P13A.7 Multi-pass objective analyses of radar data: Preliminary results

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1. Introduction

Radar data commonly are interpolated to a Cartesian grid via an objective analysis in order facilitate operations such as three-dimensional isosurface viewing, dual-Doppler wind synthesis, or simply two-dimensional contouring by a canned algorithm. Objective analysis typically is much more than just simple interpolation, rather, judiciously chosen tuning parameters (which typically are based on the data spacing, Δ) allow one to filter scales that are poorly resolved. Furthermore, it has been shown that multiple passes ("successive corrections") of an objective analysis "steepen" the response of the filter, i.e., such techniques are less damping at well-resolved scales (e.g., 8–20Δ) while still removing scales that are poorly resolved (e.g., $< 4\Delta$). Thus, a multi-pass objective analysis can provide a better fit to the observations than a single-pass objective analysis, yet still suppress small-scale noise.

The purpose of this paper is to present comparisons between single-pass and multi-pass Barnes objective analyses of synthetic radial velocity data obtained from a three-dimensional thunderstorm simulation. The objectively analyzed radial velocity data are used to produce dual-Doppler wind syntheses, and comparisons are made between the kinematic fields of the model output (which will be regarded as the "truth") and those derived from dual-Doppler wind syntheses utilizing single- and multi-pass objectively analyzed synthetic radial velocity data. The improvement of multi-pass objective analyses on higher-order calculations such as buoyancy retrievals and trajectory calculations is also assessed.

2. Data and methodology

The numerical simulation is performed using version 4.5.2 of the Advanced Regional Prediction System (ARPS; Xue et al. 2000, 2001), and is initialized with the composited sounding from the well-documented 20 May 1977 Del City, Oklahoma, supercell thunderstorm (Ray et al. 1981; Johnson et al. 1987). The simulation domain is 64×64×18 km. Both vertical and horizontal resolution are 250 m (Fig 1). Synthetic radar data were generated at (x,y)=(20 km, 14 km) and (x,y)=(20 km, 24 km), respectively (the southwest corner of the domain is the origin), "scanning" in 180° sectors centered at 270°. The radars are positioned in a way similar to that which would be utilized in an actual deployment within a field experiment, i.e., the low-level mesocyclone is near the center of the dual-Doppler lobe (Fig. 1). The azimuthal and range resolution of the synthetic radars is 1° and 100 m, respectively. Radial velocities are calculated at 15 different elevation angles between 0.5° and 22.5°. No attempt was made to emulate power-weighted volumetric radar sampling to center the synthetic radar observations. Random errors are then added to radial velocity field to simulate the errors that can be found in Doppler radars used for meteorological applications (Rabin and Zrnic 1980).

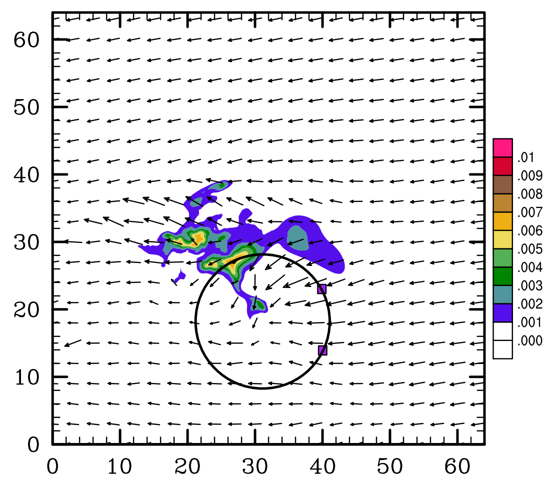

FIG. 1. ARPS model horizontal wind vectors and rainwater concentration plotted at $z = 250$ m. Purple squares denote radar locations and the solid black circle denotes dual-Doppler lobe. Units of rainwater concentration are kg/kg.

The multi-pass analyses are made following procedure described in Barnes (1964). In all three experiments, radial velocities from "Radar 1" (R1) and "Radar 2" (R2) were interpolated

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to a grid using a one-pass, two-pass, three-pass, and four-pass Barnes analyses. The grid dimensions are 20×20×3 km, with a horizontal and vertical grid spacing of 250 m, respectively.

