumetric Z. There are over 20 locations along the eastern seaboard and the Gulf of Mexico. This real-time base of information supports the acquisition and utilization of three-dimensional Z with high spatial resolution (0.54 km), in all directions, up to 250 km from each radar. It enables one to estimate rain rate near the surface to permit calibration of rain-impact NRCS for both of the QuikSCAT polarizations (Weissman et al. 2003).

c. *Developing A Rain-Impact Surface Model Function*

The consensus from previous QuikSCAT and other field measurement programs is that the normalized NRCS of rain-impact roughness is a quantity that must be known if reliable corrections are to be made for wind speeds less than 15 ms^{-1}. (Stiles and Yueh 2002; Moore et al. 1979). A model of this quantity as a function of both rain rate and wind speed is being developed. Collocations with the necessary data sets are being organized around ocean buoy locations that are situated within the coverage range of NEXRAD. Data from AMSR, which provides the vertical profiles of the precipitable water and the convective and stratiform fractions, is also being used.

A typical event for combined analysis would consist of an encounter by the scatterometer with appreciable rain covering an area spanning at least 150 km^2, sufficiently close to a NEXRAD station which would then survey the volume reflectivity of a large number of the scatterometer cells. In addition, special attention will be paid to those cells close to the ocean buoys, from which surface wind speed can be acquired. Also, meteorological analyses of sea surface wind fields are being utilized. Surface rain rate (that which affects the roughness) is being acquired either from the AMSR or NEXRAD or both.

Using the buoy and meteorological analyses of sea surface wind fields allow one to calculate, with a reasonable accuracy, the Z for the each polarization of the K_u-band scatterometer. Once atmospheric attenuation and backscatter are removed from the actual scatterometer Z, the difference between the observed Z and that calculated is the result of rain impacts on the sea surface.

This procedure now needs to be repeated over a very large population of events so that a wide range of both rain rates and wind speeds can be surveyed. Then, a two-dimension function will be created. This will then be the correction that can be used over the global ocean when the AMSR can only provide the atmospheric correction and surface rain rate.

4. CASE STUDY OF HURRICANE RAIN STRUCTURE AND SURFACE WINDS

Tropical cyclones provide excellent case studies to examine the impact of precipitation on scatterometer data. High resolution NEXRAD Z data can be adapted to probe the rain and then wind structure of a specific cyclone when it is observed near a coastal location. AMSR data can provide similar information in the open ocean. Using these data, the K_u-band attenuation and volume backscatter can be removed from the scatterometers measured NRCS. Thus allowing the sea surface NRCS to be studied. Based on previous research, the rain-impact roughness can be neglected for surface winds that exceed 20 ms^{-1} (Yueh et al. 2003).

There are several tasks about the scatterometer's capability to probe hurricane winds that are being addressed. One task seeks to develop a method for examining the three-dimensional structure of precipitation within the hurricane (using the NEXRAD), and to compare this with the inferences of rain properties and profiles from the AMSR on Midori-2. The additional information about stratiform and convective rain provided by AMSR will aid the selection of DSD's needed to convert S-band Z into that for K_u-band. At these higher rain rates, it's also necessary to examine both polarizations of the scatterometer. Once this is accomplished, a corrected set of sea surface NRCS can be created throughout the storm area.

An examination of Hurricane Isabel, which crossed the North Carolina coastline on September 18, 2003, is being conducted. A fortuitous observation by the Midori-2 scatterometer occurred at about 1600 UTC. The storm was centered in the swath of the sensors, providing a rich source of both the AMSR and scatterometer data. The eye of the storm also embraced the coastline. A sample of the NEXRAD three dimensional data for this event is shown in Fig. 2. Our wind analysis is supported by the NOAA Hurricane Research Division wind analysis. Their results for 1630 UTC are available on the internet at: http://www.aoml.noaa.gov/hrd/Storm_pages/isabel2003/wind.html, which indicates maximum winds at about 90 knots.

The Precipitation Radar on the TRMM satellite will be used in conjunction with the scatterometer data and the NEXRAD to test and evaluate the new techniques being proposed. These methods will be supported by the TMI and AMSR whenever possible.

5. CONCLUSION

Scatterometers provide high resolution wind vectors over the data void open oceans that have proven extremely valuable to meteorologists and oceanographers. An inherent problem with the data is that precipitation within the radar beam of the scatterometer can result in erroneous wind vectors.

