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IMPACTS OF PERTURBED SOIL MOISTURE CONDITIONS ON SHORT RANGE ENSEMBLE VARIABILITY

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1. INTRODUCTION

A chronic problem with ensemble forecasts is their lack of variability between members. The lack of variability is typically worse near the surface rather than higher in the troposphere (Hamill and Colucci 1997). As a means of ameliorating this problem, we propose perturbing the land surface condition. As shown in McCumber and Pielke (1981) the soil moisture is the soil parameter of primary importance in determining the partition of energy between surface heat fluxes, and in turn affecting surface temperature forecasts. Additionally, Lanicci et al. (1987) explored how the soil moisture distribution is important in the development and evolution of Southern Great Plains severe storms. Accordingly, this paper will document one method attempted thus far: perturbing the 0-10 cm soil layer volumetric soil moisture fraction. We tested this soil moisture perturbation method for a case day in May 2003 when there was a large outbreak of tornados in the Midwestern United States (see Fig. 1). In section 2 the model set-up and synoptic situation will be discussed. Section 3 describes the soil moisture perturbation method, while Section 4 discusses the results.

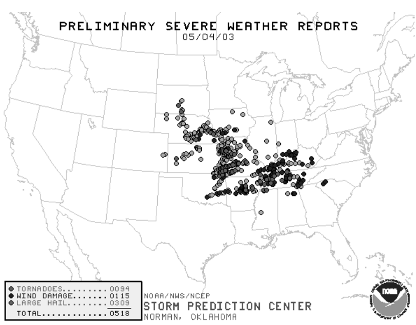

Figure 1. Preliminary severe weather reports, from NOAA SPC.

2. MODEL AND SYNOPTIC DISCUSSION

For this study, the NCAR/PSU MM5V3 modeling system was used, in conjunction with the NOAH land surface model. There were two domains, shown in Fig. 2: a larger domain encompassing the CONUS at 60 km grid spacing, and a smaller inner domain of the Midwest with 20 km grid spacing. All model output described in this paper is from the higher-resolution inner domain. The initial condition was 0900 UTC on 4 May 2003 and the simulation ended at 2100 UTC on 6 May 2003, with output every three hours. The MRF planetary boundary layer scheme was used, along with a simple ice explicit moisture scheme. The time window of primary interest was from 2100 UTC 4 May until 0300 UTC 5 May 2003. This time corresponded to the outbreak of a large number of tornadoes.

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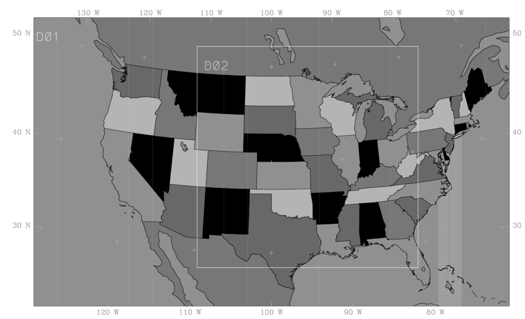

Figure 2. Domain 1: 60 km grid spacing, inner domain 20 km grid spacing.

	1	2	3
Atmos. Pert.	Bred	None	Bred
Soil Pert.	None	Yes	Yes
Convect. Pert.	Grell	Grell	Grell

	4	5	6
Atmos. Pert.	Bred	None	Bred
Soil Pert.	None	Yes	Yes
Convect. Pert.	Kain-Fritsch	Kain-Fritsch	Kain-Fritsch

Table 1. Matrix of perturbations and convective schemes for six experiments.

As shown in Table 1, there were six sets of ensemble runs, and 5 member forecasts in each set. Three sets used the Grell cumulus convection scheme, and three used the Kain-Fritsch II (KF2) cumulus convection. For each convective parameterization, there was an ensemble with a perturbed atmospheric condition, an ensemble with a perturbed top-layer soil moisture condition, and an ensemble with both perturbed atmosphere and perturbed soil moisture conditions. The atmospheric initialization and lateral boundary conditions were provided by the NCEP Eta short-range ensemble forecast (SREF) data set. There are five members in the NCEP Eta SREFs: two positive perturbations, two negative perturbations and a control. The soil data came from the 3-hourly Eta 40-km surface analysis.

