Towards better utilization of NEXRAD data in hydrology: an overview of Hydro-NEXRAD

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ABSTRACT

With a very modest investment in computer hardware and the open-source local data manager (LDM) software from University Corporation for Atmospheric Research (UCAR) Unidata Program Center, a researcher can receive a variety of NEXRAD Level III rainfall products and the unprocessed Level II data in real-time from most NEXRAD radars in the USA. Alternatively, one can receive such data from the National Climatic Data Center in Ashville, NC. Still, significant obstacles remain in order to unlock the full potential of the data. One set of obstacles is related to effective management of multi-terabyte datasets. A second set of obstacles, for hydrologists and hydrometeorologists in particular, is that the NEXRAD Level III products are not well suited for applications in hydrology. There is a strong need for the generation of high-quality products directly from the Level II data with well-documented steps that include quality control, removal of false echoes, rainfall estimation algorithms, coordinate conversion, georeferencing and integration with GIS. For hydrologists it is imperative that these procedures are basin-centered as opposed to radar-centered. The authors describe the Hydro-NEXRAD system that addresses the above challenges. With support from the National Science Foundation through its ITR program, the authors have developed a basin-centered framework for addressing all these issues in a comprehensive manner, tailored specifically for use of NEXRAD data in hydrology and hydrometeorology.

Key words | basin precipitation, Hydro-NEXRAD, NEXRAD data, radar hydrology

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INTRODUCTION

With the increased interest in effective management of our water resources comes the need for better precipitation data. As rainfall is a main driver of many hydrologic processes, reliable information about spatial and temporal variability of rainfall is crucial for predicting floods, water supply, management of agricultural lands and much more. Weather radar networks provide rainfall information over vast regions in a cost-effective way. Radar data,

doi: 10.2166/hydro.2010.056

particularly when complemented by rain gauge measurements, can provide quantitative estimates of precipitation (e.g. Wilson & Brandes 1979; Krajewski 1987; Steiner *et al.* 1999; Todini 2001; Seo *et al.* in press).

Radars collect data at high rates. For example, the Weather Surveillance Doppler Radar (WSR-88D), operated by the United States federal agencies as part of the NEXRAD system, collects a volume scan of data every 4–12 min. A volume scan is a set of about 5–14 antenna elevation scans with 1 degree azimuthal and 1 km range resolution. This translates into ~850 MB of radar reflectivity data per day. The collected data are converted into precipitation products in real-time and used for operational hydrologic forecasting and severe weather warnings. Both the original radar reflectivity data and the rainfall products are then archived at the National Climatic Data Center (NCDC) in Asheville, NC. The data are archived as they arrive, but their use in subsequent research is limited. For instance, according to the Thompson ISI Web of Knowledge bibliographic search engine, only seven peer-reviewed papers contain "Level II" and "rainfall" as key terms and/or in the abstract (also "rainfall" and "NEXRAD" yields 77 papers and "rainfall" and WSR-88D" yields 137).

To facilitate and promote the wider use of basic radar data in hydrologic research we embarked on creating the Hydro-NEXRAD software system. The project is a joint effort of researchers from The University of Iowa, Princeton University, Unidata Center Program of the University Corporation for Atmospheric Research (UCAR) and the NCDC of the National Oceanic and Atmospheric Administration (NOAA). The system is an example of cyberinfrastructure services encouraged in the recent US National Research Council report on multi-scale observations of US waters (National Research Council 2008).

Hydro-NEXRAD is a browser-enabled software system that allows users to generate custom rainfall maps from the most basic (Level II) radar reflectivity data of the NEXRAD network. Users can specify space and time resolution, different map projections, output formats, estimation algorithms, etc. Hydro-NEXRAD provides more flexibility to users with respect to available products than its only readily available alternative, i.e. the US National Weather Service (NWS) precipitation maps that represent hourly accumulations on a fixed 4 km by 4 km grid and are created using a predefined but not well-documented algorithm (Fulton *et al.* 1998). Hydro-NEXRAD users can obtain rainfall data with resolution as high as 5 min in time and 1 km in space. The rainfall data can be provided in a range of map projections that suit a broad array of applications. Hydro-NEXRAD users do not need to be radar experts, and may simply consider their needs in terms of rainfall maps. The system provides hydrologists with basin-centric rainfall maps rather than rainfall maps centered on NEXRAD radar locations.

While there are readily available NEXRAD radar-rainfall products developed by the NWS, their resolution is fixed to the Hydrologic Rainfall Analysis Project (HRAP) grid (e.g. Reed & Maidment 1999) and hourly time scale, and this limits the applications for which these products are useful. At the same time, developing custom products directly from the Weather Surveillance Radar (WSR-88D) collected Level II data (i.e. radar reflectivity and Doppler velocity) data requires expertise that is neither widespread in the hydrologic and engineering community nor easy to quickly acquire. Hydro-NEXRAD is a demonstration of a framework and the information technology tools that overcome the above constraints. We have been developing this Internet-based and browser-compatible software for access, search, selection and specification of customized radar-rainfall products based on WSR-88D radar reflectivity Level II data.

The system manages and organizes data from some 40 WSR-88D radars in the USA. For ten of them, the Hydro-NEXRAD database includes the entire record of data, from the date of the particular radar's commissioning until mid-2008 when the radar operators changed the data collection system to accommodate the so-called super-resolution mode (Istok *et al.* 2009; Seo *et al.* in press). For the remaining radars we include all Level II data since about 2002, which is when the radar operators switched the data delivery mode (Kelleher *et al.* 2007) to over-the-Internet (from an earlier mode of using magnetic tapes and the postal service.) While there are some 150 WSR-88D radars operated by the US federal agencies, the number 40 is higher than the number of weather radars in most countries in the world. Therefore, Hydro-NEXRAD should be considered as a large-scale prototype system that can serve as a meaningful example. The locations of the radars included in Hydro-NEXRAD are shown in Figure 1.

