Response of Short-term Precipitation to Initial Soil States in WRF-ARW Model

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1. INTRODUCTION

Despite agreement at large-scale and synoptic scales in numerical weather prediction models, uncertainties in initial conditions lead to significant scatter in predictions of precipitation associate with mesoscale phenomena. Of particular importance for the disagreement are errors in initial soil state, which modulates evaporation and other energy and water exchange between the atmosphere and land. Errors in soil state lead to incorrect surface water and energy partitioning and mesoscale circulation. Observed soil state (especially soil moisture) data are limited in spatial and temporal scales. soil properties (moisture and temperature) are also very much model-dependent variables (Koster et al., 2004). Therefore it is still a challenging issue to prescript accurate initial soil state in numerical models. Most current practices in soil properties initialization are to prescribe soil state with so-called observed climatology, or to use other model's prediction through interpolations or aggregations. These practices, however, may not be suitable to short to medium-range weather forecasting models because the errors in the initial soil properties may make the forecasting useless. In this study, we explore the impacts of initial soil conditions on precipitation using the state-of-art WRF-ARW model and the HRLDAS through a set of ensemble forecast under prefect-model assumption, whereby the same model used to generate a 'true' solution is used to generate ensemble forecasts. Though such 'true' state is not a direct analog to real numerical weather prediction where error contributed by model deficient may be significant or grater than that resulted from errors in initial conditions. However prefect model experiments do offer how best to design an ensemble of initial conditions in the absence of model error. Because the 'true' state and ensemble forecasts are on the same model grids, no additional errors will be induced in comparison and statistical verification. The generation of initial soil conditions and model configurations are discussed in section 2, followed by results presentation in section 3. General discussion and conclusion are given in section 4.

2. MODEL CONFIGURATION AND INITIAL SOIL CONDITIONS

The latest WRF-ARW (version 2.2,Skamarock et al., 2005) is used to perform ensemble forecasts with following physics packages chosen for this study. Eta scheme for microphysics, RRTM for long-wave radiation, two-stream multiple band scheme with climatological ozone and cloud effect for short-wave radiation, Meller-Yamada-Janjic PBL scheme, and Kain-Fritsch cumulus parameterization. The land process including soil state is dealt with the Noha land surface. Two nested domains are illustrated in Figure 1. The outer domain has spatial resolution of 45 Km and the interior domain covers continental United States with spatial resolution of 15 Km. One-way nesting is adapted (i.e., no feedback from interior domain to outer one).

The high-resolution land surface data assimilation (HRLDAS, Chen, et al., 2004) system, which has the ability to maximize the utility of available land surface observations, is used to generate a set of initial soil states for the WRF-ARW model. The HRLDAS is based on the Noha land surface model that used in current Weather Research and Forecasting (WRF) model. We run the HRLDAS with hourly precipitation (NCEP Stage IV, Lin and Mitchell, 2005), radiation and atmospheric forcing (wind, temperature and humidity) from January 1 2003 to December 31 2006 over domain 1 shown in Figure 1. The HRLDAS repeated three cycles with the same forcing to allow a full spin-up of the soil state. A set of soil states from the final cycle is chosen to construct an ensemble of initial soil conditions, which include instantaneous soil state at 00Z of June 30 2003, June 30 2004, May 31 2005, June 16 2005, June 30 2005 and June 30, 2006 to represent interannual variations of soil state, and July 16 2005, July 31 2005, August 16 2005 to take into account of intra-seasonal variations of soil state. The spread between the chosen soil states represents uncertainty in soil state initialization to some extent.

All experiments are initialized at 00Z June 30 2005 for outer domain. Interior domain is activated 24 hours later at 00Z July 1 2005. Initial atmospheric forcing and lateral boundary conditions for the outer domain are provided by NCEP 1 degree global final analysis. All forecasts are run for two weeks. This paper focuses on short forecast (48 hours of the interior domain) and investigate the impacts of initial soil state uncertainty on precipitation in WRF-ARW model. The influence of initial soil conditions on medium-range forecast will be addressed in a separate paper.

With the perfect model assumption, the 'true' state is generated by the run with June 30 2005 soil state (referred as control run: CTL). Eight other members run the same way as the control run except differing in initial soil moisture and temperature from each other and from the control.

