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14. ABSTRACT
The goal of the project is to study and develop advanced approaches for radar data quality control (QC) and assimilation that will not only optimally utilize Doppler wind information from WSR-88D and Terminal Doppler Weather Radar (TDWR) but also take full advantage of rapid and flexible agile-beam scans from the phased array radar (PAR) at NWRT.

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FINAL TECHNICAL REPORT

(5/22/2014)

Project Title: Adaptive Radar Data Quality Control and Ensemble-Based Assimilation for Analyzing and Forecasting High-Impact Weather

ONR Award No.: N000141010778
Period: 5/1/2010 - 3/31/2014

Principal investigator: Qin Xu

Long-term Goals

Study and develop advanced approaches for radar data quality control (QC) and assimilation that will not only optimally utilize Doppler wind information from WSR-88D and Terminal Doppler Weather Radar (TDWR) but also take full advantage of rapid and flexible agile-beam scans from the phased array radar (PAR) at NWRT.

Objectives

1. Investigate outstanding velocity data QC problems in operational WSR-88D and TDWR radar observations and NWRT PAR observations, and develop advanced QC techniques for various scan modes to satisfy data assimilation needs.

2. Study how to optimize PAR scans in combination with data compression strategies based on modern information theory. Develop optimal strategies to maximize PAR observation information content and minimize data redundancy for ensemble-based radar data assimilation.

3. Explore and develop new hybrid sampling approaches based on Bayesian probability theory for ensemble-based radar data assimilation to improve real-time analysis and forecast of high-impact weather.

Approaches

1. Approaches for objective-1

The automated radar-based wind analysis system (RWAS, Xu *et al.* 2009a) can be used to monitor and record various data quality problems in operational WSR-88D and TDWR radar observations as well as NWRT PAR observations. By investigating and classifying outstanding data quality problems, advanced adaptive data QC techniques can be developed for various scan modes to satisfy data assimilation needs.

2. Approaches for objective 2

By extending the theoretical formulations derived for measuring information content from observations for data assimilation (Xu 2007, Xu *et al.* 2009b), efficient data compression strategies and optimal PAR strategies can be designed based on the modern information theory to maximize the information content from observations and minimize data redundancy for ensemble-based radar data assimilation.

3. Approaches for objective 3

Built upon the success of the time-expanded sampling approach (Xu et al. 2008a,b; Lu et al. 2011), new hybrid sampling approaches can be developed for ensemble-based radar data assimilation to improve real-time analysis and forecast of high-impact weather. The 3.5Var radar data assimilation package (delivered to NRL for nowcast applications) can be upgrad ed to provide a starting point for hybrid extensions. Besides, automated algorithms can be developed to detect tornadic vortices scanned from radars and to estimate the key parameters for formulating the vortex-flow-dependent background covariance functions to improve real-time tornadic wind analyses and nowcasts.

Major research activities and accomplishments

Major research activities and accomplishments are stated for each objective in the following three subsections.

1. A real-time access to high-resolution level-II data from the OKC airport TDWR radar was acquired and established through high speed Internet. The radar data QC techniques (delivered to NRL) were tested extensively with raw level-II data collected from many operational WSR-88D (S-band) radars under various high-impact weather conditions (Xu *et al.* 2010a, 2011c). Applying these QC techniques to TDWR (C-band) radar data required modifications and additional tests especially for the scan Mod80 used by TDWR with reduced Nyquist velocities (< 18 ms^{-1}) for windy or stormy weather. To solve this problem, the alias-robust variational radar wind analysis (Xu et al., 2009b) was used in place of the AR-VAD analysis (Xu et al. 2010a) for the reference check in the radar vicinity area, and then the block-to-point continuity check procedure (Xu *et al.* 2011c) was used adaptively to extend the dealiased data areas away from the radar at the lowest few tilts. The real-time RWAS was used to monitor the performance of the radar data QC techniques by displaying the dealiased radial velocities and their produced wind in comparison with observations from other sources (Xu et al. 2011b, 2012).

The AR-VAD analysis (Xu et al. 2010a) and the alias-robust variational analysis (Xu et al. 2009b) were further developed and combined into a two-step alias-robust variational analysis technique, called AR-Var (Xu and Nai 2013), to estimate the radial-velocity field from raw aliased radial-velocity observations on each range circle. This two-step AR-Var analysis can provide a reliable reference radial-velocity field for the reference check in radar velocity dealiasing even when the Nyquist velocity v_N is reduced below 12 m s^{-1}. By using the AR-Var analysis for the reference check, a new adaptive AR-Var-based dealiasing method was developed for radar radial velocities scanned with small Nyquist velocities. This new method was successfully tested with severely aliased velocity data scanned by the KTLX radar using volume coverage pattern 31 (VCP31) with v_N reduced below 12 m s^{-1} for severe winter ice storms. The method was also successfully tested with aliased velocity data (127 volumes) scanned by the TDWR (TOKC near the Oklahoma City Airport) using Mode80 with v_N < 18 m s^{-1}. Since this new method costs triply more CPU time than the AR-VAD-based method (Xu *et al.* 2011c), it is used adaptively only when VCP31 is used by WRS-88D or Mode80 is used by TDWR. The detailed technique and superior performance of this new adaptive method were published in Xu and Nai (2012).