In the first experiment, we use an isotropic, spherical Barnes weight function and smoothing parameter, κ, of 0.34 km^2. This smoothing parameter was chosen following recommendations (Pauley and Wu 1989; Trapp and Doswell 2000) that the optimal smoothing parameter should be $\kappa = (1.33\Delta)^2$, where Δ here equals the coarsest data separation in the analysis domain. In multi-pass analyses, in each subsequent pass after the first one, κ is scaled by a correction parameter γ. In the experiments we used following values for γ: 0.1, 0.3, 0.5, 0.7 and 0.9.

The extrapolation of data to grid points was not permitted. The three-dimensional winds were retrieved by integrating the anelastic mass continuity equation upward from the ground, where vertical velocity was assumed to be zero. Because extrapolation was forbidden in the objective analysis stage, wind data were not retrieved at the lowest grid level ($z = 0$ m). After the retrieval of three-dimensional winds, buoyancy and perturbation pressure were retrieved using technique described in Hane and Ray (1985).

To investigate how close the analyzed horizontal wind components, vertical wind velocity, vertical vorticity, and divergence are to the simulation results (the "truth"), the lowest 1 km of analyses are compared to the numerical simulation results and two statistics were computed, root mean square errors (RMSE) and correlation coefficient. The same is done for buoyancy and perturbation pressure, but they are compared on a single level of $z = 750$ m. Buoyancy and perturbation pressure are compared on a single level, because a constant is added to the retrieved buoyancy and perturbation pressure field so that the mean buoyancy and pressure of the given analysis is equal to buoyancy and pressure of ARPS output, respectively. Since the constant added is different at different levels, RMSE and correlation coefficient have to be computed separately at each height level.

Also, trajectory calculations are performed on both ARPS output and different analyses. Trajectories are initialized at $z = 600$ m on a 10×10 km domain located in the center of dual-Doppler analyses. Initial positions are 1 km apart in both x and y directions, respectively, giving a total of 121 trajectories. The timestep in trajectory calculations is 20 seconds, and the integration method is the 4th order Runge-Kutta. At each timestep the average distance between trajectories in ARPS output and dual-Doppler analyses is computed only for the trajectories that stayed in the domain through all 15 minutes of integration.

3. Results

The comparison of RMSE and correlation coefficients of all different analyses performed (not shown) revealed that the best improvement over 1-pass analysis can be achieved by using a 2-pass analysis with either $\gamma = 0.1$ or $\gamma = 0.3$. Almost similar results can sometimes be obtained by using other analyses approaches but at much high computational expense (e.g. 4-pass analysis with $\gamma = 0.9$). In this section we are presenting

Variable	1-pass	2-pass, $\gamma = 0.1$	2-pass, $\gamma = 0.3$
u wind	1.34	0.75	0.85
v wind	2.15	1.44	1.41
w wind	1.13	1.12	0.99
vorticity	2.85	1.87	2.02
divergence	2.44	1.86	1.92
p'	0.54	0.53	0.64

Table 1. Root mean square errors for different variables in the lowest 1 km of analysis domain. Smoothing parameter in all three analyses is $\kappa = 0.34$. Units of u, v, w are 1 m s^{-1}). Units of vorticity and divergence are 0.001 s^{-1}. Perturbation pressure errors are computed at $z = 500$ m. Units of perturbation pressure are mb.

Variable	1-pass	2-pass, $\gamma = 0.1$	2-pass, $\gamma = 0.3$
u wind	0.97	0.99	0.99
v wind	0.96	0.99	0.99
w wind	0.86	0.86	0.89
vorticity	0.78	0.91	0.89
divergence	0.72	0.85	0.83
p'	0.75	0.95	0.92

Table 2. Correlation coefficitent for different variables between ARPS output and analyses in the lowest 1 km of analysis domain. Smoothing parameter in all three analyses is $\kappa = 0.34$. Perturbation pressure correlation coefficients are computed at $z = 500$ m.