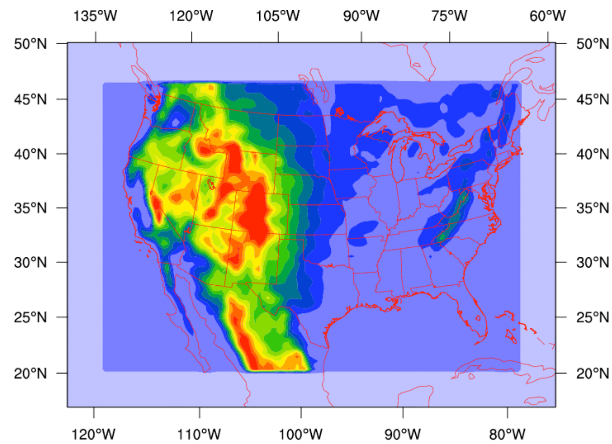

Figure 1 Model Domain used in this study, Interior domain is highlighted covering continental United States.

Four soil layers are used in WRF-ARW and HRLDAS. Initial top layer (10cm) soil moisture and temperature are shown in Figure 2 (top panel). Great plain and the East United States are relatively wet (volumetric soil water is greater than 0.25 mm^3/mm^3) while the southeast and the west are relatively dry (volumetric soil water is less than 0.15 mm^3/mm^3). The soil moisture indicates mesoscale spatial variation. On the other hand, soil temperature is dominant by large-scale spatial variation with clear north-south gradients. The differences between ensemble mean initial soil state and the control are illustrated in the bottom panel of Figure 2. Relatively to the control, the soil in the ensemble mean is drier in the great plain and the mountain region while wetter in the South and Ohio River valley. Change in soil temperature is in the same patterns as the moisture: warmer in drier area and colder in wetter region. To estimate the variation spread in soil property between ensemble members, figure 3 is the standard deviations in soil moisture and temperature. The spread in soil moisture variation in the west United States is larger (0.06 mm3/mm3) relative to the rest. The spread in temperature is about 1 to 1.5 K in the most part of the domain except the great plain area where the spread is about 2 K.

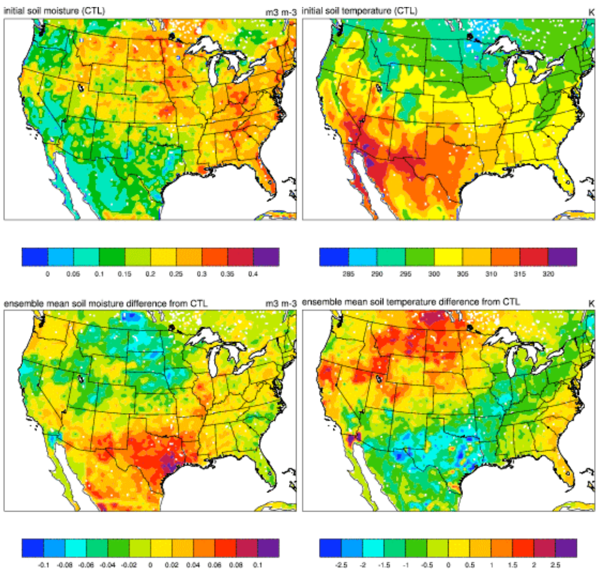

Figure 2. Initial soil moisture and temperature at 10 cm depth (top panel), and differences between ensemble means and the control (bottom panel).

3. RESULTS AND DISCUSSION

Soil temperature responses to the atmosphere much fast relative to soil moisture. Therefore most studies in soil-precipitation feedback focus on the role of soil moisture. However for short-term forecasts, soil temperature, particularly in the top layer, may play an important role in modulating regional scale circulation and convective weather systems. An additional experiment is conducted to examine the relative role of soil temperature. Figure 3 represents simulated 48-hour accumulated precipitation from three experiments: CTL (top panel), control run as pointed out in last section; CSM (middle panel), changed initial soil moisture only from CTL; CMT (bottom panel), changed both initial soil moisture and temperature from CTL. Taking the intensive precipitation near the Northeastern Texas shown in the CTL as example, It is clear that soil moisture plays the primary role in reducing the precipitation in that area, and soil temperature makes secondary, but not negligible impact to alter the precipitation further. Therefore both soil moisture and temperature are different between our ensemble members and the control.