Synoptically, on 4-5 May 2003 there was a particularly strong upper-level jet streak propagating through the southern Great Plains, its left exit region at 0000 UTC focused over southern Missouri. An associated surface low was located in NE Kansas (Fig. 3), and there was a strong fetch of southerly warm moist air from the Gulf of Mexico ahead of the system. As the system pushed across the southern Great Plains, there were numerous preliminary reports of tornadoes, large hail, and damaging winds (see Fig. 1).

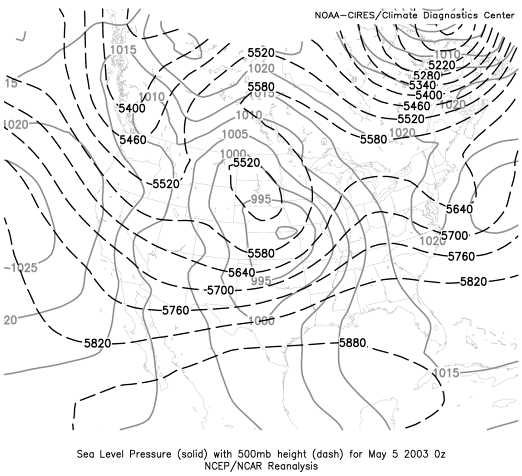

Figure 3. SLP & 500 hPa heights for 0Z 5 May 2003.

3. SOIL PERTURBATION METHOD

The data used to generate the 0-10 cm soil moisture fraction perturbations was from Eta 40 km land-surface analyses. An empirical orthogonal function (EOF) method (Wilks 1995, Houtekamer 1993) was used to generate random perturbations that had the same spatial structure as the daily deviations of soil moisture from a running-mean climatology. Because of the EOF structure, drier regions had smaller perturbations, while regions with more day-to-day moisture variability had larger perturbations; presumably, the more day-to-day variability, the larger the typical errors in the soil moisture analyses.

To start, 244 days of soil moisture data, corresponding to 15 Apr – 15 Jun 2000, 2001, 2002, and 2003 were used, and a 30-day running mean was calculated. The mean was subtracted from the daily soil moisture analysis to get daily deviations. Using the daily deviations as input, an EOF analysis was performed, and the soil moisture EOFs (also called singular vectors, or SVs) and associated singular values (the square root of the eigenvalues) were calculated and ordered from largest to smallest variability. The algorithm used to generate the EOF analysis was from Press et al. (1992).

In order to create perturbations possessing the same spatial structure as the daily deviations from the running mean state, a perturbation method from Houtekamer (1993) was used:

$$\varepsilon_j = \sum_{i=1}^{244} r_i \cdot u_i \cdot \sigma_i \qquad (1)$$

The jth perturbation e_j is the summation of the product of a standard normally distributed random number r_i, the ith singular vector u_i, and the ith singular value s_i. In this case, there were 244 singular vectors corresponding the 244 days worth of observations. The perturbations were added to the 0-10 cm soil moisture and the resulting fractional soil moisture, was constrained to between 3% and 100%.

4. RESULTS

The following maps are for the 6-hour precipitation totals for 2100 UTC May 4 – 0300 UTC 5 May 2003 (Figs. 4-15). The analysis in this section is also for the same period of time. These times corresponded to a six-hour time span where there was frequent tornadic activity around the Kansas-Missouri border, and near Omaha, NE. The verification was taken from NOAA's River Forecast Center multi-gauge and radar analysis.

Figures 4-9 show the verification and 6-hr total precipitation maps for the Grell scheme. Figures 10-15 show the same, but for the KF2 scheme. Members in both schemes missed the northeasterly tornadic storm tracks over Missouri and Nebraska's eastern borders. Additionally, both schemes had more widespread precipitation than the verification. The KF2 simulations concentrated the precipitation in a narrower band than the Grell scheme but produced higher totals. Between members of the ensembles, there was small scale variation between members, and both perturbations shifted the cells of precipitation.