The Hydro-NEXRAD system contains some 21 M volume scan files, equivalent to 316 radar-years, and occupying some 11.6 TB of on-line storage. The metadata database includes close to 2.5 billion data values for the 40 radars. The database also manages metadata for 800 basins as defined by the United States Geological Survey (USGS) through its system of Hydrologic Unit Codes (HUCs). There are currently over 100 users of the system.

In Figure 2 we show the overall structure of the system and in Figure 3 we include more information technology specifics. In this paper, we highlight and briefly discuss the main technological aspects of the project. We provide more details in two companion papers (Kruger *et al.* (in press) and Seo *et al.* (in press)), both in this issue. The Hydro-NEXRAD software system consists of the following main elements:

1. Efficient storage and fast read time Level II data format (Kruger & Krajewski 1997);
2. A relational database that enables flexible data storage organization (Kruger *et al.* 2006);
3. Hydrologic radar-centric and basin-centric metadata (Kruger *et al.* in press);
4. Level II data quality control;
5. A set of modular radar-rainfall estimation algorithms;
6. A set of utilities for final product generation and dissemination;
7. A Graphical User Interface that allows users (research hydrologists) to specify the products they need;
8. Documentation of the entire system.

In the following sections we elaborate on the functionality and other aspects of each element. The two companion papers focus on the metadata calculations (Kruger *et al.* in press) and the radar-rainfall products and algorithms used to compute them (Seo *et al.* in press).

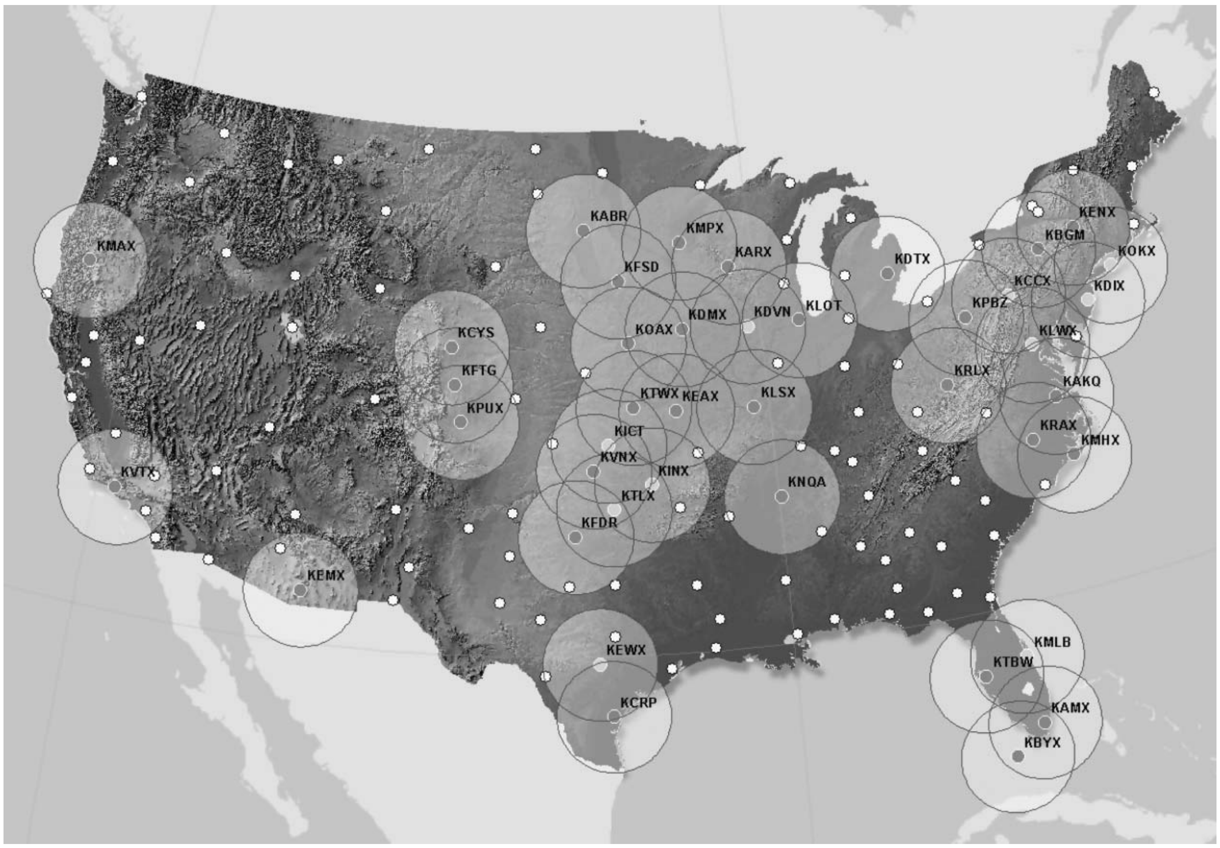

Figure 1 | Locations of WSR-88D radars included in Hydro-NEXRAD. The radars indicated with solid red dots have full record of data available in Hydro-NEXRAD. The letter symbols are the official site identifiers used by US federal agencies. The circles shown indicate the nominal range of 230 km of the hydrologic products.

