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THE USE OF AN EVAPORATION SCHEME IN A BOUNDARY-LAYER MODEL FOR REAL-TIME 4D-VAR RADAR DATA ASSIMILATION AND FORECASTING OF CONVERGENCE LINES

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1. INTRODUCTION

Over the past decade, radar data assimilation has been developed at the research level. A lot of progress has been made and prototype systems are now implemented in operational environments to test their robustness in real-time applications (Sun and Crook, 2001; Crook and Sun, 2002). A dry boundary layer model has been used in the first operational experiments (Sun and Crook, 2001).

In the presence of convective precipitation, the dry boundary layer model becomes deficient because it cannot represent moist processes. In complex situations, intense convective cells generate gust fronts that propagate, interact and produce new convective elements. These gust fronts and convergence lines are driven primarily by the buoyancy field in the boundary layer. On the other hand, the most important moist process occurring in the boundary layer during these phenomena is the evaporation of rain in subsaturated air. As a first step towards the use of a deep convection model with full microphysics, a parameterization of the evaporative cooling due to precipitation is added to the dry boundary layer model in this work to improve the temperature field.

2. THE ASSIMILATION METHOD

In this section, the evaporation parameterization scheme is presented to show how it is implemented in the dry boundary layer model and the variational problem is formulated.

2.1 *The evaporation scheme*

The dry boundary layer model of Sun et al. (1991) is used for the assimilation in the present study. The model is constructed under the anelastic approximation. The governing equation for the potential temperature θ is

$$\frac{\partial \theta}{\partial t} = -\left(\vec{V}\cdot\nabla\right)\theta + \kappa\nabla^2\theta + \frac{L_v}{\overline{\rho} c_p} R_e, \qquad (1)$$

where $\overline{\rho}$ is the reference density profile, θ is the potential temperature perturbation, κ is the thermal diffusivity, L_v = 2.5 $\times$ 10^6 J kg^{-1} is the latent heat of vaporization, and c_p = 1004 J deg^{-1} kg^{-1} is the specific heat at constant pressure. The evaporation of rain R_e used to calculate the latent heat released in the thermodynamic equation (1) is parameterized as in Sun and Crook (1997):

$$R_e = \beta(q_v - q_{vs})(\overline{\rho} q_r)^{0.65}, \qquad (2)$$

where β = 0.0486s^{-1}, q_v is the vapor mixing ratio, and q_r is the rain-water content. The saturation mixing ratio q_{vs} is calculated from the potential temperature of the model.

The rain-water content q_r is not a prognostic variable of the model but it is required for the calculation of the evaporation. When the model is used for the assimilation, q_r is directly estimated from the radar reflectivity and time interpolated onto the model time levels. During a free forecast, q_r is simply advected with the 4-km horizontal mean wind. The vapor mixing ratio q_v also does not have a prognostic equation in the model. As a first guess, it is estimated using a vertical sounding. The 3D field q_v is then retrieved during the assimilation and is kept constant during a free forecast.

2.2 *The assimilation problem*

The assimilation is based on the 4D-Var formalism. It uses the model as a strong constraint to assimilate radar data in the boundary layer. The analysis is obtained by minimizing a cost function which measures the difference between the model solution and all the sources of available information. For the present problem, the cost function is written as

$$J = \sum_{\sigma,\tau,i} \eta_v \left(V_{r,i} - V_{r,i}^{\text{ob}}\right)^2 + \sum_{\sigma} \eta_b \left(x - x_b\right) + J_p, \quad (3)$$