In order to quantify the variability added by the perturbations, the domain-averaged standard deviations of the 6-hour precipitation totals were calculated over the five ensemble forecasts. Table 2 contains the standard deviations of the six-hour precipitation totals, in centimeters, for the period of interest.

Grell convection	**s**
Atmos. pert.	0.267 cm
Soil pert.	0.205 cm
Both pert.	0.294 cm

KF 2 convection	**s**
Atmos. pert.	0.530 cm
Soil pert.	0.543 cm

KF 2 vs. Grell	**s**
Atmos. Pert.	0.289 cm
Soil pert.	0.236 cm

Table 2. Standard deviations of 6 hr. total precip. (cm) for 2100 UTC May 4 – 0300 UTC 5 May 2003. Both perturbations for KF2 not available.

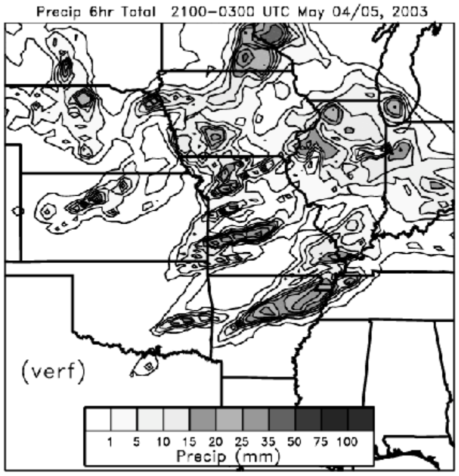

Figure 4. Precip verification.

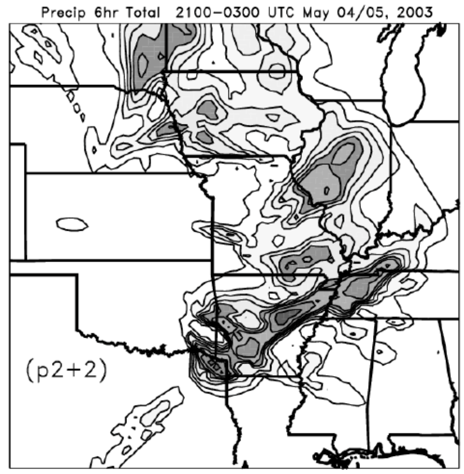

Figure 5. Grell:2nd bred pert. & 2nd soil pert

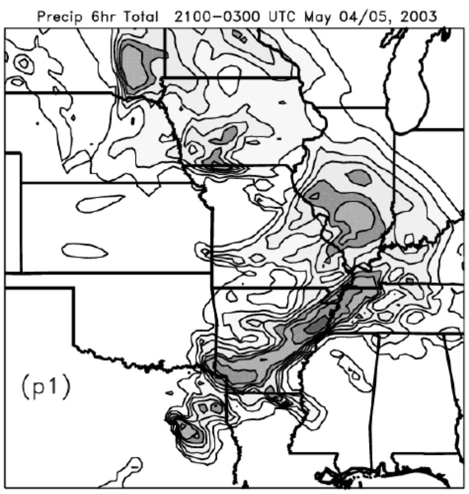

Figure 6. Grell: 1st bred pert.

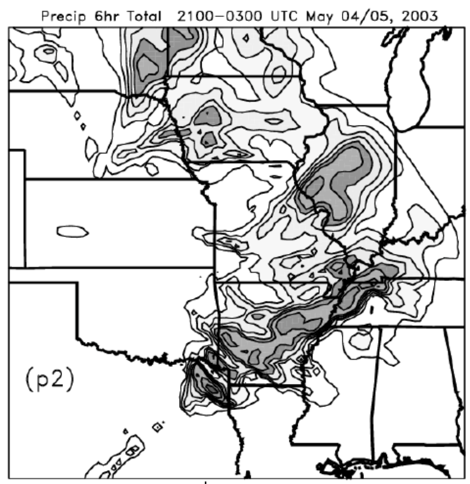

Figure 7. Grell: 2nd bred pert.

