ABSTRACT
This paper reports the improved radar wind data quality control and analysis techniques in the radar wind analysis system (RWAS) developed for monitoring hazardous wind conditions at high spatial (2-5 km) and temporal (5-10 min) resolutions.

1. INTRODUCTION
The radar wind analysis system (RWAS) uses the statistical interpolation formulated for radar radial and tangential velocity components to retrieve the horizontal vector wind field from radar observed radial velocities [1], while the background error covariance is estimated from the differences between the radar observed and background radial velocities by using the innovation method [2]. The early RWAS was designed to retrieve the vector wind field on each tilt of radar scan in real time, so the retrieved wind field can be used to drive high-resolution emergency response dispersion models for homeland security applications [3]. To monitor hazardous wind conditions at high spatial and temporal resolutions, the RWAS has been upgraded to retrieve the real-time vector wind field in a mesoscale domain by using radial velocities scanned from operational WSR-88D radars. In addition, real-time Oklahoma Mesonet wind data are also ingested into the system to improve the retrievals. The upgraded RWAS includes a variational dealiasing method for radar wind data quality control, and a multi-step approach for vector wind analysis. These techniques are briefed below.

2. RADAR DATA QUALITY CONTROL
The radar velocity dealiasing method [4] for radar data quality control in RWAS performs two steps: (i) the reference check with the reference radial-velocity field produced by the alias-robust velocity azimuth display (VAD) analysis [5], and (ii) the block-to-point continuity check with an enhanced use of available (dealiased and de-flagged) seed data in a properly enlarged block area near each flagged data point being checked. The method has been tested with raw radial velocities scanned from operational WSR-88D radars under various weather conditions and it can correct aliased velocities without false dealiasing in most cases. However, since the VAD analysis is inherently limited by its uniform-wind assumption, the resultant reference radial velocities are often lack of the desired variability to allow most raw data to pass the stringent threshold conditions especially when the Nyquist velocity \( v_N \) is reduced and thus the threshold ranges are further narrowed. Because of this, the method occasionally fails to correct or flag severely aliased radial velocities around and above strongly sheared inversion layers in severe winter ice storms scanned by operational WSR-88D radars using volume coverage pattern 31 (VCP31) with \( v_N < 12 \text{ m s}^{-1} \). To solve this problem, the alias-robust variational analysis [6] is refined and used in place of the alias-robust VAD analysis for the reference check, whereas the latter is modified by relaxing the VAD uniform-wind assumption and is used to produce a first-guess background radial-velocity field for the alias-robust variational analysis. This upgrades the reference check adaptively for VCP31, and its satisfactory performance is shown by the example in Fig. 1. As shown, the raw velocities in Fig. 1a are severely and even doubly aliased in broad areas to the northeast and southwest of the radar. In Fig. 2a, there are few remaining flagged data as indicated by the blacked data points in the near zero radial-velocity areas (between the light-green and light-red strips) to the northwest and southeast of the radar. These flagged data are mostly recovered (not shown) by the block-to-point continuity check in the second step.

The seed data produced by the reference check in the first step are free of false dealiasing but often have limited coverage unless the raw data cover nearly the entire radial range on each tilt of radar scan (as shown in Fig. 1a for a typical winter ice storm). For spring and summer convective storms, the raw data are often scattered in storm areas, so the seed data produced by the reference check cover only a limited radial range on each tilt. To expand the see data coverage, the block-to-point continuity check in the second step is upgraded from the original one-way procedure (going forward away from the radar) to a double two-way procedure (going forward and backward twice on each tilt). Additional sub-steps are also designed to recheck remaining flagged data around each mesocyclone. The performance of the upgraded continuity check is shown by the example in Fig. 2. If the original block-to-point continuity check is used, then most data around the tornado-generating mesocyclone (marked by the yellow circle in Fig. 2b) will remain flagged (not shown).
Figure 1. (a) Raw velocity image scanned by the KTLX radar with $v_N = 11.51$ m s$^{-1}$ at 1.5$^\circ$ tilt for the ice storm at 043637 UTC on 27 January 2009. (b) Dealiased velocity image by the upgraded reference check.

Figure 2. (a) Raw radial-velocity image scanned by the KTLX radar with $v_N = 26.1$ m s$^{-1}$ at 4.0$^\circ$ tilt for a tornadic storm at 221637 UTC on 24 May 2011. (b) Dealiased radial-velocity image by the upgraded method. The two white letters “A” mark the main aliased-velocity areas in panel (a). The yellow circle with an arrowhead in panel (b) marks a tornado-generating mesocyclone. The KTLX radar site is marked by the blue dot on the bottom of panel (b).

3. VECTOR WIND ANALYSIS

The wind analysis performs the following steps:
I. Produce a vertical profile of VAD vector wind $\mathbf{v} = (u, v)$ from dealiased radial velocities for each radar, and then assimilate the VAD winds into a prior background field at each vertical level (every $50$ m above the radar site) with $\sigma_b \geq \sigma_o$ and $L = 150$ km, where $\sigma_b$ (or $\sigma_o$) denotes the background (or observation) error variance and $L$ the background error de-correlation length. The nearest forecasts from the NCEP operational rapid refresh (RAP) model are interpolated in time and space to generate the background wind field. The analysis in this first step can also use zero background wind.
II. Use the wind field produced in step-I as a new background to assimilate the Oklahoma Mesonet wind data (at $z = 10$ m) with $\sigma_b \geq \sigma_o$ and $L = 60$ km.
III. Use the wind field produced in step-II as a new background to assimilate super-observations generated by combining dealiased radar velocities in three batches with the resolution coarsened to 13, 21 and 30 km (in both the radial and azimuthal directions), respectively, over the near ($r \leq 40$ km), middle ($40$ km $< r \leq 80$ km) and far ($r > 80$ km) radial ranges. The observation error is estimated (between $1$ m s$^{-1} \leq \sigma_o \leq 2$ m s$^{-1}$) for each super-observation based on the number of dealiased radial velocities within the area represented by that super-observation.