Time (min)	1-pass	2-pass, $\gamma = 0.1$	2-pass, $\gamma = 0.3$
1	0.14	0.10	0.12
2	0.28	0.19	0.23
3	0.45	0.31	0.36
4	0.64	0.46	0.49
5	0.85	0.62	0.61
10	2.42	1.91	1.51
15	4.34	3.39	2.67

Table 3. Average distance between trajectories computed in ARPS output and the trajectories in three different analyses. Smoothing parameter in all three analyses is $\kappa = 0.34$. Trajectories are initialized at $z = 600$ m.

only the results of 1-pass, 2-pass with $\gamma = 0.1$, and 2-pass with $\gamma = 0.3$ analyses.

In Table 1 we present the RMSE of the horizontal and vertical wind components, and the vorticity and divergence in the lowest 1 km of the wind syntheses performed with the recommended smoothing parameter of $\kappa = 0.34$. Comparison of 1-pass and 2-pass RMSE show that 2-pass analyses can reduce the RMSE of horizontal wind components up to 30% compared to the RMSE of 1-pass analysis. Reduction of RMSE of the vertical wind component is around 13%, whereas reduction of the RMSE of vorticity and divergence are up to 34%.

Correlation coefficients are presented in Table 2. Results show that in the lowest 1 km of analysis domainthe biggest improvement over 1-pass analysis in achieved in improving the correlation coefficients between the ARPS output and analyses for vertical vorticity and divergence.

The results of trajectory calculations are given in Table 3. The results show that average distance between trajectories in ARPS model output and trajectories in the analyses is smaller for 2-pass analyses at all times. The use of 2-pass analyses can reduce the error by almost 40%.

Figure 2 presents thr zonal wind component at $z = 500$ m in the ARPS output and three different analyses: the 1-pass analysis, the 2-pass analysis with $\gamma = 0.1$ and the 2-pass analysis with $\gamma = 0.3$. All three analysis are very close to the ARPS output. The two 2-pass analyses show more detail and smaller scale features, especially the 2-pass analysis with $\gamma = 0.1$ (Fig. 2c).

Figure 3 presents the vertical wind component at $z = 1$ km in the ARPS output and three different analyses: the 1-pass analysis, the 2-pass analysis with $\gamma = 0.1$, and the 2-pass analysis with $\gamma = 0.3$. Both 2-pass analyses show more detail and look closer to the ARPS output than the 1-pass analysis, although 2-pass analysis with $\gamma = 0.1$ is noisier than the 2-pass analysis with $\gamma = 0.3$. The 2-pass analyses are especially good in depicting the fine details of the narrow downdraft line behind the main updraft altough the maximum in the downdraft is displaced a little.

Figure 4 presents the vertical vorticity component at $z = 500$ m in the ARPS output and three different analyses: the 1-pass analysis, the 2-pass analysis with $\gamma = 0.1$, and the 2-pass analysis with $\gamma = 0.3$. Both 2-pass analyses show much improvement over the 1-pass analysis. Improvement is especially visible in the depiction of locations and the amplitudes of vorticity minima and maxima. The 2-pass analyses are slightly noisier than the 1-pass analysis but benefits seem to outweigh the drawbacks of introduced noise. The same comparison done for divergence shows similar results (not shown).

Figure 5 presents the perturbation pressure at $z = 500$ m in the ARPS output and three different analyses: the 1-pass analysis, the 2-pass analysis with $\gamma = 0.1$, and the 2-pass analysis with $\gamma = 0.3$. Both 2-pass analyses show improvement over the 1-pass analysis in depicting the location, amplitude and size of the perturbation pressure minimum. All three analysis seem to have to high values of perturbation pressure in the western part of the domain. That in turn increases the analyzed gradient of perturbation pressure southwest of the location of perturbation pressure minimum.