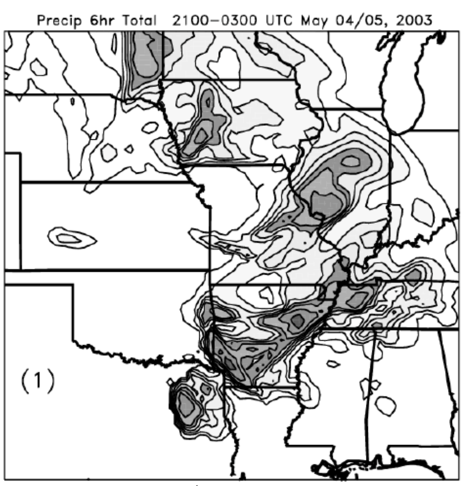

Figure 8. Grell: 1st soil pert.

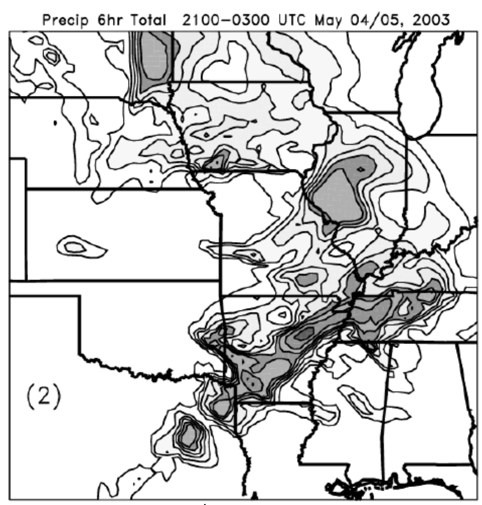

Figure 9. Grell: 2nd soil pert.

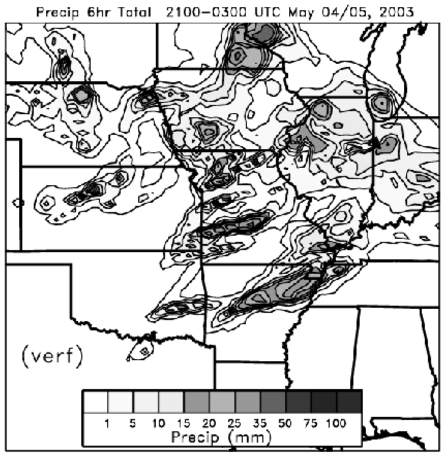

Figure 10. Precip verification.

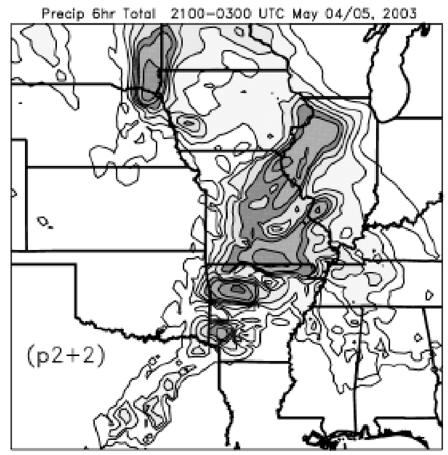

Figure 11. KF2:2nd bred pert. & 2nd soil pert

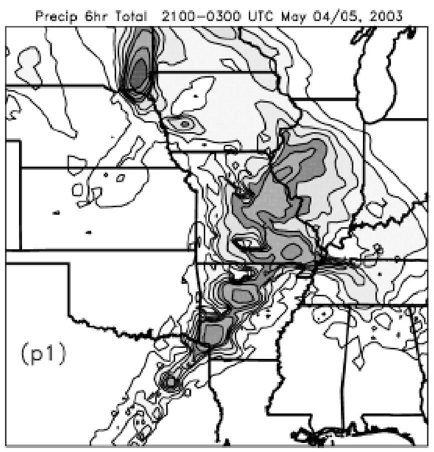

Figure 12. KF2: 1st bred pert.

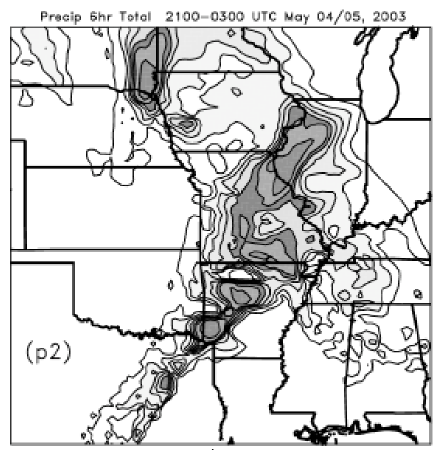

Figure 13. KF2: 2nd bred pert.