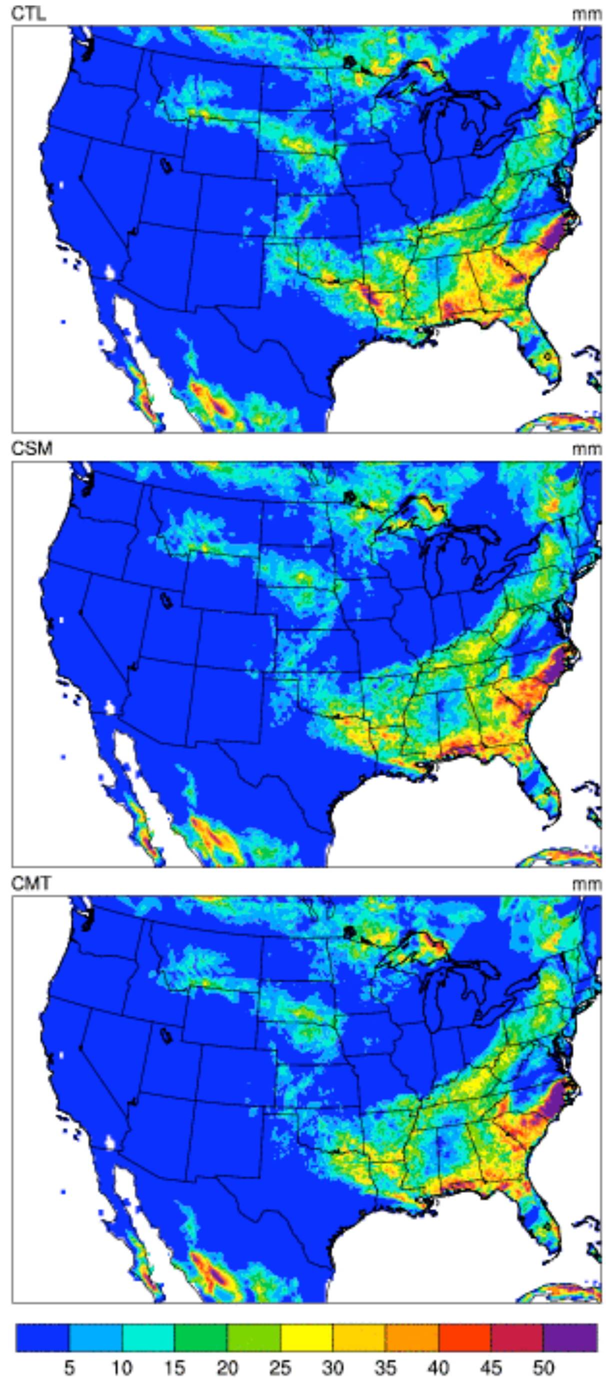

Figure 3. 48-hour accumulated convective precipitation from CTL, CSM and CMT experiments.

Figure 4 shows simulated 48-hour (convective and non-convective) precipitation from the CTL and ensemble means. It is obvious that rainfall in that 48-hour period is dominant by convective weather processes except few spots (e.g., the region in south Mexico and the Oklahoma and Texas border) where large-scale precipitation is significant. Interestingly, the ensemble mean reproduces large-scale precipitation seen in the control run reasonably well in terms of intensity and area, but only misses few large-scale precipitation including the one near Texas-Oklahoma border. For the convective precipitation, the ensemble mean captures the rainfall belts in good agreement with the control. However, the precipitation intensity in the ensemble mean is generally weak compared to the control, particularly in the southeast United States where 48-hour precipitation is 25 mm or higher.

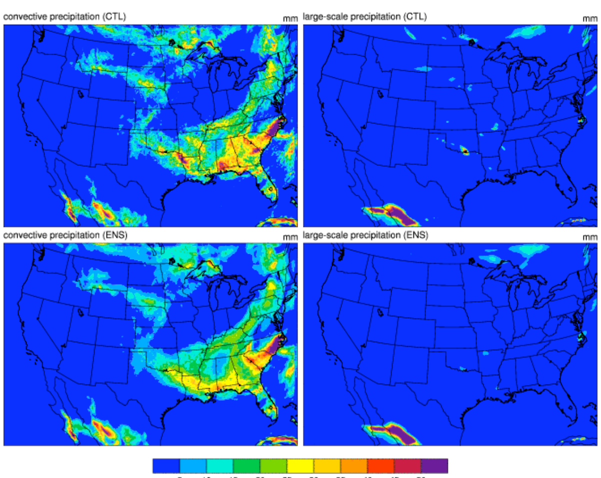

Figure 4. 48-hour accumulated convective (left panels) and large-scale precipitation from the control (top) and ensemble means (bottom).