Figure 6 presents the perturbation density potential temperature at $z = 500$ m in the ARPS output and three different analyses: the 1-pass analysis, the 2-pass analysis with $\gamma = 0.1$, and the 2-pass analysis with $\gamma = 0.3$. The analyzed buoyancy in all three analyses is not as close to the buoyancy from the ARPS model output as was the case for other variables discussed in this section. The 2-pass analyses seem to depict the pattern better, but also seem to increase the RMSE by increasing the amplitude of the minima and maxima.

4. Summary and conclusions

The results shown in the previous section suggest that in many cases the 2-pass Barnes filter objective analyses have smaller root mean square errors and are better correlated to the ARPS model output than the 1-pass Barnes filter analysis. The improvements are more substantial in objective analysis of the first order derivatives of wind field, such as vertical vorticity and divergence. Even better improvement can be seen in trajectory calculations with 2-pass analyses, which benefits from more the accurate horizontal and vertical wind fields.

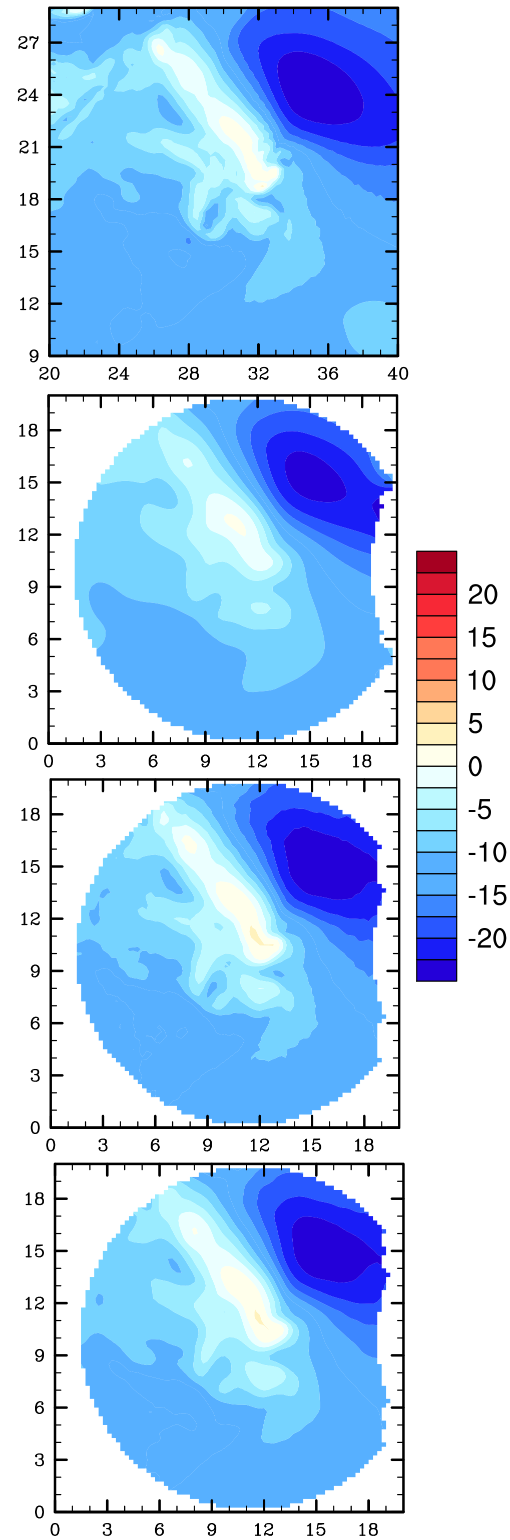

FIG. 2. Zonal wind component at $z = 500$ m. Units are m s^{-1}. (a) ARPS (b) 1-pass analysis (c) 2-pass analysis $\gamma = 0.1$ (d) 2-pass analysis $\gamma = 0.3$