The above adaptive dealiasing was also incorporated into the radar data QC package in the RWAS running with real-time radar data (including dual-polarization data) to monitor data quality problems in radar observations. From the real-time run, the adaptive dealiasing technique was found to be capable of correcting alias errors without false dealiasing, but the dealiased data still encoutered difficulties to cover isolated data areas far away from the radar or localized areas of strong and complex winds such as those around mesocyclones. Dedicated efforts were made to further improve the dealiasing technique, so the dealiased data can have increased coverage but remain to be completely free of false dealiasing, especially over storm-scale areas threatened by intense mesocyclones and their generated tornados. Substantial improvements were made in both the first-step reference check and the second-step continuity check. The improved technique has been successfully tested with more than 400 volumes of severely aliased raw radial-velocity data scanned from tornadic storms. The detailed technique were published in Xu et al. (2013a). The technique is being continuously improved and will be incorporated into the radar data QC package and delivered to NRL Montcrey for radar data assimilation applications.

An alias-robust least-squares method was devcloped to estimate thc maximum tangential velocity V_M and its radial distance R_M from the hurricane vortex center by fitting a parametric vortex model directly to raw aliased velocities scanned from a hurricane. In this method, aliasing-caused zigzag-discontinuities are formulated into the cost-function via the unconventional approach of Xu et al. (2009b) rooted in the Bayesian estimation theory (Xu 2009) to ensure the cost-function to be smooth and concave around the global minimum. Simulated radar velocity observations were used to examine the cost-function geometry around the global minimum in the space of control parameters (V_M, R_M). With elaborated refinements, the method can produce reliable reference radial-velocity fields to improve the automatcd dealiasing (Xu et al. 2011c) adaptively for severely aliased velocities scanned from hurricanes. The method was successfully tested with more than 600 volumes of severely aliased raw velocity data scanned from three hurricane cases by four operational radars (KLIX, KMOB, KHGX, KMHX). The detailed method and results were published in Xu et al. (2014).

By using real-time dual-polarization observations from the operational WSR-88D radars, a fuzzy-logic technique was developed to identify contaminated Doppler velocities by birds, especially migrating birds. As a necessary and important part of the radar QC, this technique is new in terms of using newly available dual-polarization observations, and it replaces the previous technique (Zhang et al. 2005; Liu et al. 2005) developed from a past ONR-funded project before the operational WSR-88D radars in the US were upgraded with dual-polarization.
Without dual-polarization observations, the previous technique could only crudely detect bird-contaminated velocities volume-wise or tilt-wise (for each sweep), so it would reject the entire volume (or tilt) of velocity observations even when only a fraction of the volume (or tilt) were contaminated by migrating birds. By using the dual-polarization observations, the new technique can detect and remove bird-contaminated velocities pixel-by-pixel. The new technique was tested with polarimetric data collected from the operational KVNX and KICT radars during several spring and fall migrating seasons. The detailed technique and results were published in Jiang et al. (2013).

2. The singular-value formulations for measuring information content from observations for data assimilation (Xu 2007; Xu *et al.* 2009c) were further explored in spectral spaces. By using discrete Fourier transformation and generalized Fourier transformation, the formulations were converted into spectral forms in the wavenumber space for uniformly distributed observations. The spectral formulations exhibited the following advantages over their counterpart singular-value formulations: (i) The information contents from densely distributed observations can be calculated very efficiently even if the background and observation space dimensions become

both too large to compute for the singular-value formulations. (ii) The information contents and their asymptotic properties can be analyzed explicitly for each wavenumber. (iii) Super-observations can be not only constructed by a truncated spectral expansion of the original observations with zero or minimum loss of information but also explicitly related to the original observations in the physical space. The spectral formulations also revealed that (i) uniformly thinning densely distributed observations will always cause a loss of information and (ii) compressing densely distributed observations into properly coarsened super-observations by local averaging may cause no loss of information under certain circumstances. The detailed mathematical derivations and expositions were published in Xu (2011).