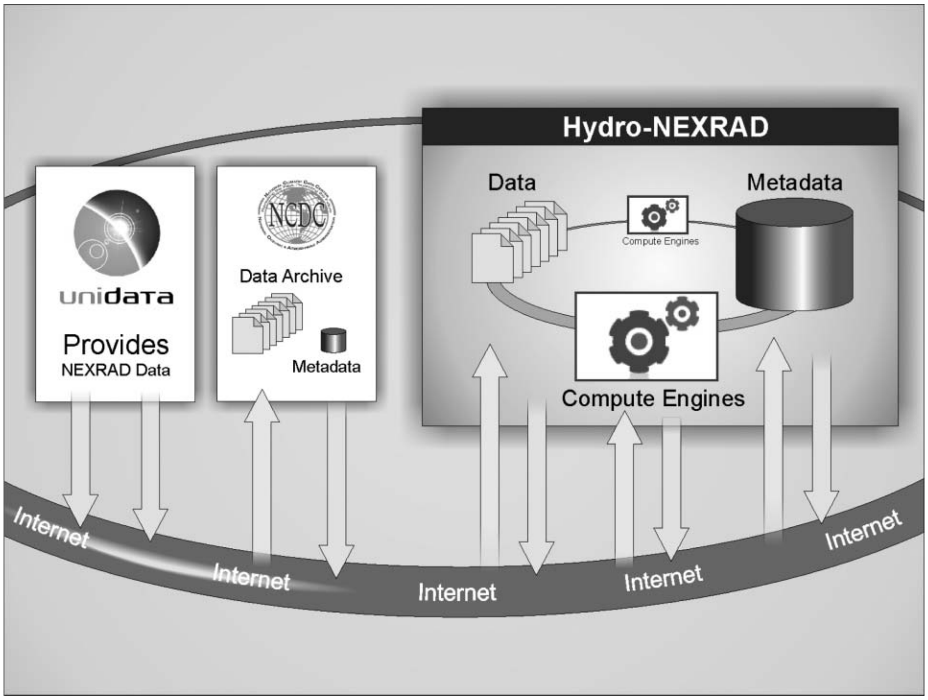

Figure 2 | A general schematic of Hydro-NEXRAD functionality. Basic data are provided in two modes: (1) in real-time from Unidata and (2) by accessing the NCDC archives. Both data acquisition and products dissemination occur over the Internet.

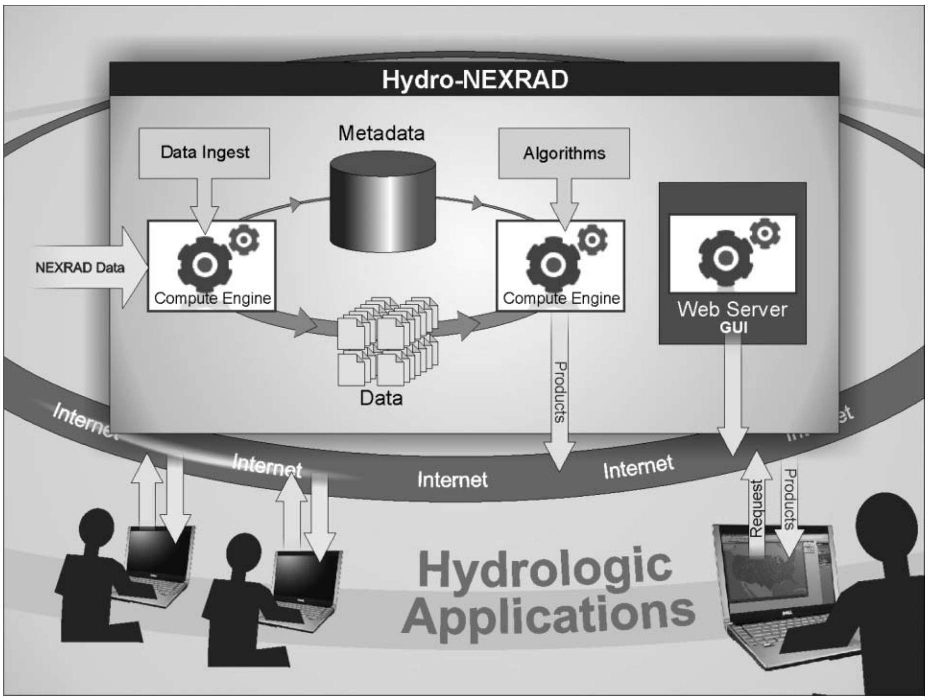

Figure 3 | Information technology elements of Hydro-NEXRAD. Shown are (1) file servers' dedicated storage of the data and the database; (2) compute servers dedicated to ingesting the data and calculating the metadata, computation of the products and running various utilities and (3) web servers to provide web services via graphical user interface and a mapserver.

COMPONENTS OF THE HYDRO-NEXRAD SYSTEM

Efficient data format

Level II data collected by the NEXRAD radars and available at the NCDC are organized so that one volume scan defines a file. Level II files are large–in addition to reflectivity and Doppler velocity information, Level II files contain low-level control messages. Further, data are stored uncompressed but NCDC compressed the Level II files with standard compression software such as *compress* and *gzip*. In order to process Level II files, users have to *uncompress/gunzip* such files, which is time-consuming. In Hydro-NEXRAD we use an ASCII Run Length Encoding (RLE) format we had developed for radar data several years ago (Kruger & Krajewski 1997). Despite fast progress in computer storage and processing speed, this lossless format continues to offer advantages as compared to other popular data compression utilities. Portability, fast read times and storage efficiency comparable to *gzip* are the main reasons for our decision. Also, in the process of converting Level II data from its native format to the RLE format we perform a number of quality control checks identifying corrupt files and headers and marking them with a system of flags. This ensures robustness of our overall system. All RLE files that are included in the Hydro-NEXRAD database are readable, which is not always the case for the original Level II data available from the NCDC, some of which are corrupt and cause programs that attempt to read them to fail.