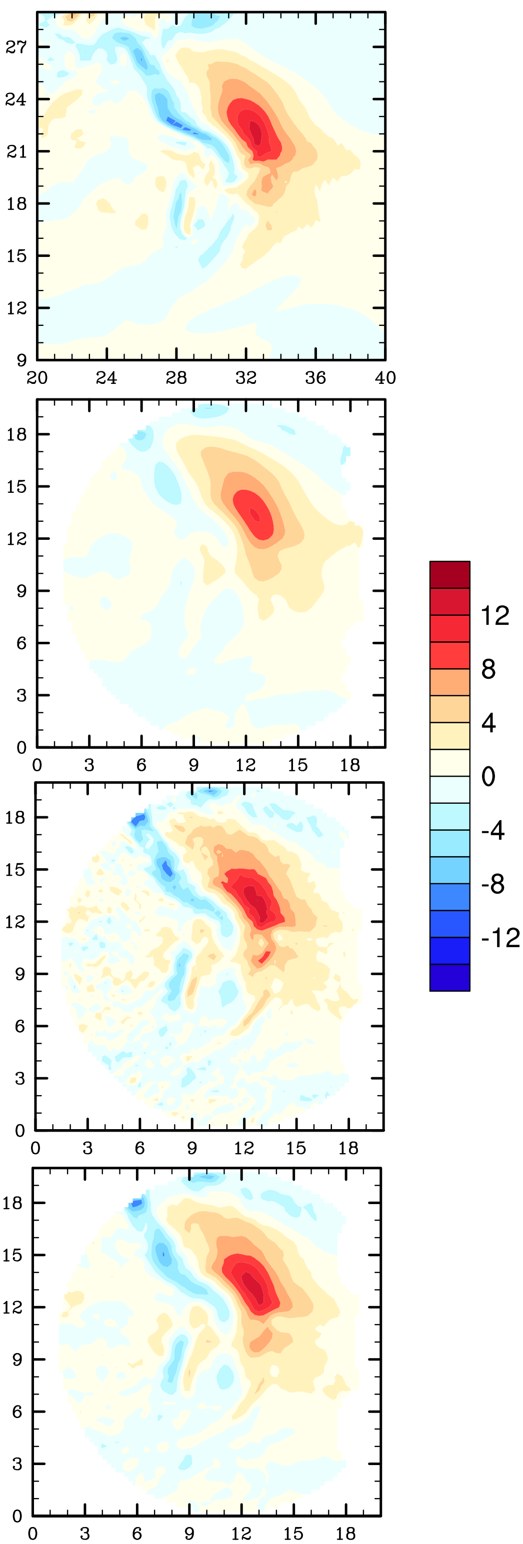

FIG. 3. Vertical wind component at $z = 1$ km. Units are m s^{-1}. (a) ARPS (b) 1-pass analysis (c) 2-pass analysis $\gamma = 0.1$ (d) 2-pass analysis $\gamma = 0.3$

