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Radar Data Processing for Gridpoint Statistical Interpolation Radar Data Assimilation

by Huaqing Cai, Brian P Reen, and John W Raby

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14. ABSTRACT

The CCDC Army Research Laboratory (ARL) has developed and tested a software tool named radx2bufr. This tool fills a gap in ARL's capability of converting Universal Format radar reflectivity data into BUFR (Binary Universal Form for the Representation of meteorological data) so that Gridpoint Statistical Interpolation radar data assimilation can be applied to Weather Running Estimate – Nowcast (WRE-N), ARL's own nowcasting model based on the Weather Research and Forecasting model. The capability of assimilating radar reflectivity data into WRE-N greatly improved WRE-N's storm forecasting skills, especially from the first to a few hours. The successful development, implementation, and testing of this software tool plays a key role in enhancing ARL's nowcasting capabilities for Army system and operations.

15. SUBJECT TERMS

data assimilation, radar, BUFR, UF format, RADX, mesoscale modeling, WRF, Weather Research and Forecasting, WRE-N

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1. Introduction

It is a well-known fact that convective storms have large impacts on Army systems and operations. Therefore, providing time- and location-specific nowcasting of convective storms in the 0- to 6-h time frame becomes imperative. To better address the Army's needs in terms of its operating environment, the US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) has developed a nowcasting system called Weather Running Estimate – Nowcast (WRE-N; Dumais et al. 2013; Reen and Dawson 2018; Reen et al. 2019), which is a tailored version of Weather Research and Forecasting model, Advanced Research Version (WRF-ARW; Skamarock et al. 2019). WRF-ARW itself was developed by the National Center for Atmospheric Research (NCAR). WRE-N utilizes the four-dimensional data assimilation (FDDA) technique to assimilate conventional observations such as surface and sounding data, but it lacks the crucial capability to assimilate unconventional (i.e., remote sensing) data such as radar and satellite observations. In order to expand the data assimilation (DA) capability of WRE-N, we select a DA tool called Gridpoint Statistical Interpolation (GSI; Shao et al. 2016) developed by the National Center for Environmental Prediction (NCEP). GSI is widely used by many NCEP operational forecasting systems such as the Global Forecasting System. It is a community software package that is readily available and relatively well supported by the Developmental Testbed Center hosted by NCAR. GSI is capable of assimilating both conventional and unconventional data; specifically, we want to use GSI to assimilate radar reflectivity into WRE-N to improve its storm nowcasting skill in the first few hours of forecasts. Unfortunately, GSI requires all observational data to be in a format called BUFR (the Binary Universal Form for the Representation of meteorological data), while in reality almost no radar data are available in BUFR format; therefore, a software tool to perform the format conversion becomes absolutely necessary before GSI radar data assimilation can be applied to WRE-N.

The objective of this project is to develop a software tool that can convert radar data into BUFR format. The method for converting radar data into BUFR and testing if the conversion was successful is presented in Section 2. Section 3 provides a summary and discussion.

2. Methods

Radar data can come in many different formats depending on the kind of radar system and the manufacturer. In this project, the radar data are collected by a dual-polarization S-band Doppler radar located in Kwajalein Atoll. This radar system is very similar to the WSR-88Ds widely deployed in the continental United States, and its archived data are processed and quality-controlled by NASA. The radar data downloaded from NASA are in a widely used radar data format called Universal Format (UF). Unfortunately, a converter to change UF to BUFR format does not exist. In order to assimilate radar data using GSI, we have to develop a software tool to make this format conversion possible.

The conversion efforts start with utilizing a software package called RADX, which is part of a radar community software tool named the Lidar Radar Open Software Environment (LROSE; https://www.eol.ucar.edu/content/lidar-radar-open-software-environment) developed by NCAR and supported by the National Science Foundation. RADX can perform many kinds of operations on radar data, including radar data interpolation and format conversion, but BUFR is not a format RADX supports. On the other hand, one utility of RADX, which is called radx2grid, can read the UF radar data, interpolate them into 3D Cartesian coordinates from radar coordinates, and write the data out in NetCDF format. The next challenge is to determine how to change NetCDF to BUFR format.