In the above multi-step analysis, the 2D statistical
interpolation formulated in [1] is extended to a 3D version to assimilate super-observations from each batch (serially from the far range to the near range) and update the background. After each update, $\alpha_0^2$ is re-estimated for the next update by subtracting the spatially averaged super-observation variance $\alpha_0^2$ from the spatially averaged variance of super-observation minus background. The 3D background error auto-correlation function between the radial winds $v_{11}$ at $(x_1, z_1)$ and $v_{21}$ at $(x_2, z_2)$ and the cross-correlation function between the radial wind $v_{11}$ at $(x_1, z_1)$ and tangential wind $v_{22}$ at $(x_2, z_2)$ are formulated by modifying (2.5a, b) of [1] into

$$C(v_{11}, v_{21}) = \cos\Delta\beta \exp[-(\Delta x^2/L^2 + \Delta z^2/D^2 + |\Delta v|^2/V^2)/2],$$

$$C(v_{11}, v_{22}) = \sin\Delta\beta \exp[-(\Delta x^2/L^2 + \Delta z^2/D^2 + |\Delta v|^2/V^2)/2],$$

where $\Delta\beta = \beta_2 - \beta_1$, $\beta_1$ (or $\beta_2$) is the azimuthal angle of point $x_1$ (or $x_2$) viewed from the concerned radar, $\Delta x = x_2 - x_1$ is the horizontal separation between the two points, $D$ is the de-correlation depth, $\Delta\beta = v(z_2) - v(z_1)$ is the increment of the VAD wind $v = (u, v)$ over $\Delta z$, and $V$ scales the de-correlation enhanced by $|\Delta v|$. The background error de-correlation length $L$ (or depth $D$) is set to 25 (or 2), 18 (or 1) and 11 (or 0.3) km for the three serial updates, respectively. As a new shear-dependent term, $|\Delta v|^2/V^2$ is introduced (with $V = 1$ m s$^{-1}$) in the above correlation functions to reduce the vertical correlation adaptively across a strong vertical-shear layer. This term improves the wind analysis especially when the flow field contains a strong vertical-shear layer, as often observed in winter ice storms. Note that the sharp wind direction reverse around $r \approx 26$ km on 1.5° tilt in Fig. 1b reveals a strong vertical shear around $z \approx 0.8$ km. This sharp wind reverse is well captured by the analyzed wind fields at $z = 0.75$ and 1 km in Fig. 3, although the analysis is produced by using only radial-velocity observations from the KTLX radar with zero background wind in the first step.

For the tornadic storm in Fig. 2, the step-I analysis uses a nonzero background wind field (see Fig. 4a) obtained from the operational RAP forecast, while the analyzed wind field (see Fig. 4b) is produced by using radial velocities scanned from five operational WSR-88D radars plus Oklahoma Mesonet wind data. In comparison with the background winds in Fig. 4a, the analyzed winds in Fig. 4b are adjusted moderately toward radar observed radial winds mainly and only in areas covered by radar radial-velocity observations. As shown in Fig. 4b, the analyzed winds are deflected and curved around the tornado-generating mesocyclone (marked by the small yellow circle) but still too smooth to resolve the mesocyclone. Thus, an additional step of analysis needs to be performed in a nested domain (with $\Delta x \leq 1$ km and $L \leq 3$ km) to retrieve the mesocyclone from the original dealiased radial velocities without combining into super-observations. If radial-velocity observations are available from only single radar for a mesocyclone, then the simple adjoint method [7, 8] needs to be modified and used to perform this additional step of analysis. The related technique and results will be presented at the conference.

![Fig. 3. Analyzed winds fields (plotted by arrows every 4 grid points in each direction) (a) at $z = 0.75$ km superimposed on the dealiased radial-velocity image at 0.5° tilt and (b) at $z = 1.0$ km superimposed on the dealiased radial-velocity image at 1.5° tilt for the same winter ice storm scanned by the KTLX radar as in Fig. 1. The two panels use the same colour scale and vector scale, the colour scale is plotted on the top of panel (a), and the vector scale is plotted at the lower-left corner of panel (a). The analysis domain is centred at the KTLX radar. The domain size is $160 \times 160 \times 5$ km$^3$. The horizontal resolution is $\Delta x = \Delta y = 2$ km and the vertical resolution is $\Delta z = 50$ m.](image)
Figure 4. (a) Background wind field at $z = 0.75$ km from the operational RAP forecast superimposed on the combined reflectivity image from five radars for the same storm system at the same time as shown in Fig. 2. (b) Analyzed wind field at $z = 0.75$ km superimposed on the dealiased radial-velocity images at 4.0° tilt from KVNX and KTLX, 0.9° tilt from KFDR, and 0.5° tilt from KINX and KSRX radars. The image from KLXX is on the top of that from KVNX and each radar site is marked by a blue dot with the radar name in panel (b). The small yellow circle in panel (b) marks the same tornado-generating mesocyclone as marked in Fig. 2b. The analysis domain is centred at the KTLX radar. The domain size is 800x800x5 km$^3$. The horizontal resolution is $\Delta x = \Delta y = 5$ km and the vertical resolution is $\Delta z = 250$ m.

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5. REFERENCES