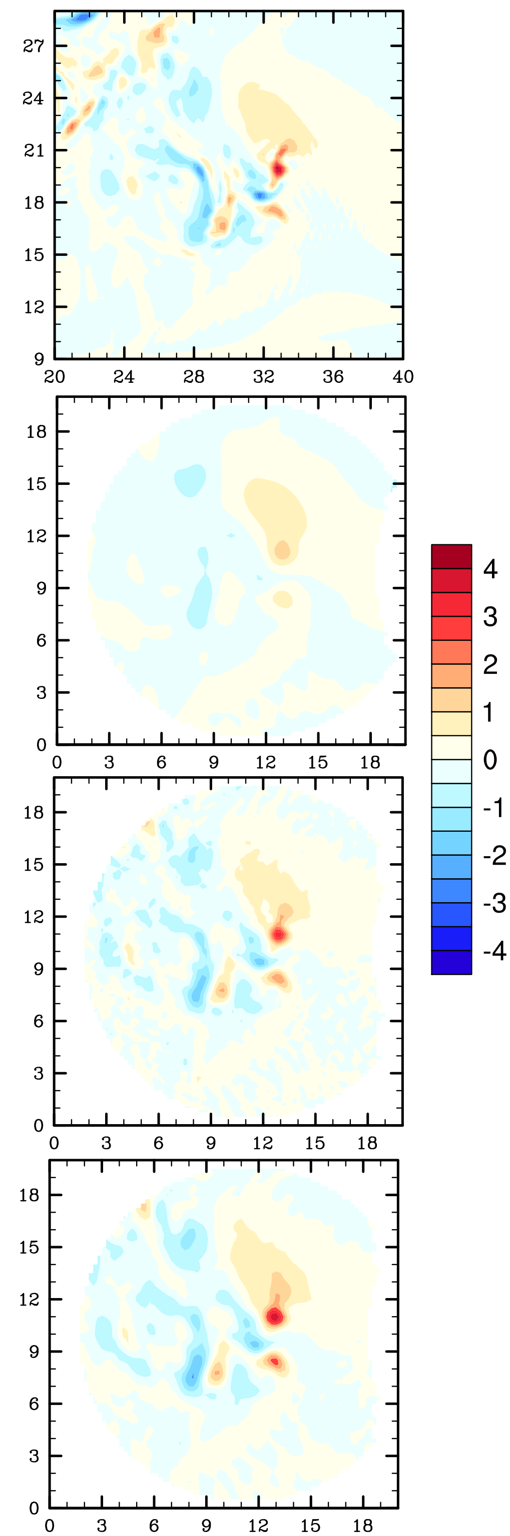

FIG. 4. Vertical vorticity at $z = 500$ m. Units are $10^{-2}s^{-1}$ (a) ARPS (b) 1-pass analysis (c) 2-pass analysis $\gamma = 0.1$ (d) 2-pass analysis $\gamma = 0.3$

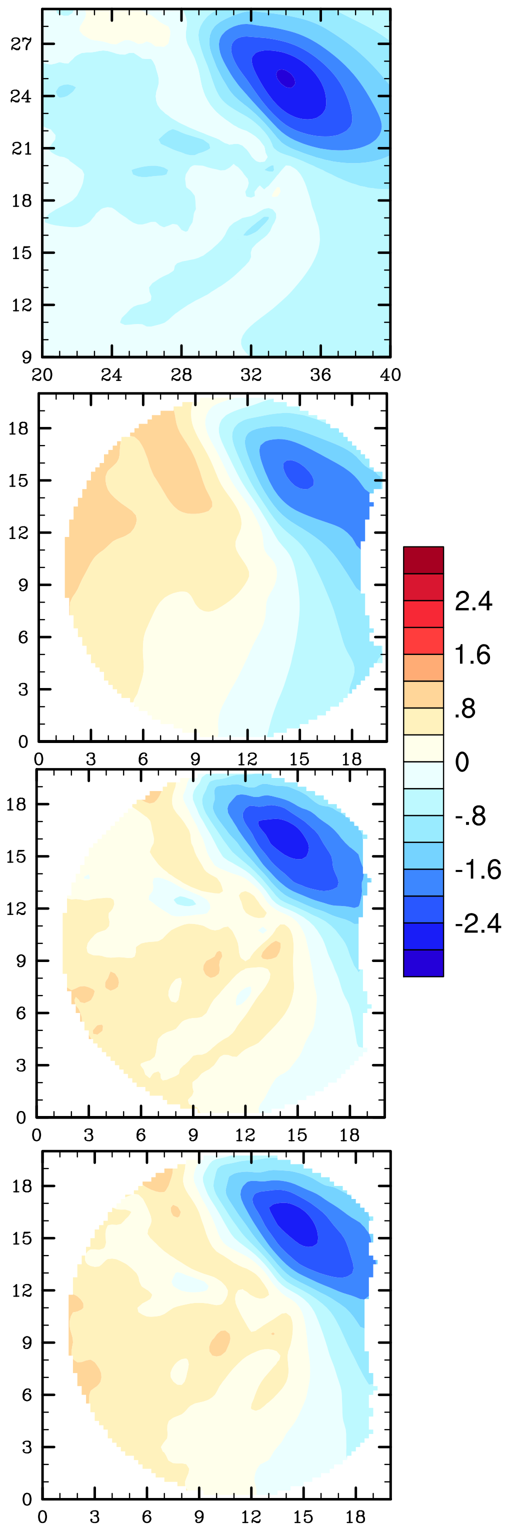

FIG. 5. Perturbation pressure at $z = 500$ m. Units are mb. (a) ARPS (b) 1-pass analysis (c) 2-pass analysis $\gamma = 0.1$ (d) 2-pass analysis $\gamma = 0.3$