GSI comes with a cloud analysis package, which was written by Dr Ming Hu from the National Oceanic and Atmospheric Administration's Global Systems Division. Dr Hu kindly provided his code, which can read National Severe Storm Laboratory (NSSL) multi-radar multi-sensor (MRMS) radar mosaic data in NetCDF format and convert them into BUFR. The only change needed is to modify Dr Hu's code so that it can read the NetCDF data created by RADX.

A simple flowchart showing the process of converting radar data from UF to BUFR format is presented in Fig. 1. The software tool consists of two major components. One is RADX from NCAR, and the other is called process_radx developed by ARL by modifying the code designed for converting NSSL MRMS radar data to BUFR. RADX is used to read UF radar data and interpolate them into 3D Cartesian grids in NetCDF format, while process_radx is responsible for reading the NetCDF from RADX and converting them into BUFR. Each step in the flowchart is discussed in detail in the following subsections.

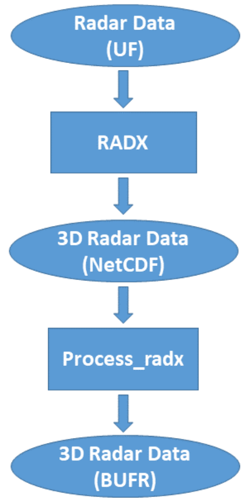

Fig. 1 **A flowchart describing the processes employed by the radx2bufr software tool to convert original radar reflectivity data from UF to 3D gridded radar reflectivity data in BUFR format**

2.1 Convert Radar Data from UF to Gridded NetCDF Format

GSI requires radar reflectivity data to be in 3D Cartesian coordinates, which should have the same map projection as that of WRF. Fortunately, RADX provides such a capability and other much-needed flexibility. In RADX, we can specify map projection, domain origin, size, grid spacing, and vertical levels for interpolation of radar data from polar coordinates to 3D Cartesian coordinates. A proper selection of those parameters ensures the gridded NetCDF radar data are on the same grid as that of WRF. Table 1 lists the parameters used by RADX for map projection and domain configurations.

Table 1 **RADX parameters that control the 3D Cartesian domain of interpolated radar reflectivity data**

Domain origin latitude (deg)	Domain origin longitude (deg)	dx (km)	dy (km)	Z levels (km)	nx	ny	Map projection
Grid_origin_lat = 9.05	Grid_origin_lon = 167.45	1	1	33 levels from 0.5 to 19.0	222	210	Lambert-Conformal Grid_lat1= 9.05 Grid_lat2= 9.05

To ensure that the RADX-created grid is the same as the particular WRF grid we used for this project, the grid origin latitude (i.e., the parameter grid_origin_lat in Table 1) must be set as the same as the Lambert-Conformal reference latitude 1 and 2 (i.e., parameters grid_lat1 and grid_lat2 in Table 1), which are the same as the WRF model map projection for the Kwajalein domain. For the purpose of testing if the NetCDF grid based on RADX settings in Table 1 is indeed the same as the WRF grid, we calculated the differences of latitude/longitude/distance between these two set of grids and presented the results in Fig. 2. As shown by Fig. 2, the two grids are fairly close, with the maximum distance less than approximately 229 m, which is approximately one-fourth of the 1-km grid spacing. The rather small distance difference is probably caused by the slightly different assumption of earth radius in WRF (~6370.0 km) and in RADX (~6378.1 km) since both WRF and RADX treat earth as a sphere.