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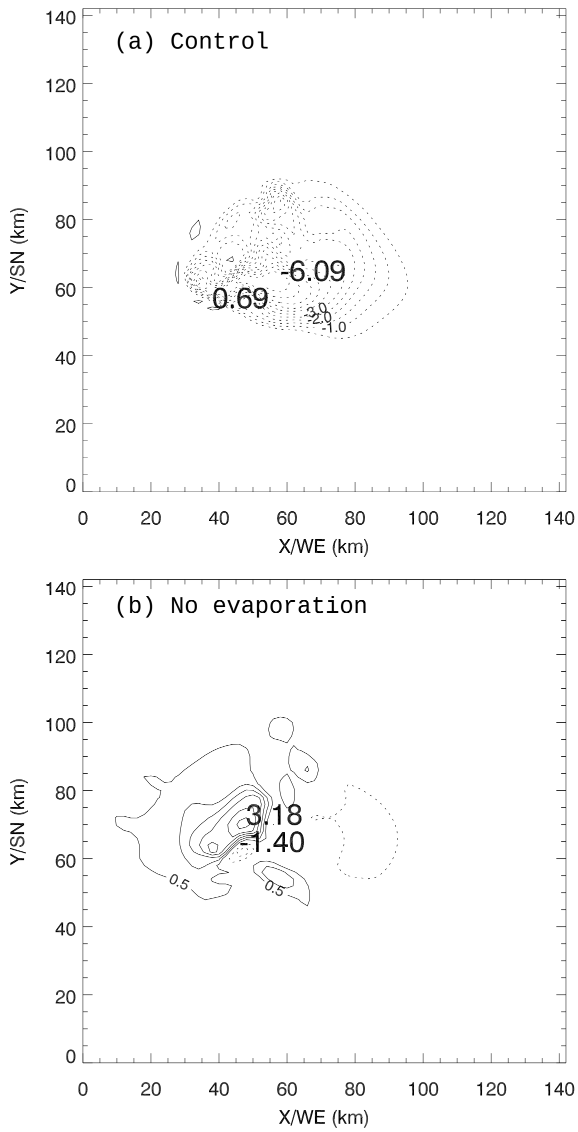

Figure 1. Temperature perturbations at 250 m at 80 minutes. (a) control simulation, (b) analysis without the evaporative cooling. The contour interval is 0.5 K, dotted lines indicating negative values and full lines positive values.

where σ represents the spatial domain and τ the assimilation window. The quantity $V_{r,i}^{\mathrm{ob}}$ is the observed radial velocity from the ith radar, and $V_{r,i}$ is its model representation. The weight η_v is the inverse of the observational-error variance of the radial velocities. The control variables x are the state variables of the model at the beginning of the assimilation window and include q_v. The background x_b is a mesoscale analysis made of surface observations, VAD wind profiles from the surrounding radars, and temperature and humidity profiles from a mesoscale model. The term J_p

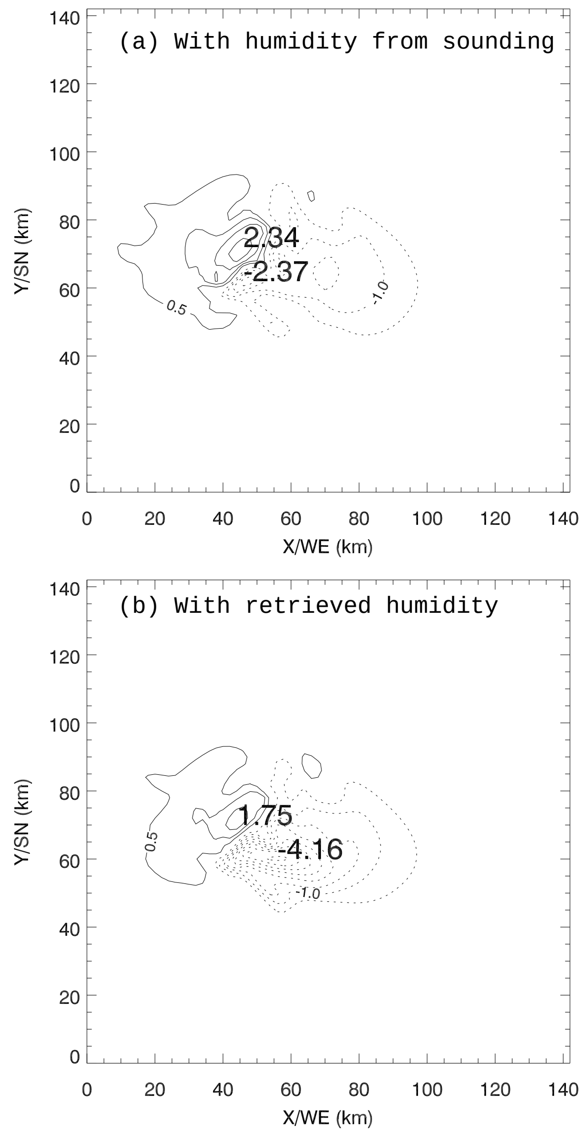

Figure 2. Analysis of temperature perturbations at 250 m at 80 minutes with the evaporation parameterization. (a) The humidity field is fixed and corresponds to the sounding in the environment. (b) The humidity field is adjusted during the minimization of the cost function.

in the cost function is the spatial and temporal smoothing constraints used to remove noise and to obtain better convergence properties during the minimization of the cost function.