Using multiple sensing platforms, a technique that will remove the effects of rain inherent in scatterometer data is being developed. This technique will account for atmospheric attenuation and backscatter, as well as sea surface “slash” affects. Through use of this new technique, scatterometer data in the vicinity of important rain producing atmospheric features including fronts and cyclones is usable.

ACKNOWLEDGMENTS

The authors acknowledge Michael Istok and Brian Klein from NOAA's National Weather Service Headquarters for providing the ORPG CODE software and for their expert assistance in installation and utilizing of the software, without which this effort would not have been possible. NOAA's National Weather Service Eastern Region is acknowledged for their review of this manuscript and for assistance with funding of this project.

The authors also acknowledge Dr. Larry Bliven for his ongoing research program in this area and him agreeing to maintain close advisement and collaboration with this project.

REFERENCES

Bliven, L.F., and J-.P. Giovanangeli, 1993: An experimental study of microwave scattering from rain and wind-roughened seas, *Int. J. Remote Sensing*, **14,** 855-869.

Bliven, L.F., P.W. Sobieski and C. Craeye, 1997: Rain generated ring-waves: measurements and modeling for remote sensing, *Int. J. Remote Sensing*, **18,** 221-228.

Bringi, V.N. and V. Chandrasekhar, 2001: *Polarimetric Doppler Weather Radar: Principles and Applications*, Cambridge University Press, 636 pp.

Chelton, D.B., M.G. Schlax, M.H. Freilich and R.F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean winds", *Science*, **303,** 978-983.

Contreras, R.F., W.J. Plant, W.C. Keller, K. Hayes and J. Nysteun, 2003: Effects of rain on Ku-band backscatter from the ocean, *J. Geophys. Res*., **108**, 34-1 to 34-13.

Doviak., R.J. and D.S. Zrnic, 1993: Doppler Radar and Weather Observations, 2nd Edition, Academic Press

Haddad, Z.S., D.A. Short, S.L. Durden, E.Im, S. Hensley, M. Grable, and R.A. Black, 1997: A new parameterization of the rain drop size distribution, *IEEE Trans. Geosci. Remote Sens.*, **35,** 532-539.

Istok, M.J., A. D. Stern, T. J. Ganger, D. J. Smalley, D.-J. Seo, and C. J. McAdie, 2002: Experiences using WSR-88D CODE as a Developmental Tool for Radar Algorithm Development. Preprints, *18th Intl Conf on IIPS*, City, State, Amer. Meteorl. Soc., CD-ROM, 5.9.

Klazura, G.E. and D. A. Imy, 1993: A description of the initial set of analysis products available from the NEXRAD WSR-88D system, *Bull. Amer. Meteor. Soc.,***74**, 1293-1311.

Milliff, R.F., J. Morzel, D.B. Chelton and M.H. Freilich, 2004: Wind stress curl and wind stress divergence biases from rain effects on QSCAT surface wind retrievals", *J. Atmos. Oceanic Technol*., in press.

Moore, R.K., Y.S. Yu, A.K. Fung, D. Kaneko, G.J. Dome and R.E. Werp, 1979: Preliminary study of rain effects on radar scattering from water surfaces, *IEEE J. Oceanic Eng.*, **OE-4,** 31-32.

Stiles, B.W. and S.H. Yueh, 2002: Impact of rain on spaceborne Ku-band wind scatterometer data, *IEEE Trans. Geosci. Remote Sens.*, **40,** 1973-83.

Yueh, S.H., B.W. Stiles and W. Timothy Liu, 2003: QuikSCAT wind retrievals for tropical cyclones, *IEEE Trans. Geosci. Remote Sens.*, **41,** 2616-2628.

Weissman, D.E., M.A. Bourassa and J. Tongue, 2002: Effects of rain-rate and wind magnitude on SeaWinds scatterometer wind speed errors, *J. Atmos. Oceanic Technol.*, **19,** 738-746.

Weissman, D.E., M.A. Bourassa, J.J. O'Brien and J. Tongue, 2003: Calibrating the QuikSCAT/ SeaWinds radar for measuring rainrate over the oceans, *IEEE Trans. Geosci. Remote Sens.*, **41,** 2814-2820.