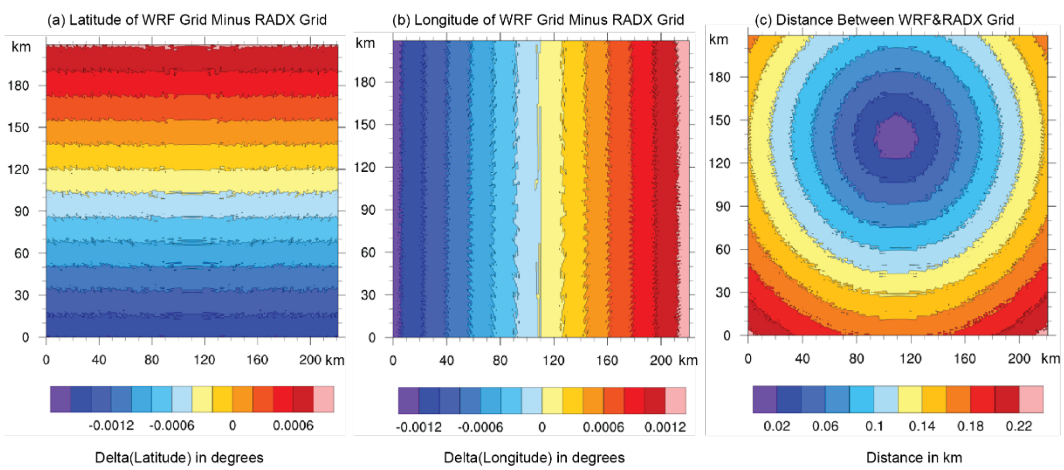

Fig. 2 Differences of WRF minus RADX grid for a) latitude in degrees, b) longitude in degrees, and c) distance in kilometers

After setting up the domains properly in RADX, we have to think about what kind of fields to output from RADX. Theoretically, since we only assimilate radar reflectivity data, the only field that matters is the radar reflectivity field itself. However, in the radar reflectivity field, we actually should have three kinds of values. The first is an actual radar reflectivity in decibels relative to Z (dBZ), the second is a flag for missing/out of range data, and the third is another flag for no echoes/no storms. It is very important to be able to distinguish between missing versus no echo since GSI could use the no echo information to suppress false convection. Unfortunately, RADX does not distinguish between missing and no echo. Both of them are represented by –9999.0 in a RADX-derived 3D Cartesian grid.

To get around this problem and avoid problems down the road when using GSI radar data assimilation, we let RADX create an additional field named "coverage".

This coverage field is on the same Cartesian grid as the radar reflectivity field, but on each grid point, it has a value of one if the grid is within radar beam coverage and zero if the grid is out of radar coverage. Combined with the radar reflectivity field, the radar coverage field will help in distinguishing between missing and no echo in process_radx, which is discussed in the next subsection.

An example of original radar reflectivity in polar coordinates at low elevation (0.4°) compared to an interpolated radar reflectivity image at 0.5 km above ground level (AGL) is shown in Fig. 3. Notice that the reflectivity pattern in Fig. 3b is very similar to the reflectivity pattern inside the red box in Fig. 3a, which indicates that RADX did a decent job in interpolating radar data onto a 3D Cartesian grid. An exact match between Fig. 3a and 3b is not expected because of the differences in the coordinates and the completely different color tables employed in making those figures.