An additional advantage of the RLE format is that we do not need to read the entire file when processing information and generating rainfall products for a basin, often just a small subsection of the entire radar umbrella. This results in processing speed gains. In contrast, *compress*-ed or *gzip*-ed files require uncompressing the entire volume file data every time a piece of information is needed that is contained within it.

To illustrate the storage gains, consider that one year of Level II data for Davenport (KDVN) radar requires about 800 GB of storage in the uncompressed Level II format. The RLE format reduces it to 25 GB. Regarding the read time, it takes 48 min to read the entire year of data in the original format while it takes only 12 min to read the corresponding RLE files. These figures are summarized in Table 1.

Table 1 | Table summarizing benefits of using the RLE file format over the WSR (raw) file format. Statistics are computed based on one year (2006) of Davenport, IA (KDVN) radar data

Level II file format	WSR (raw)	RLE
One year of radar data	796 GB	25 GB
Avg. single file read time	37 ms	11 ms
One year of data read time	48 min	12 min

Relational database

Researchers usually manage radar data using a hierarchical file and directory system, organizing radar volume scan files by radar and date. NEXRAD radars produce large amounts of data, namely a ~3.5 MB volume file every 4–12 min, and there are over 140 such radars. The file system approach suffices for small datasets, but quickly becomes unwieldy as the dataset grows. Organizations such as the National Climatic Data Center also follow this approach, but employ sophisticated hardware such as robotic tape loaders and large RAIDs to help with data retrieval. To help navigate a file-based archive, one can maintain a catalog of "interesting" portions of the data, such as severe rain or flood events.

Web servers play an important role in Hydro-NEXRAD. The relational database and the data are behind web servers. All access to the data and the relational database are through these servers. A client (human, compiled program or script) accesses the data through a two-step process: (a) query the database, which returns a URL (i.e. web address) to the data and (b) request the web server to serve up the data. The original concept and implementation follows on from earlier work documented in Kruger *et al.* (2006). Currently, our system provides *ad hoc* web services via HTTP and XML-RCP using Python and the FAstCGI protocol in conjunction with the web servers. Future work includes moving to standard interfaces (SOAP, OWL, etc.).

Radar- and basin-centric metadata

A key idea in Hydro-NEXRAD is that of metadata–data about (NEXRAD) data–managed in a relational database. It greatly eases the management of the data and allows researchers to search for and find interesting subsets in a very flexible manner. There are several aspects of the metadata that we consider in the Hydro-NEXRAD database. The first is a common use of data file description. The metadata are simply file descriptors such as name, location, date and quality control flags that pertain to formal completeness and correctness of the data and header format. The second aspect is that of the actual file location. In Hydro-NEXRAD we do not keep data in the database; instead the database stores information on the file location, together with the complete file path in several formats. Files are located across several disk systems, at many different physical locations. As Level II files are moved between locations, the database table entries are updated accordingly. The files could be duplicated to physically dislocated systems. This organization is useful for the use of multiple file servers to serve the community of users.

The third aspect regards hydrologically meaningful information. Briefly, for each of the raw (Level II) NEXRAD volume scan files that a radar collects, we compute descriptive statistics. For example, the areal coverage statistic is the area of the radar scan that has reflectivity (Z) values above a certain threshold. Thresholds can be used to distinguish in a quick, although only approximate way, frontal from convective systems. We use several thresholds that help classify available data. The full set of metadata computed for Level II NEXRAD files with a brief description can be found in Table 2.

Hydrologic studies are often organized around basins, i.e. land units defined by a point on a stream channel network. All water fallen on a given basin passes through the outlet that defines it. In the United States, surface waters are organized into a hierarchy system of basins (or basin sections) defined by the USGS. Basins of different sizes are assigned a Hydrologic Unit Code (HUC) that provides a unique identification and defines membership within larger units. Large basins, e.g. the Upper Mississippi River Basin (USGS HUC 0708), are covered by many NEXRAD WSR-88D radars and contain many smaller basins or units (see Figure 4). The numbering is hierarchical: watersheds with 4-digit HUC are comprised of smaller, 6-digit HUCs, and each 6-digit HUC watershed is comprised of 8-digit HUC watersheds, and so on. Lower-level units are as small as $10\,km^2$. Clearly, many such units are within each WSR-88D radar coverage.

Since there are many more small basins than large basins, it is likely that most hydrologic studies require rainfall information from a small portion of a given radar umbrella. To facilitate fast search for required data, we have developed a system of storing information relevant to each basin. To accomplish this we used the first four levels of the USGS system. As a result, we have developed a database for each of the 2199 fourth-level (8-digit HUC) basins. We have constructed an indexing system that links each basin with every radar. Thus, a user can quickly determine how many and which radars are "looking" over each basin. Each basin is associated with a latitude/longitude box for which a user is likely to request precipitation products. Each basin is also assigned a polar box for each relevant radar. The box defines the azimuth and range of data required for processing.

For each HUC domain included in Hydro-NEXRAD, we computed simple rainfall indicators. These include

Table 2 | List of radar-based metadata as computed by the Hydro-NEXRAD system

Radar metadata name	Short description
Coverage with reflectivity above 20 dBZ	This group of metadata has been designed to identify different precipitation conditions from light rainfall (20 dBZ) to heavy rain and possible hail (50 dBZ) observed over a radar umbrella.
Coverage with reflectivity above 30 dBZ	
Coverage with reflectivity above 40 dBZ	
Coverage with reflectivity above 50 dBZ	
Maximum reflectivity value	Metadata used to store maximum observed reflectivity at a given time.
Scan duration	Time (in seconds) it took to complete a volume scan. Designed to identify scanning strategies, missing data periods, etc.
Volume Coverage Pattern (VCP)	Scanning strategy used by radar. Based on this value, user can learn how many elevation tilts were used or identify rainfall/clear air mode.