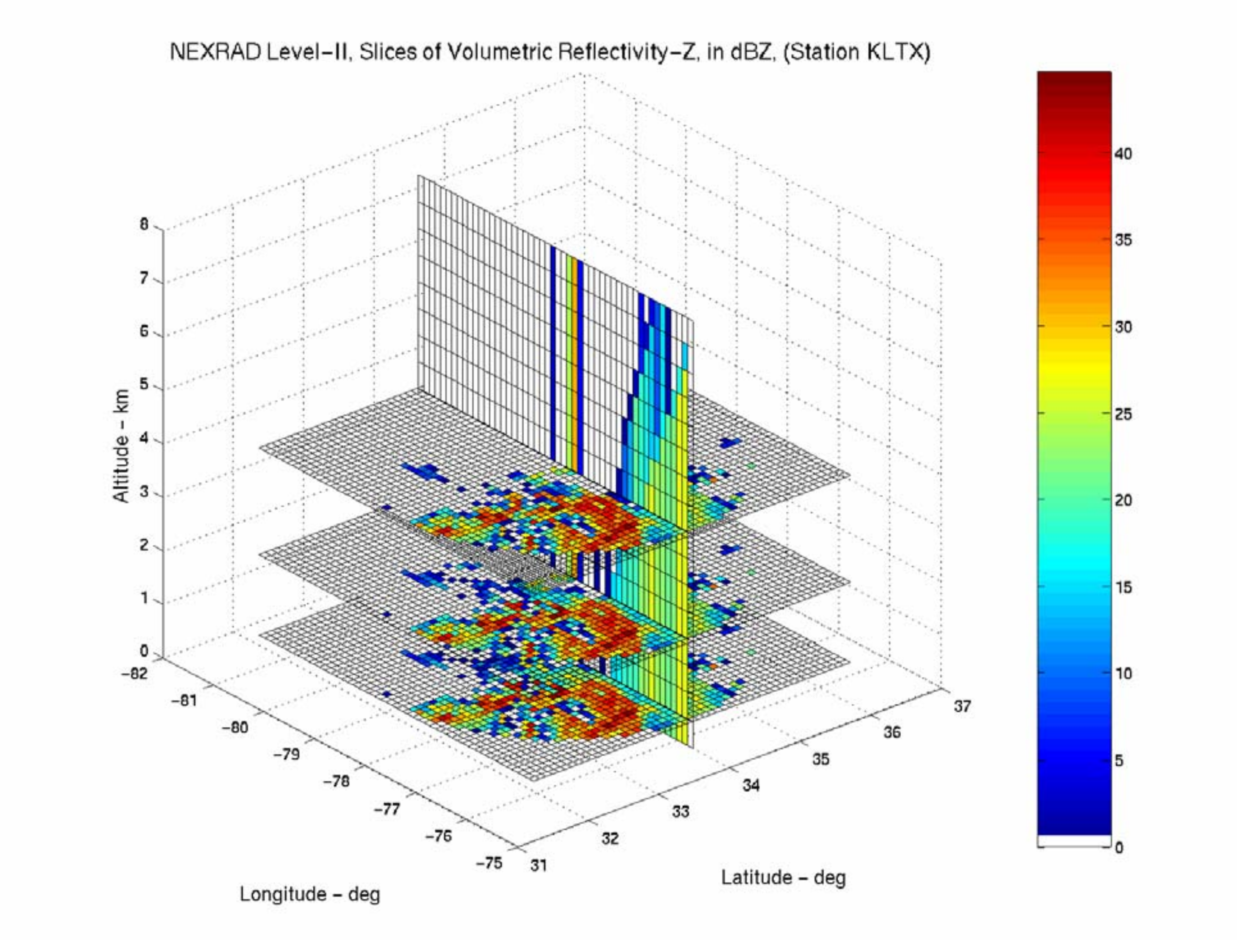

Fig 1. Example of archive Level II WSR-88D volumetric Z data (from Wilmington, N.C. on Sept. 9, 1999) converted to Cartesian coordinates using MATLAB. This example was collocated coincident to a QuikSCAT overpass (Weissman et al. 2003). The three horizontal slices were made at altitudes of 0.5, 2 and 4 km. The elevation plane shows quantized vertical steps of 0.5 km. Reflectivity shown in dBZ.