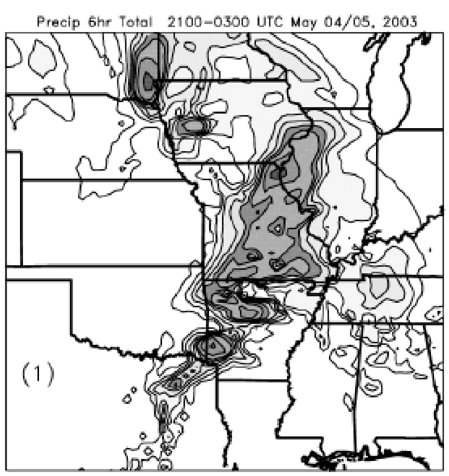

Figure 14. KF2: 1st soil pert.

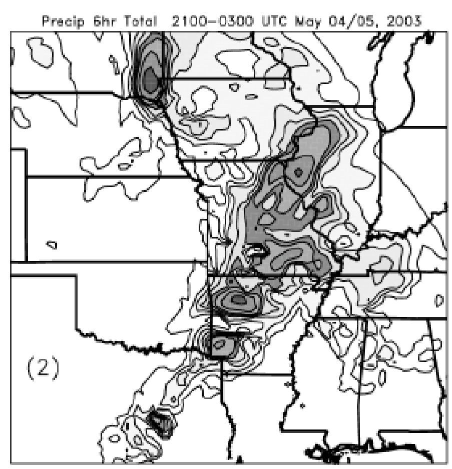

Figure 15. KF2: 2nd soil pert.

For the Grell cumulus parameterization, the combined perturbations (bred vectors and perturbed soil moisture) yielded the largest variability for the chosen parameterization, yet the perturbed soil case domain averaged standard deviation was approximately the same size as the standard deviation from the perturbed atmosphere case. Note that the precipitation due to atmospheric perturbations were not entirely independent of the precipitation from the soil perturbations; were they independent: $s^2_{both} = s^2_{atmos} + s^2_{soil}$. If the atmospheric bred vector perturbations and soil moisture perturbations were indeed independent the standard deviation for both perturbations would be equal to 0.337 cm, not 0.294 cm.

The KF2 parameterization yielded a domain averaged standard deviation two times larger than the Grell scheme for both perturbed atmosphere and perturbed soil. This is probably an artifact of the KF2 scheme simulations exhibiting higher six-hour precipitation totals than the Grell scheme on average. When the same atmospheric perturbations or soil moisture perturbations were used, the domain-averaged standard deviation of the difference between Grell and KF2 simulation members were on the order of a quarter of a centimeter, indicating that varying the convective parameterization introduced a comparable amount of forecast diversity to the ensemble diversity in the Grell scheme due to soil or atmospheric perturbations.

5. CONCLUSIONS

One of the problems with ensemble forecasts is a lack of variability between members, or more simply that the members look too similar to each other and too dissimilar from the truth. Here we examined the effects of perturbing soil moisture in ensemble forecasts. Our test case was a tornado outbreak on 4 May 2003. We ran a set of limited area ensemble forecasts where the atmosphere, the soil moisture, and the convective parameterization were perturbed (Grell and KF2).

In general, because the KF2 ensembles were generally moister than the Grell ensembles, and there was more ensemble variability due to both soil and atmospheric perturbations associated with the KF2 scheme than with Grell. Comparing the variability introduced by perturbing the soil, atmosphere, and convective parameterization, all appeared to have first-order effects for this case. Verifying these results over a wider range of cases is certainly warranted. Nonetheless; these results suggest that perturbing the soil condition is ensemble forecasts may be one important way to realistically increase their diversity.

6. ACKNOWLEDGEMENTS

This material is based upon work supported by the National Sciene Foundation under Grant No. 0130154.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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