3. ASSIMILATION OF SIMULATED DATA

To measure the impact of the evaporative cooling during the assimilation, the method is first tested by using simulated data from the cloud-model of Sun and Crook (1997). The

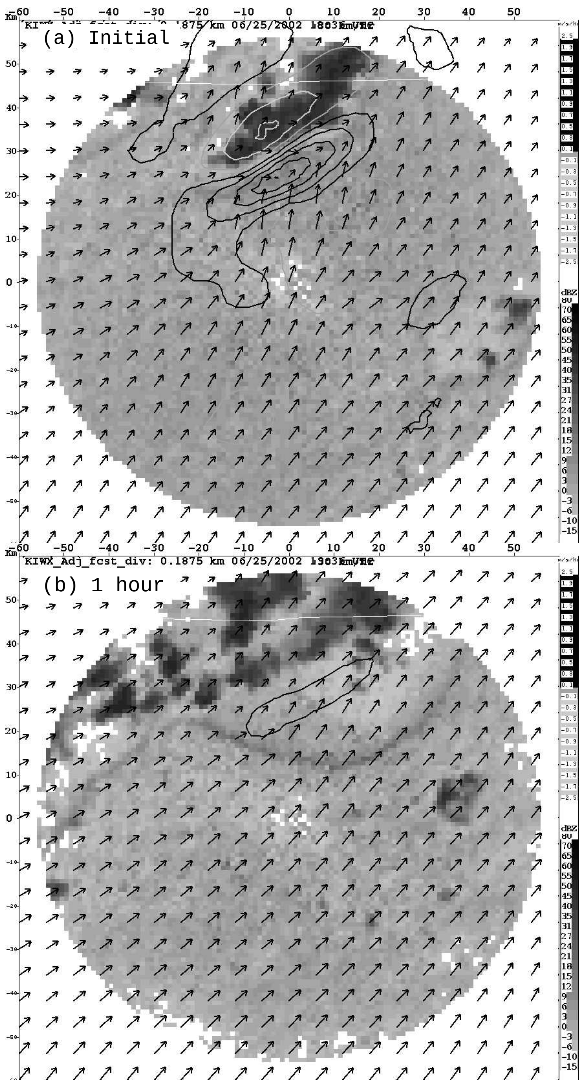

Figure 3. Convergence analysis and forecast initialized at 1836 UTC, June 25 2002, for the case without evaporative cooling. (a) Initial conditions (analysis), (b) 1 hour forecast. The vectors and line contours depict the horizontal wind and convergence at 200 m AGL, respectively, while the radar reflectivity is shown in gray scale at 500 m AGL. Contour interval for convergence is 2.0×10^{-4} s^{-1}. Black contours are convergence and light gray contours are divergence.

cloud-model is initialized with the 00 UTC 29 June 2000 sounding from the STEPS experiment, where a warm bubble is superimposed to generate a supercell storm. The model equations are integrated with a time step of 5 s. The model domain is 140x140x15 km^3, with 2 km resolution in the horizontal and 500 m in the vertical.

The boundary layer model with the parameterization of evaporation is then used to assimilate the simulated radial velocities as seen by a radar located in the south-west corner of the domain. The radial velocity simulated observations between 70 and 80 minutes, when the storm structure is well established, are assimilated. The domain of the boundary layer model for the assimilation is 140x140x5 km^3, with the same resolution as the model that produce the control simulation. It has thus only 10 vertical levels. The time step is 20 s, four times larger than in the control simulation.