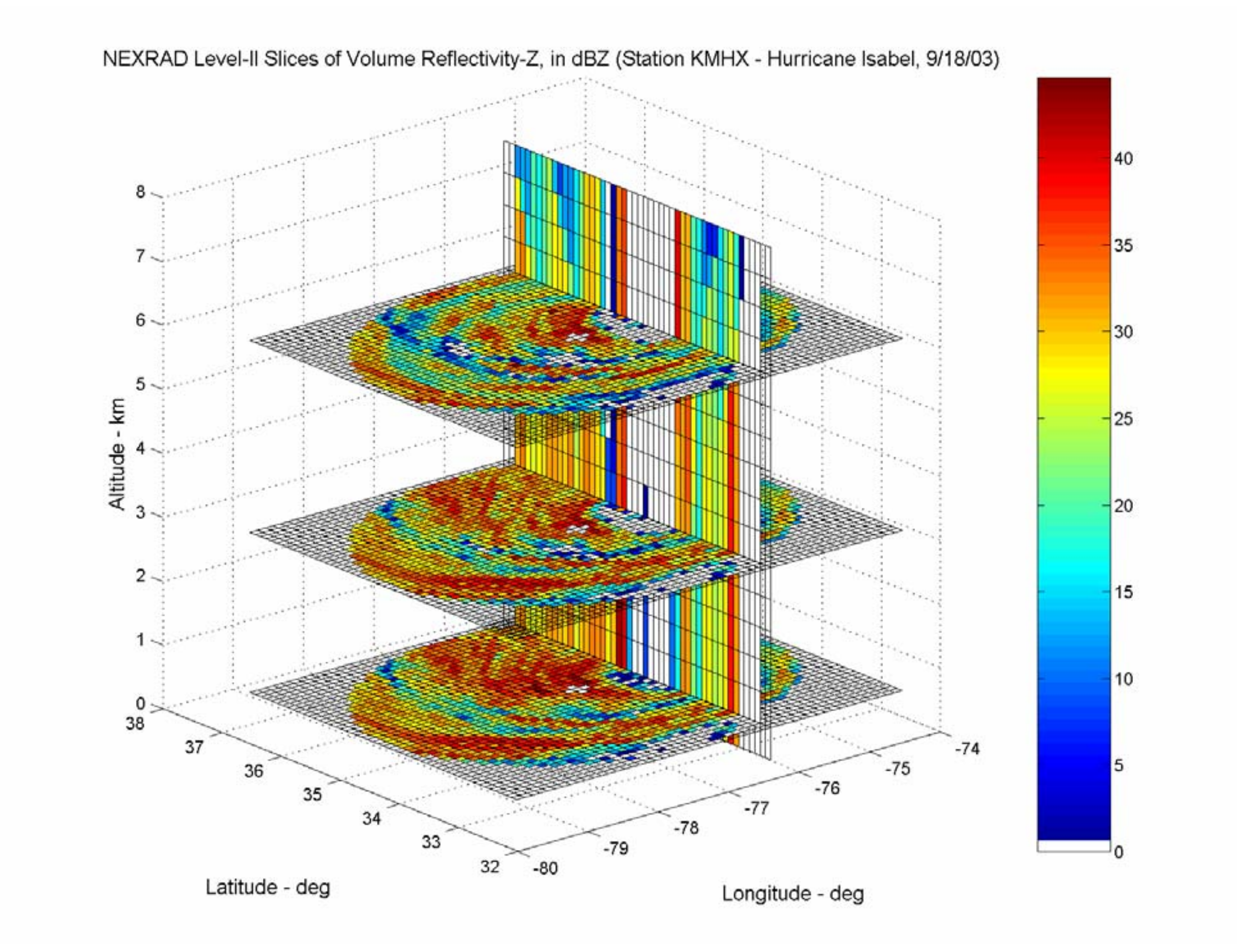

Fig. 2. WSR-88D volumetric reflectivity (from Morehead City, N.C. on Sept. 18, 2003). This was collocated with a Midori-2 scatterometer overpass of Hurricane Isabel. The three horizontal slices were made at altitudes of 0.5, 3.0 and 6.0 km. The elevation plane shows quantized vertical steps of 0.5 km. The Eye of the Isabel was located at approximately 35^{o} N, 76^{o} W. Reflectivity is shown in dBZ.