Figure 4 | Example of the USGS Hydrologic Units. The large basins correspond to the two-digit Hydrologic Unit Codes. The Upper Mississippi HUC is divided into four-digit HUCs.

daily summaries of mean area rainfall, maximum rainfall, percentage of basin area covered by rain and more. Browsing these statistics allows users to quickly select interesting cases for their studies. For detailed metadata definitions and computations we refer to Kruger *et al.* (in press).

Data quality control

Since the main product of the Hydro-NEXRAD system is precipitation, radar echos due to other phenomena should be identified and excluded from further processing. This needs to be accomplished at the volume scan level, before Level II data are used for precipitation estimation. The problem, known as ground clutter and anomalous propagation (AP) echo identification and removal, has been discussed in the literature by several researchers (e.g. Moszkowicz *et al.* 1994; Grecu & Krajewski 2000; Vignal & Krajewski 2001). To address this problem we have implemented the algorithm of Steiner & Smith (2002). The algorithm is applied at each volume scan as it considers the vertical extent and structure of the radar echo in its classification decisions. The first time the use of the algorithm is requested, (e.g. at data ingest and processing time) a mask is produced that classifies each pixel in the base scan as precipitation or non-precipitation. Subsequent users of the volume scan data have an option of applying or not applying the mask. This organization of the problem speeds up the computation involved in the quality control of radar scans, but also facilitates future research on improved algorithms for AP detection, as the masks we compute are available for comparison.

We have also implemented an option that uses a CAPPI (Constant Altitude Plan Position Indicator (Battan 1973)). To avoid sharp boundaries between various antenna elevation scans, we use a smoothing lognormal kernel that is applied along the radar range. Such calculation of the CAPPI also helps mitigate the effect of ground clutter and anomalous propagation echo (for details see Seo *et al.* (in press)).

Rainfall estimation algorithms

Radar-based rainfall estimation algorithms differ in complexity and performance (e.g. Fulton *et al.* 1998; Steiner *et al.* 1995; Ciach *et al.* 1997; Anagnostou & Krajewski 1999). Unfortunately, regarding their performance, there is no system in place that would enable objective evaluation. As a consequence, there is no consensus on what is the best algorithm and optimality criterion. To address this situation our strategy is to provide users with flexibility in selecting different options and parameter values for the algorithms. While it is impossible to be fully comprehensive in providing such options, our system offers significant flexibility, much more than what is possible with the NWS "official" Precipitation Processing System (PPS) (Fulton *et al.* 1998) or use of Level III data products (Klazura & Imy 1993).

Among different algorithm options that users are able to choose from, are three predefined algorithms and one customizable algorithm. The predefined algorithms are a "quick look" algorithm, a default algorithm and a quasi-PPS algorithm. The custom algorithm includes options for correcting for advection and range effects, specifying different Z–R parameters, hail cap and no-rain thresholds, and hybrid scan construction parameters, among others. Users who do not have sufficient weather radar expertise can simply select one of the predefined alternatives. Comparison of products obtained using different approaches can lead to the selection of the optimal quality product, depending on the specific application.

We considered providing an option to reproduce the PPS results as a fundamental link connecting Hydro-NEXRAD and the NWS products, but this turned out to be a "mission impossible." While we have received the source code for the PPS from the Office of Hydrology of the NWS, it is buried within a much larger piece of software called *CODE* developed by the NEXRAD agencies and their private contractors. There is no stand-alone PPS available for use outside of the NWS. Also, the PPS is constantly changing and it is hard to keep track of all the minor fixes and code modifications. As a result, the closest we have come to reproducing the PPS results is about 5%. This is the reason why we refer to this option as "pseudo-PPS".

To facilitate the mix-and-match approach we have developed basic modules for the following elements: hybrid scan construction using the concept of CAPPI and kernel smoothing to avoid ring appearance common in long-term accumulations of the PPS products, rainfall rate calculations, rainfall accumulation, advection correction that improves rainfall accumulation by ensuring that pixels are not skipped over under certain combinations of storm velocity and product grid resolution (e.g. Fabry *et al.* 1994; Liu & Krajewski 1996) and range correction (e.g. Andrieu & Creutin 1995; Vignal & Krajewski 2001). We provide more details about the algorithms in the companion paper by Seo *et al.* (in press).

We continue performing extensive tests of the algorithms and the codes running them on multi-month periods of Level II data to make sure that they do not crash under varied data conditions. Thus far, several studies published in the literature used Hydro-NEXRAD products (e.g. Ntelekos *et al.* 2008; Villarini & Krajewski 2010).

Final product utilities

To provide users with further flexibility, our system will output precipitation products in several coordinate systems and resolutions. While the operational NEXRAD precipitation products are provided on the so-called Hydrologic Rainfall Analysis Project (HRAP) grid, which is about 4 km by 4 km, many distributed hydrologic models of basin processes require rainfall input at much finer resolution, e.g. 1 km by 1 km. Some models require input on a latitude/longitude grid, while others work using a local Cartesian system.

Our software accommodates many of these scenarios. Users can specify HRAP, Super-HRAP (1/16 of HRAP but using the same polar stereographic projection), latitude/longitude and NASA's Land Data Assimilation System (0.25° LDAS) grids (Mitchell *et al.* 1999). Since these grid systems are fixed, we have developed lookup tables for each basin for each grid that allows fast projection of the precipitation products generated in polar coordinates for a relevant radar onto the grid. Depending on the final product projection and spatial resolution, we considered three interpolation methods: nearest-neighbor, simple averaging and weighted averaging that accounts for the radar beam pattern. Radar beam geometry changes with range and requires an adaptive resampling technique. In the process of system development we conducted extensive tests to find an optimal strategy depending on final product selection. Use of different options implies different computational effort, even using the lookup tables. Additional interpolation methods are needed when data from multiple radars is merged into one rainfall product. More details on that can be found in Seo *et al.* (in press).