The spread of the ensemble rainfall forecasts are evaluated through statistical verification against the control. The statistics includes probability of detection (POD), frequency bias (FB), false alarm ratio (FAR) and the equitable threat score (ETS). Details about these statistics can be found in Hamill (1999) and others in literature. Figure 5 is the statistics for 48-hour accumulated precipitation as a function of precipitation theshold. The threshold used here is the same as in NCEP operational forecasts. All ensemble members do well in terms of POD and FAR particularly for the low thresholds, but the scores in POD drop off rapidly as increasing threshold and false alarm ratio increase exponentially with threshold increases. The Frequency bias (FB) indicates over-forecast (>1) and under-forecast (<1). Again, the ensemble members have FB score close to 1 in lower threshold, but get away from 1 rapidly as the threshold increases, especially when threshold reaches 25 mm. The ETS score is somewhat puzzling, which starts low (~0.3) at the low end of the threshold, but increases (up to 0.5) for the middle range threshold, then drops down. It is no surprise that the members with intra-seasonal soil state variations overall score higher than the members with interannual soil state variations in all four statistics. Importantly, the ensemble mean score the highest except the frequency bias at high threshold. This indicates that ensemble forecast with perturbed soil states can enhance forecast skill relative to a single realization due to uncertainty in initial soil conditions. The low score at high threshold may imply the model is not skillful enough to capture intensive rainfall events.

4. SUMMARY

An ensemble forecast has been conducted with the latest WRF model using the HRLDAS generated soil moisture and temperature. Different from other soil perturbation ensemble studies, the HRLDAS creates consistent (and accurate) soil states for the WRF model since both HRLDAS and WRF share the same Noha Land Surface model and the HRLDAS is driven with observed atmospheric forcing. We also used ‘perfect-model’ assumption in this study. The advantage of the assumption is to minimize possible additional errors (e.g., model errors and errors induced by data mapping). This is crucial to ensemble design and to ensemble verification, particularly for precipitation. Our preliminary results based on eight ensemble members indicate that the HRLDAS can be effectively used to create quality initial soil state for the WRF model in operational and research modes. The number of ensemble members needs to increase to better count the uncertainty spread in soil property, and to draw more concrete guideline for ensemble forecasts design relate to perturbing soil state and to investigate possible mechanism in soil-precipitation feedback.

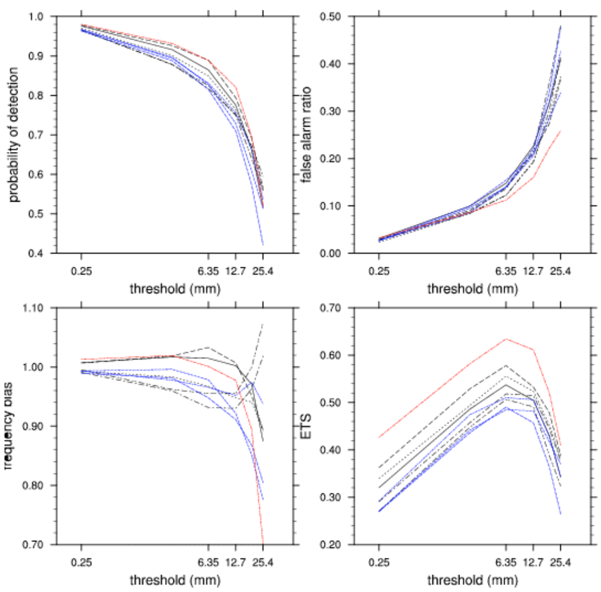

Figure 5. Statistical verification: POD, FB, FAR and ETS as a function of rainfall threshold. Red lines represent ensemble means, blue lines indicate the members that initial soil states are constructed with interanual variability and the black lines are the members that constructed by intra-seasonal variations.

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