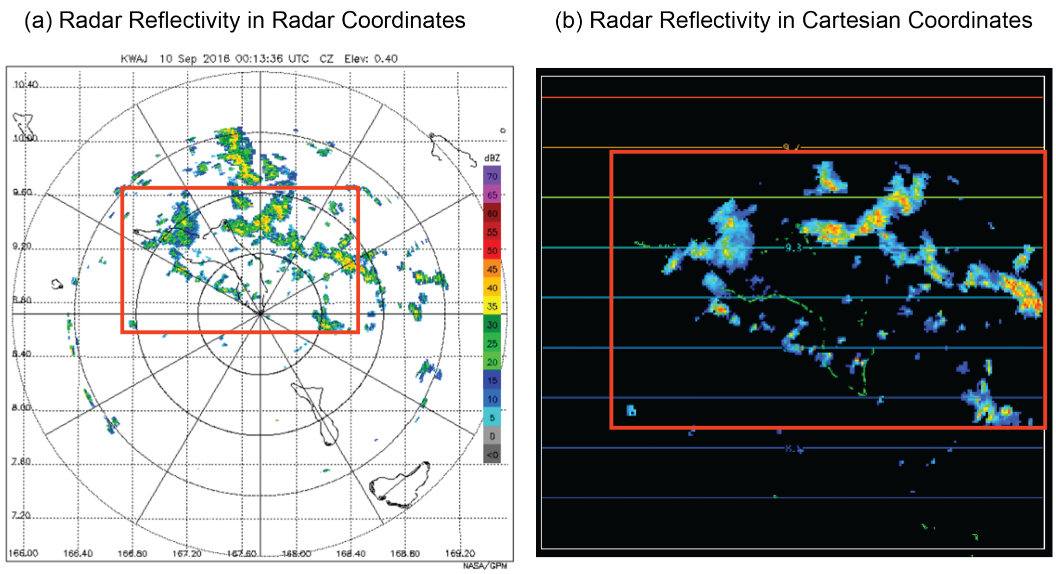

Fig. 3 An example of comparing original reflectivity data from Kwajalein radar with interpolated 3D gridded radar reflectivity from RADX. a) radar reflectivity in polar coordinates from elevation of 0.4° at 0013 UTC on 10 September 2016; and b) RADX-derived gridded radar reflectivity in 3D Cartesian coordinates at 0.5 km AGL. The red box in both panels a) and b) indicates roughly the same area in both plots.

2.2 Convert Radar Data from Gridded NetCDF to BUFR Format

As shown in Fig. 1, we developed a piece of software named process_radx to convert radar data from gridded NetCDF to BUFR format. Process_radx is written in Fortran 90 and calls a number of special libraries, such as NetCDF libraries from Unidata and BUFR libraries from NCEP, to fulfill the task of converting RADX-created NetCDF files into BUFR format. Process_radx is based on Dr Ming Hu's code, which has the capability of reading NSSL radar mosaic data in NetCDF format and converting them into BUFR. However, to make Dr Hu's code work for our data, a number of modifications to the code had to be completed. First, an additional field of radar coverage has to be read and processed so that the missing versus no echo issues discussed in the previous section can be resolved. Second, the field name and other NetCDF parameters dealing with field dimensions have to be modified so that the correct field and dimension from RADX can be obtained. Third, many codes dealing with interpolating NSSL mosaic radar reflectivity onto the WRF grid have to be carefully removed since they are not needed anymore, and fourth, codes handling parallel computing for different NSSL mosaic tiles at the same time have to be modified. All of these code modifications were nontrivial since they required profound understanding of RADX, NetCDF, BUFR, and Dr Hu's code.

The final output files from radx2bufr consist of radar reflectivity on a 3D Cartesian grid in BUFR format with three kinds of values possible on any given grid point: 1) a normal radar reflectivity with values greater than –63 dBZ, 2) –63, indicating no echo, and 3) –64, indicating missing data or out of radar coverage. Subsequently, this output can be processed by GSI to produce latent heating temperature tendency (LHT) profiles based on radar reflectivity data.

An example showing RADX-created radar reflectivity and its corresponding GSI-created LHT field at similar heights is presented in Fig. 4. Notice the very similar pattern between Fig. 4a and 4b, as well as Fig. 4c and 4d, which confirms the radar data was correctly ingested by GSI and the conversion of radar data from UF to BUFR format was working correctly. As in Fig. 3, color tables are not needed in Fig. 4 because we are only interested in comparing patterns/locations of radar reflectivity from RADX and LHT from GSI, not their specific values.

The radar-derived LHT calculated by GSI is then put into WRF (i.e., WRE-N) to replace the temperature tendency created by the model's microphysics parameterization. For details on assimilating GSI-derived LHT into WRE-N, the reader is referred to Reen et al. (2019).