Once the products are generated and ready to be transferred to the user they are formatted as ASCII, ArcASCII or netCDF files, and can be used in many different applications, including Geographic Information Systems (GIS). For example, the format ArcASCII has the header structure "understood" by ESRI ArcGIS. We have developed a file naming and header structure convention so that one can tell at a glance what product and with what options is contained in the file. The naming convention also facilitates file level manipulation by various utility scripts.

Graphical User Interface

To facilitate users' interaction with our database and the algorithms we have designed a web-browser-based Graphical User Interface (GUI). Through the GUI users can locate their basin or domain of interest, radars that cover it, visualize the grid on which the final products will be provided, find cases (data periods) of interest using metadata-based searches and specify algorithmic options.

We have developed a browser-based GUI (see Figures 5 and 6 for screen shots). It communicates with a map server to provide user-specified map detail at four levels of zooming (the first level is the entire United States). The main elements shown on the maps are the hydrologic

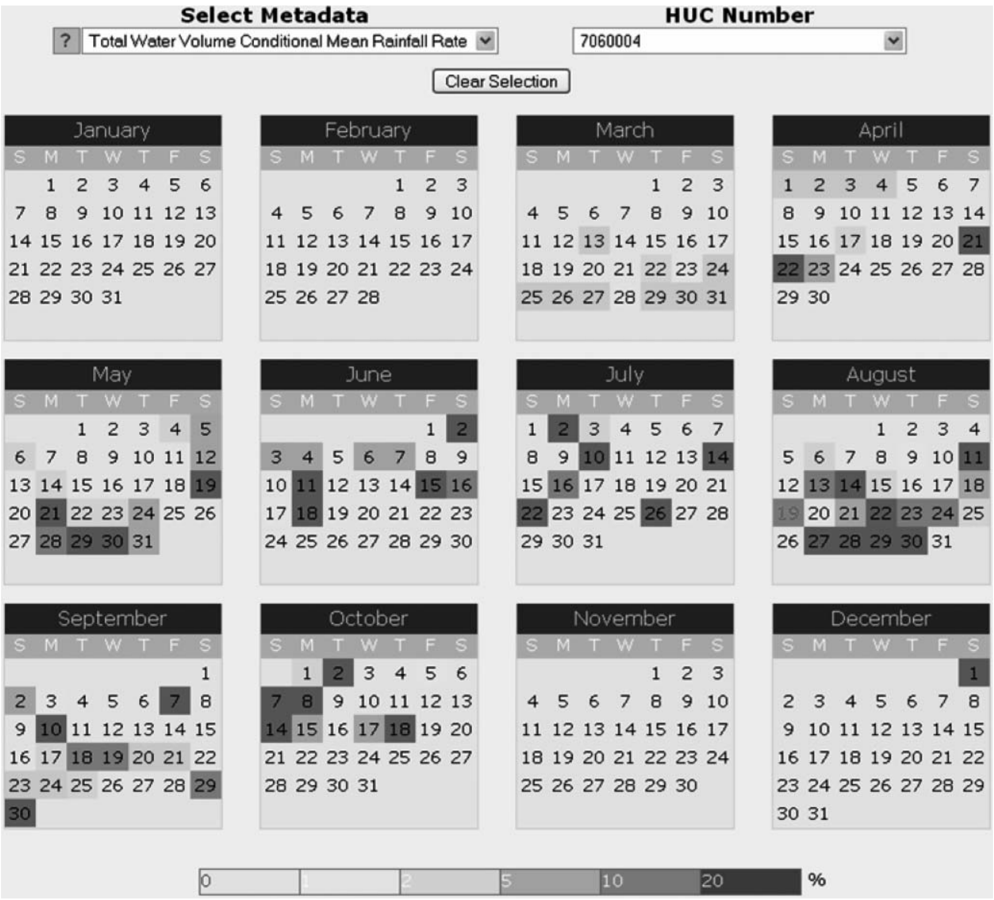

Figure 5 | A screen shot of the Hydro-NEXRAD GUI. The calendar shows daily aggregates of metadata for a specified HUC. The values are color-coded for easy interpretation.