Numerical experiments were designed with PAR observations to explore and demonstrate the merits and utilities of the spectral formulations. In particular, the information contents from radar observations for data assimilation were computed by the spectral formulations and verified against the results computed accurately but costly from the singular-value formulations. The results demonstrated that the spectral formulations can be used (i) to precisely compute the information contents from one-dimensional radar data uniformly distributed along the radar beam, (ii) to approximately estimate the information contents from two-dimensional radar observations non-uniformly distributed on the conical surface of radar scan, and thus (iii) to estimate the information losses caused by super-observations generated by local averaging with a series of successively coarsened resolutions to find an optimally coarsened resolution for radar data compression with zero or near-zero minimal loss of information. As the background and observation error power spectra can be derived analytically for the above utilities, the spectral formulations are computationally much more efficient and affordable than the singular-value formulations, especially when the background space and observation space are both extremely large and too large to be computed by the singular-value formulations. The detailed results were published in Xu and Wei (2011).

3. The time-expanded sampling (TExS) approach (Xu et al. 2008a,b; Lu et al. 2011) was upgraded and tested through various assimilation experiments with the KTLX radar data plus the Oklahoma Mesonet data. In particular, the background covariance localization was modified adaptively for each type of data, and an adaptive covariance inflation was designed for the TExS based on the required consistency between the ensemble spread and the ensemble mean error variance (computed by subtracting the observation error variance from the innovation variance). The upgraded adaptive TExS was tested successfully with the radial-velocity and reflectivity data collected by the operational KTLX radar for the Oklahoma City tornadic storm on 8 May 2003. The collected radar data were processed through quality control and compressed into super observations to reduce the spatial-resolution redundancy. These super observations were used to test the upgraded adaptive TExS in comparison with the original TExS (Xu et al. 2008b; Lu et al. 2011) as well as the conventional ensemble sampling approach. As shown by the examples in Fig. 2 of the FY11 annual report (MMxu2011.doc), the upgraded adaptive TExS is effective in reducing the computational cost and improving the accuracy of the anlysis as well as the subsequent prediction.

New ideas were explored to improve the 3.5Var radar data assimilation method (Xu et al. 2010b) in the following two aspects: (i) Ensemble-based statistical relationships between the reflectivity and thermodynamic perturbations were derived for the reflectivity analysis. (ii) The radial-velocity prognostic equation was derived for the 3.5Var in a concise and accurate form by considering atmospheric refraction and earth curvature (Xu and Wei 2013). The pressure and potential temperature increments produced by the reflectivity analysis using the statistical relationships can be treated as "observations" and used together with the radar observed radial velocities (after quality control) to combine the vector wind analysis and thermodynamic analysis in the original 3.5Var into a single analysis step with all the analysis incremental fields constrained by properly simplified COAMPS-model equations (including the newly derived radial-velocity prognostic equation). This provides a good starting point for hybrid extensions of the 3.5Var with the time-expanded ensemble approach for further improvement.

Automated algorithms were developed to detect mesocyclones imbedded within severe thunderstorms scanned from radars and to estimate their key parameters, such as the vortex center location and moving speed and direction, maximum rotational winds and radius of maximum wind (Xu 2013a). From the estimated key parameters, vortex-flow-dependent background covariance functions were formulated in terms of stream-function and velocity-potential for the flow field around each detected mesocyclone. By applying the convolution theorem to the formulated covariance functions in discrete forms, the square root of background covariance matrix was derived analytically and used to transform the control variables for preconditioning the cost-function. Using this preconditioned cost-function, a new and efficient variational method was developed in an incremental form for analyzing tornadic vortex winds from radar radial-velocity observations in a nested vortex-following domain on each tilt of radar scan. The method was successfully tested with tornadic mesocyclones observed by operational radars in Oklahoma on 24 May 2011 and 19-20 May 2013, and it can be either used independently or incorporated into the upgraded RWAS (Xu et al. 2012) as an adaptive incremental step for real-time applications.

The new variatonal method for tornadic vortex wind analysis has the following attractive features. (a) The analysis domain is centered at and moving with the detected vortex center on each tilt of radar scan. (b) Vortex-flow-dependent background error covariance functions are formulated for the control variables (stream-function and velocity-potential) in the moving frame. (c) The square root of the background covariance matrix is derived analytically from each covariance function and is used to transform the control variables and formulate the cost-function in a concisely preconditioned form. (d) The control variables are discretized adaptively based on the background de-correlation length scales to achieve the desired high-computational efficiency and accuracy. An example of analyzed vortex winds was shown in Fig. 3 of the FY13 annual report (MMxu2013.doc) for the mesocyclone and its produced EF5 tornado that struck the city of Moore, Oklahoma in the afternoon on 20 May 2013. The detailed method and test results were presented in Xu et al. (2013b).

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