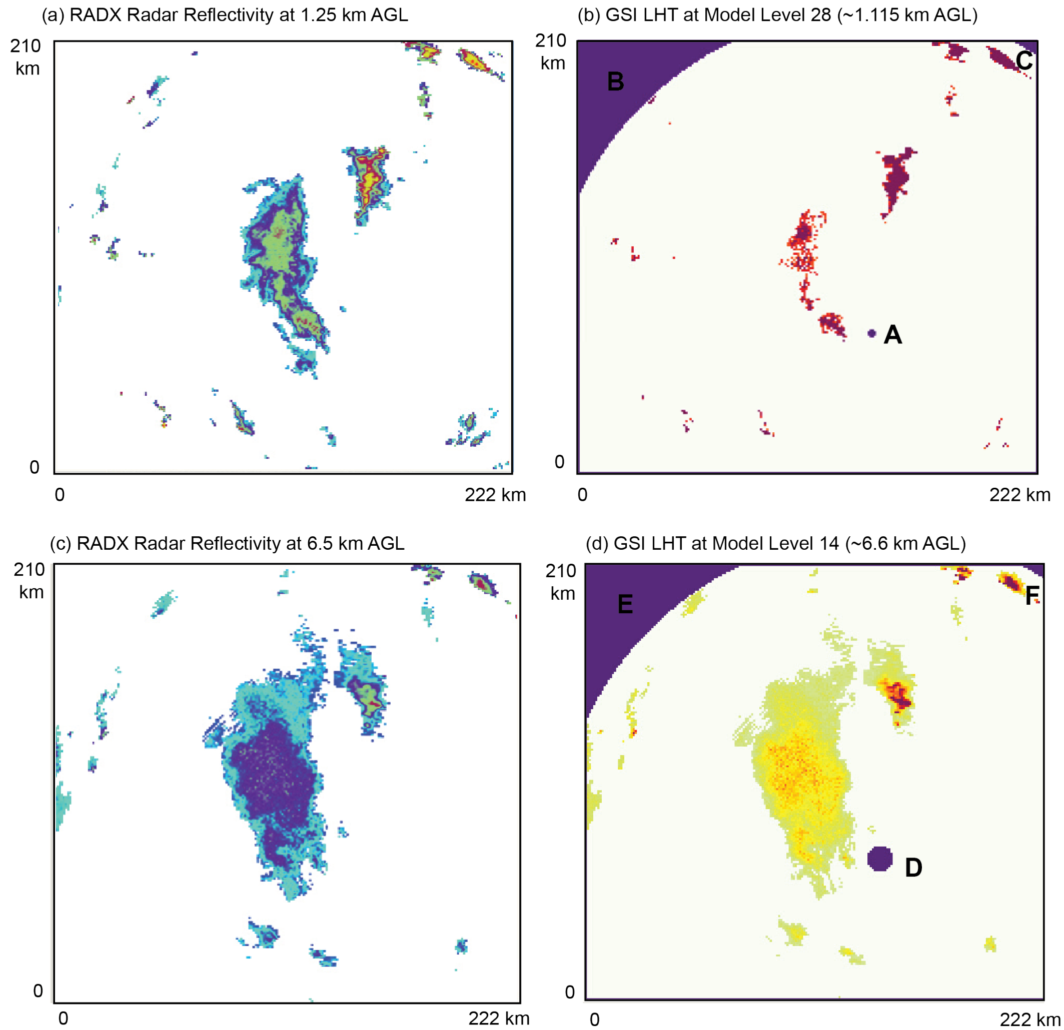

Fig. 4 Comparison of radar reflectivity from RADX and its corresponding LHT field from GSI at ~0517 UTC on 9 September 2016 over Kwajalein Atoll. a) RADX radar reflectivity at 1.25 km AGL, b) GSI-derived LHT at ~1.115 km AGL, c) RADX radar reflectivity at 6.5 km AGL, and d) GSI-derived LHT at ~6.6 km AGL. The radar coverage is clearly indicated in panels b) and d) with missing data represented by dark blue areas of A, B, C, D, E, and F. Specifically, both areas A and D are the result of the radar's cone of silence, whereas areas B, C, E, and F are out of radar range.