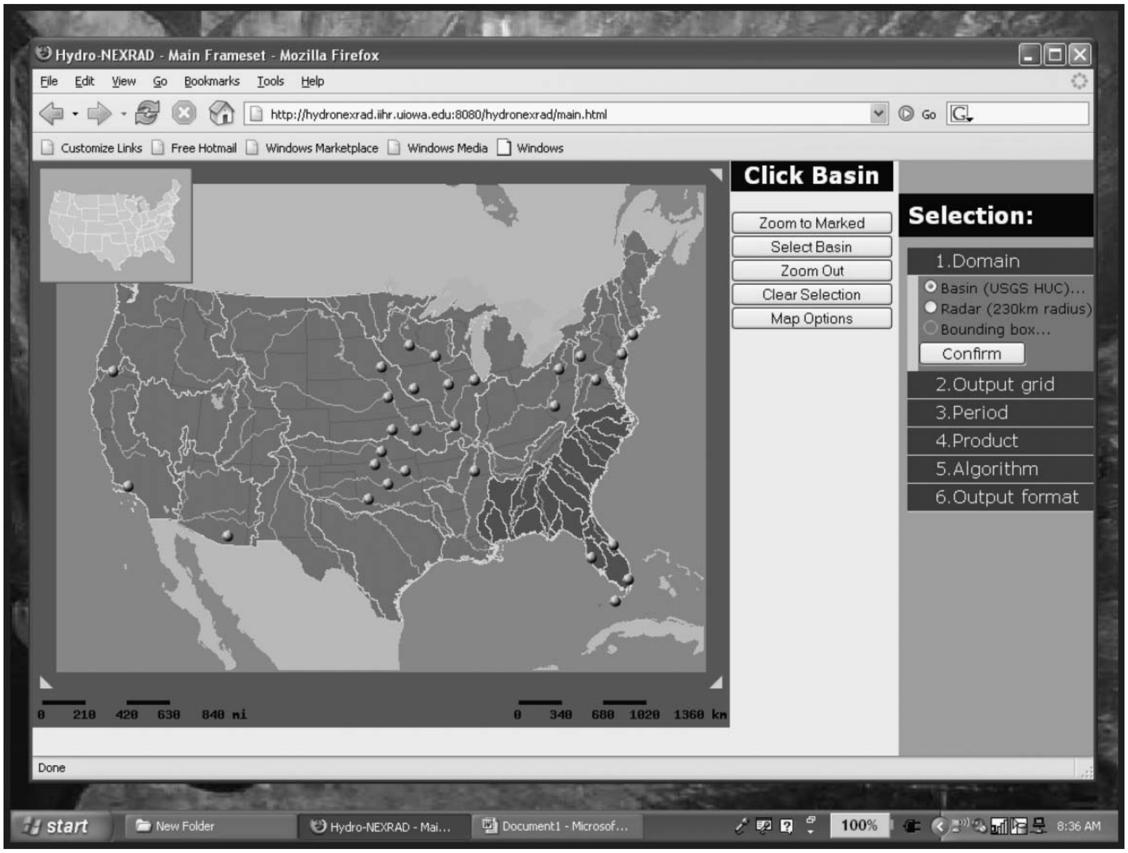

Figure 6 | A screen shot of the Hydro-NEXRAD GUI. The menu on the RHS shows the main phases of product selection. The menu expands showing available options when the particular phase becomes relevant (active).

basin boundaries according to the USGS classification system. Users can select large basins that contain their (smaller) basin of interest (hydrologists usually are familiar with this information). Zooming allows finding the basin of interest and selecting it for further processing. Next, users specify the periods of interest. If a user knows the dates, she/he can simply use the calendar display to enter them. The alternative is to use metadata in search of interesting cases.

Once the periods are selected, the user specifies algorithm options (discussed by Seo *et al.* (in press)). Again, the description of these options is provided in plain language, avoiding radar jargon, so that hydrologists can think in terms of rainfall variables and not so much the radar context. Specification of the grid resolution and formatting option completes the dialog. What follows ("behind the scenes") is spawning of a fully autonomous process that executes the user's request. The system informs the user as to when they can expect their request will be completed.

Currently, it takes about one day to process data and produce hourly products for one year's worth of Level II data. This represents a 10–20 times improvement vs. using *CODE* (see above) from the Office of Hydrology of the NWS.

The Graphical User Interface is also a place where users can access the system's documentation; learn about available options and find information about the system's functionality. The interface also provides all necessary information for users to communicate with the authors, submit comments and questions regarding the system.

SUMMARY

Hydro-NEXRAD is an over-the-Internet-accessible software system that provides custom radar-rainfall maps for use in hydrologic research and applications. The software was also designed to create real-time data stream and rainfall product generation over a specified region at a specified spatial grid. However, in the middle of 2008, WSR-88D radars began collecting the so-called "super-resolution" (0.5° in azimuth and 250 m in range) data (see Istok *et al.* (2009) for details). This necessitated data format changes and rendered previous algorithms useless. Rather than adapt the algorithms to the new data, the National Weather Service has developed a procedure to "recombine" the super-resolution data into the previous (legacy) resolution that could be used by the existing algorithms. As the change coincided with the expiration of the funding for the Hydro-NEXDAR project, we decided to use this "opportunity" to close the prototype system. Currently, we manage data from some 40 WSR-88D radars (see Figure 1) around the country and have close to 316 radar-years of Level II data in our 11.6 TB database.

The Hydro-NEXRAD products are radar-only estimates of rainfall, but could be easily merged with rain gauge estimates to reduce systematic and random errors involved in the measurement and estimation process. Discussing the problem of optimal merging is beyond the scope of this paper, but any minimum error variance procedure obviously requires quantified knowledge of product uncertainty. An uncertainty model limited to the official radar-only products generated by the NWS PPS is described by Ciach *et al.* (2007).

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation Award ATM 0427422. The first author also acknowledges partial support of the Rose & Joseph Summers endowment.

REFERENCES

Anagnostou, E. N. & Krajewski, W. F. 1999 Real-time radar rainfall estimation. Part 1: algorithm formulation. *J. Atmos. Oceanic Technol.* **16** (2), 189–197.

Andrieu, H. & Creutin, J. D. 1995 Identification of vertical profiles of radar reflectivity for hydrological applications using an inverse method. Part I: Formulation. *J. Appl. Meteorol.* **34**, 225–239.

Battan, L. J. 1973 *Radar observation of the atmosphere*. University of Chicago Press, Chicago.

Ciach, G. J., Krajewski, W. F., Anagnostou, E. N., McCollum, J. R., Baeck, M. L., Smith, J. A. & Kruger, A. 1997 Radar rainfall estimation for ground validation studies of the Tropical Rainfall Measuring Mission. *J. Appl. Meteorol.* **36** (6), 735–747.

Ciach, G. J., Krajewski, W. F. & Villarini, G. 2007 Product-error-driven uncertainty model for probabilistic quantitative precipitation estimation with NEXRAD data. *J. Hydrometeorol.* **8** (6), 1325–1347.