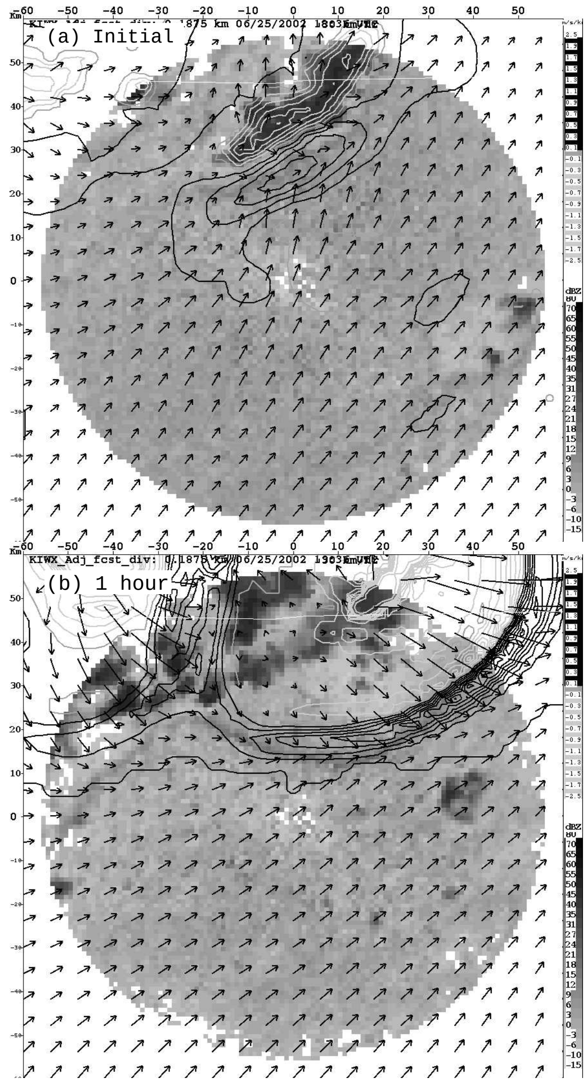

Figure 4. Same as figure 3 except for the case where the evaporation scheme is applied during the assimilation and forecast.

3.1 *Temperature analyses*

The temperature deviation from the sounding in the control simulation at the lowest model level is depicted in Fig. 1(a). The cold pool under the precipitation core shows a maximum of 6 degrees cooler than the environment.

The temperature deviation from the sounding analyzed with the model without evaporative cooling is plotted in Fig. 1(b). As can be seen, the cold pool is essentially not present with only a very small region with a maximum of only 1.4 degree colder than the environment. The region of positive buoyancy of over 3 degrees is too large and too intense. The main reason why the temperature perturbations are not correctly retrieved without the evaporative cooling is because the method rely essentially on the radar observations of the temporal evolution of the wind field.

In the second experiment, the evaporative cooling is applied while the humidity field corresponds to the sounding and is kept constant. As shown in Fig. 2(a), the maximum temperature deviation from the sounding in the cold pool is 2.4 degrees, 1 degrees colder than for the experiment without the evaporative cooling. Furthermore, the positive temperature deviation is reduced to 2.3 degrees. Overall, the temperature field is in better agreement with the control simulation when the evaporative cooling is used during the assimilation.

The third experiment, where the humidity field is adjusted during the assimilation, results in a cold pool with a 4.2 degrees maximum deviation from the environment, as seen in Fig. 2(b). The positive perturbation is now only 1.7 degrees. Thus, both the evaporative cooling and the humidity retrieval are beneficial for the temperature analysis. The colder temperature analyzed is explained by the drier air analyzed at the surface in the precipitation area, which is consistent with the control simulation (not shown).

4. ASSIMILATION OF REAL DATA AND FORECASTING

The impact of evaporative cooling is now tested with real data, under real-time operational constraints. The convergence-line case of June 25, 2002 from the KIWX radar, Fort-Wayne, Indiana, is presented.

The domain of the boundary layer model is 150x150x3.5 km^3, with 3 km resolution in the horizontal and 375 m in the vertical. The time step is 25 s. The number of iterations for the minimization of the cost function is limited to 35. This configuration of the assimilation system allows for real-time analysis.

On June 25, 2002, at 18:36 UTC, the precipitation area located 40 km north of the radar has already emitted a convergence line propagating south-eastward. The convergence line can be seen by the arc of reflectivity with maxima around 20 dBZ just south of the precipitation area in Fig. 3(a).

Figure 3 shows the forecast initialized at 18:36 UTC for the case where the evaporative cooling is not applied during the assimilation, whereas Fig. 4 is for the case where the evaporative cooling is applied during the assimilation. Both analyses (Fig. 3(a) and Fig. 4(a)) correctly located the convergence zone because it is essentially obtained from the radial velocity field observation. A divergence pattern is analyzed at the surface under the precipitation core, consistent with the negative buoyancy and the accompanying subsidence, but the divergence is much more intense in the analysis with the evaporative cooling. The 1-hour forecast without the evaporative cooling is unable to correctly propagate the convergence line (figure 3 (b)). On the other hand, the 1-hour forecast with the evaporative cooling shows a convergence line very close to the one indicated by the observed reflectivity field (figure 4 (b)).

5. SUMMARY

When the evaporative cooling is applied during the assimilation, colder pools of air and stronger divergence appear at the surface under the precipitation core, in better agreement with the surface observations and our knowledge of the phenomenon. The evaporative cooling seems to be critical for the forecast of the cold pool spreading and the associated leading convergence line. Indeed, a crude estimation of the precipitation and humidity fields is sufficient to greatly improve the convergence line forecast.

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