2.3 Automate the Running of radx2bufr Software Tool

The whole process of converting UF radar reflectivity data into BUFR format as described in Fig. 1 can be fully automated using shell scripts. The RADX software package can be downloaded from the LROSE website (https://www.eol.ucar.edu/content/lidar-radar-open-software-environment). The parameters used to control the execution of RADX (or to be exact, one of the RADX utilities called radx2grid as mentioned earlier) are contained in a text file and can be easily edited. Although the text file is rather long (~40 pages), only a few parameters regarding input/output directory, data format, map projection, and domain specification, among others, need to be changed. Most other parameters were either not used or used their default values. On the other hand, controls for process_radx are very simple, requiring just a short text file (called mosaic.namelist) that contains a flag indicating the kind of input data, a time stamp for the radar data, and the input radar data directory. In our case, the input data format flag was set as option 14, which indicates the input file is a single NetCDF file. In the current version of radx2bufr, the analysis time in the mosaic.namelist file can only be specified at the top of each hour, which was put into the output BUFR file. To get around this limitation and accurately represent radar data in minutes instead of hours, the radar data time stamp was actually put into the file names of BUFR files. Therefore, GSI has to get the exact time of the radar data from the BUFR file names and completely ignore the time stamp inside the BUFR files.

The RADX software package is written in C/C++ while process_radx is in Fortran 90. To successfully compile process_radx, both NetCDF and BUFR libraries, as well as other Fortran 90 libraries, are required. Because of the relatively small domains used in this project (~200 km × 200 km with 1-km grid spacing), the computational time for process_radx is less than a minute on a single processor on an ARL high-performance computer (Excalibur). However, RADX took a much longer time (on the order of several minutes) to run.

3. Summary and Conclusions

Numerous studies in nowcasting storms suggest that assimilating radar data into numerical weather prediction (NWP) models is a must in order for the models to be of any use in the first few hours of nowcasting storms (Sun et al. 2014). Unfortunately, up until recently ARL's nowcasting model (i.e., WRE-N) still lacked the capability of assimilating radar reflectivity data. To fill this gap and make WRE-N a state-of-the-art NWP-based nowcasting model, we have conducted research on how to best assimilate radar data into WRE-N using GSI. Since GSI requires radar reflectivity data in BUFR format, a software tool called radx2bufr is developed and tested. Radx2bufr consists of two major components. The first component was developed by NCAR and called RADX, which reads the original radar data in UF and interpolates them onto a 3D Cartesian grid in NetCDF. The second component was developed by ARL and called process_radx, which reads RADX-created NetCDF grid and converts them into BUFR. In addition to format conversion, process_radx also takes care of the missing versus no echo issues related to RADX. The radx2bufr software tool is driven by a shell script and has been mostly automated. The codes are uploaded to an ARL GitLab site for easy sharing with other ARL colleagues.

After successful implementation and testing of radx2bufr, we were able to use this software package to convert radar data from two cases over Kwajalein Atoll into BUFR, run GSI to create LHT profiles based on the radar reflectivity, and assimilate them into the WRE-N model at 15-min intervals for various preforecast periods. Preliminary results, which are very promising, show that the model nowcasting skills are greatly improved in the first hour to the first few hours of the forecast based on fractions skill score. For details of data assimilation methods and verification of nowcasting results, the readers are referred to Reen et al. (2019) and Raby et al. (2019).

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List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
AGL	above ground level
ARL	Army Research Laboratory
BUFR	Binary Universal Form for the Representation of meteorological data
CCDC	US Army Combat Capabilities Development Command
DA	data assimilation
dBZ	decibels relative to Z
GSI	Gridpoint Statistical Interpolation
LHT	latent heating temperature tendency
LROSE	Lidar Radar Open Software Environment
MRMS	multi-radar multi-sensor
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NetCDF	Network Common Data Form
NSSL	National Severe Storms Laboratory
NWP	numerical weather prediction
RADX	Radial Radar Data Software Package
UF	Universal Format
UTC	Coordinated Universal Time
WREN	Weather Running Estimate – Nowcast
WREN_RT	Weather Running Estimate – Nowcast Realtime
WRF	Weather Research and Forecasting
WRF-ARW	Advanced Research version of the Weather Research and Forecasting

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