Fabry, F., Bellon, A., Duncan, M. R. & Austin, G. L. 1994 High resolution rainfall measurements by radar for very small basins: the sampling problem reexamined. *J. Hydrol.* **161**, 415–428.

Fulton, R. A., Breidenbach, J. P., Seo, D. J. & Miller, D. A. 1998 WSR-88D rainfall algorithm. *Weather Forecast.* **13**, 377–395.

Grecu, M. & Krajewski, W. F. 2000 An efficient methodology for detection of anomalous propagation echoes in radar reflectivity data using neural networks. *J. Oceanic Atmos. Technol.* **17** (2), 121–129.

Istok, M., Fresch, M. A., Smith, S. D., Jing, Z., Murnan, R., Ryzhkov, A. V., Krause, J., Jain, M. H., Ferree, J. T., Schlatter, P. T., Klein, B., Stein, D. J., Cate, G. S. & Saffle, R. E. 2009 WSR-88D dual polarization initial operational capabilities. In *Preprints 25th Conference on International Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, Phoenix, AZ*. American Meteorological Society, Phoenix, AZ, 15.5.

Kelleher, K. E., Droegemeier, K. K., Levit, J. J., Sinclair, C., Jahn, D. E., Hill, S. D., Mueller, L., Qualley, G., Crum, T. D., Smith, S. D., Del Greco, S. A., Lakshmivarahan, S., Miller, L., Ramamurthy, M., Domenico, B. & Fulker, D. W. 2007 Project CRAFT: a real-time delivery system for NEXRAD Level II data via the internet. *Bull. Am. Meteorol. Soc.* **88**, 1045–1057.

Klazura, G. E. & Imy, D. A. 1993 A description of the initial set of analysis products available from the NEXRAD WSR-88D system. *Bull. Am. Meteorol. Soc.* **74**, 1293–1311.

Krajewski, W. F. 1987 Co-kriging of radar-rainfall and rain gage data. *J. Geophys. Res.-Atmos.* **92** (D8), 9571–9580.

Kruger, A. & Krajewski, W. F. 1997 Efficient storage of weather radar data. *Softw. Pract. Exp.* **27** (6), 623–635.

Kruger, A., Krajewski, W. F., Domaszczynski, P. & Smith, J. A. (In press) Hydro-NEXRAD: metadata computation and use. *J. Hydroinf*.

Kruger, A., Lawrence, R. & Dragut, E. C. 2006 Building a terabyte NEXRAD radar database for hydrometeorology research. *Comput. Geosci.* **32** (2), 247–258.

Liu, C. & Krajewski, W. F. 1996 A comparison of methods for calculation of radar-rainfall hourly accumulations. *Water Res. Bull.* **32** (2), 305–315.

Mitchell, K., Houser, E. P., Wood, E., Schaake, J., Tarpley, D., Lettenmaier, D., Higgins, W., Marshall, C., Lohmann, D., Ek, M., Cosgrove, B., Entin, J., Duan, Q., Pinker, R., Robock, A., Habets, F. & Vinnikov, K. 1999 GCIP Land Data Assimilation System (LDAS) project now underway. *Gewex News* **9** (4), 3–6.

Moszkowicz, S., Ciach, G. J. & Krajewski, W. F. 1994 Statistical detection of anomalous propagation in radar reflectivity patterns. *J. Oceanic Atmos. Technol.* **11**, 1026–1034.

National Research Council (US), Committee on Integrated Observations for Hydrologic and Related Sciences 2008 *Integrating multiscale observations of U.S. waters*, vol. XII. National Academies Press, Washington, DC.

Ntelekos, A. A., Smith, J. A., Baeck, M.-L., Krajewski, W. F., Miller, A. J. & Goska, R. 2008 Extreme hydrometeorological events and the urban environment: dissecting the 7 July 2004 thunderstorm over the Baltimore, MD, metropolitan region. *Water Resour. Res.* **44**, W08446.

Reed, S. M. & Maidment, D. R. 1999 Coordinate transformations for using NEXRAD data in GIS-based hydrologic modeling. *J. Hydrol. Eng.* **4**, 174–182.

Seo, B., Krajewski, W. F., Kruger, A., Domaszczynski, P., Steiner, M. & Smith, J. A. (In press) Radar-rainfall estimation algorithms of Hydro-NEXRAD. *J. Hydroinf*.

Steiner, M., Houze, R. A., Jr & Yuter, S. E. 1995 Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data. *J. Appl. Meteorol.* **34** (9), 1978–2007.

Steiner, M. & Smith, J. A. 2002 Use of three-dimensional reflectivity structure for automated detection and removal of nonprecipitating echoes in radar data. *J. Atmos. Oceanic Technol.* **19** (5), 673–686.

Steiner, M., Smith, J. A., Burges, S. J., Alonso, C. V. & Darden, R. W. 1999 Effect of bias adjustment and rain gauge data quality control on radar rainfall estimation. *Water Resour. Res.* **35** (8), 2487–2503.

Todini, E. 2001 Bayesian conditioning of RADAR to rain gauges. *Hydrol. Earth Syst. Sci.* **5**, 225–232.

Vignal, B. & Krajewski, W. F. 2001 Large sample evaluation of two methods to correct range-dependent error for WSR-88D rainfall estimates. *J. Hydrometeorol.* **2** (5), 490–504.

Villarini, G. & Krajewski, W. F. 2010 Sensitivity studies of the models of radar-rainfall uncertainties. *J. Appl. Meteorol. Climatol.* **49**, 288–309.

Wilson, J. W. & Brandes, E. A. 1979 Radar measurement of rainfall – A summary. *Bull. Am. Meteorol. Soc.* **60**, 1048–1058.

First received 29 July 2009; accepted in revised form 11 December 2009. Available online 29 April 2010