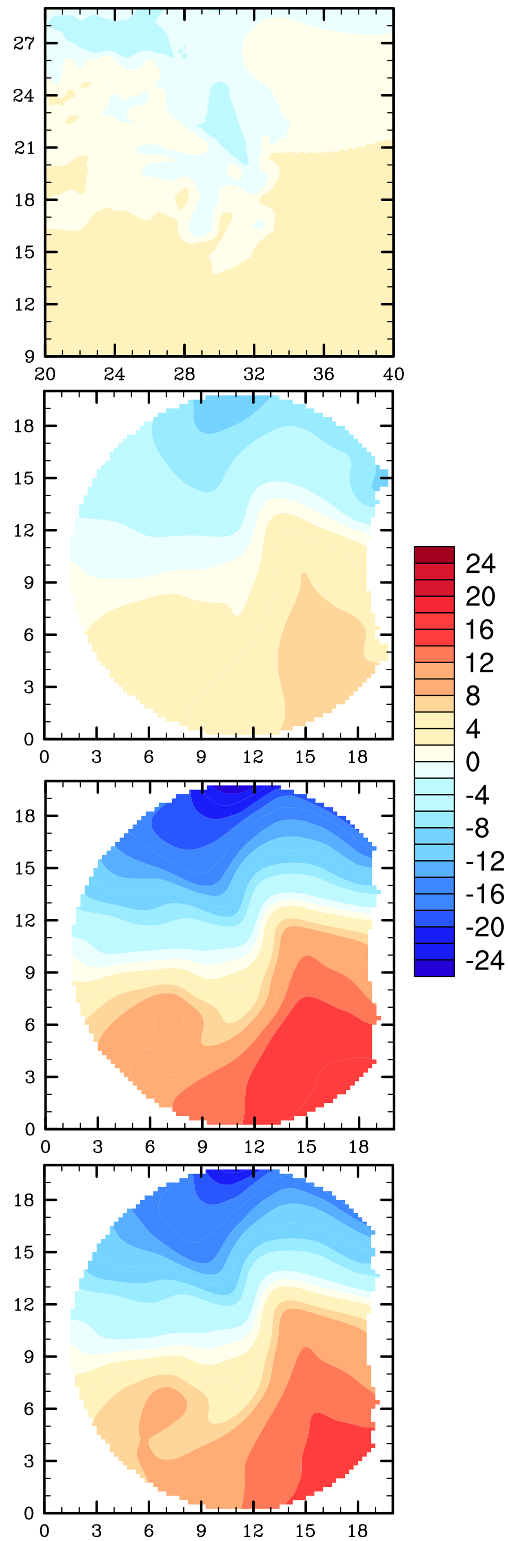

FIG. 6. Perturbation density temperature at $z = 500$ m. Units are °C. (a) ARPS (b) 1-pass analysis (c) 2-pass analysis $\gamma = 0.1$ (d) 2-pass analysis $\gamma = 0.3$

Correct representation of vertical vorticity and divergence is especially important in analyzing thunderstorms. Together with better representation vertical wind component, these improved analyses can be used to produce more accurate vorticity budgets along the parcel trajectories in thunderstorms.

In our experience, the computational cost of 2-pass analysis is about 2–3 times the cost of running 1-pass analysis. If the extra computational cost can be afforded, the 2-pass Barnes filter analysis is recommended in order to produce more accurate analyses of horizontal and vertical wind fields, vertical vorticity, divergence and perturbation pressure.

The only variable where 2-pass analyses produce mixed results is the buoyancy retrieval where the use of the 2-pass Barnes filter improves the correlation between the analysis and the model output but unfortunately also increases the root mean square error. The identification of the sources of error in the buoyancy retrieval is part of our future work.

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