Impact of the ECMWF reanalysis soil water on forecasts of the July 1993 Mississippi flood

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Abstract. We reexamine the impact of soil water on the precipitation for the United States for July 1993 (the time of the Mississippi flood), previously discussed by *Beljaars et al.* [1996], using soil moisture from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA). Ensembles of three precipitation forecasts for the month of July, initialized on July 1, 2, and 3, using different initial soil water fields, are compared with the 12 to 24 hour ERA precipitation forecasts for the month and the observed precipitation. Both the 12 to 24 hour forecasts and the July integrations depict the July mean anomaly field well, although the mid-West precipitation maximum is displaced northward in both the ECMWF short and long-term forecasts. The July 1993 ERA soil water anomaly does not account for the anomalous July precipitation, but replacing the July 1, 1993, soil water with the much drier soil water from June 1988 reduces the July 1993 ensemble forecast precipitation by about 40%. It is probable that soil water nudging has reduced the variability of soil water in the ERA fields.

1. Introduction

Beliaars et al. [1996] discussed the sensitivity of the extreme rainfall over the central United States in July 1993 to the landsurface parameterization and soil water anomalies in the European Centre for Medium-Range Weather Forecasts (ECMWF) model. They showed how the introduction of a prognostic four layer soil water model [Viterbo and Beljaars, 1995] in the ECMWF operational model in 1993, combined with wetter initial soils, greatly increased the accuracy of 2-3 day precipitation forecasts. They also showed the sensitivity of precipitation in July integrations to initial soil water. The difference in the July precipitation from a three member ensemble of July integations starting with wet soils on July 1, 2 and 3 and an ensemble starting with dry soils qualitatively resembled the observed July precipitation anomaly, which showed a maximum over the mid-West (producing the 1993 Mississippi flood) and minima over the southeastern and southwestern United States (see Plate 2 later).

At that time a soil water analysis was not available for initialization, so *Beljaars et al.* [1996] used hypothetical idealized fields. They defined these idealized soil wetness fields in terms of a percent of available soil water A_w , defined as

$$A_{w} = 100 \left(\frac{SW - PWP}{NS - PWP}\right) \tag{1}$$

in terms of the model root-zone volumetric soil water (SW) between the upper and the lower thresholds, which determine the model vegetative resistance to evaporation [Viterbo and Beljaars, 1995]. $A_w = 0$ corresponds to the lower threshold, the model permanent wilting point, PWP = 0.171 m³ m⁻³, and $A_w = 100\%$ to the upper soil water limit, NS = 0.323 m³ m⁻³, when the model evaporation from the vegetation is "unstressed." For the 100 cm root zone (the first three layers of the soil model) this dynamic range of soil water totals 152 mm [Viterbo and Beljaars, 1995]. The idealized soil

Paper number 1999JD900449. 0148-0227/99/1999JD900449\$09.00 wetness fields used for the July integrations of *Beljaars et al.* [1996] are discussed in section 3.1.

Soil water fields are now available at four levels from the ECMWF reanalysis for the 15 years of 1979-1993 (ERA-15) [Gibson et al., 1997]. The data assimilation system includes nudging of soil water based on short-term forecast errors in the lowest-level mixing ratio [Viterbo and Courtier, 1995] to constrain long-term drifts of soil water. Here we repeat the T-106 1993 July integrations using these initial soil water values from ERA-15 and reconsider our assessment both of the impact of soil water variations and the role of evaporation over the western United States in determining the location and intensity of the July 1993 precipitation maximum in the model. These ERA soil water fields are more realistic than the idealized fields used by Beljaars et al. [1996], but they are nonetheless fields that are simulated by the model, using the model precipitation and land-surface scheme (and the model radiation fields), as well as the nudging scheme. Studies suggest [Betts et al., 1998, this issue; Douville et al., 1999] that the variability of the simulated soil water in the reanalysis is probably reduced by the soil water nudging scheme.

There has been some disagreement regarding the sensitivity of precipitation to soil moisture anomalies between global model studies, such as *Beljaars et al.* [1996] and this study, and limited area model studies, such as *Paegle at al.* [1996] and *Giorgi et al.* [1996], which do not show the same positive feedback. Seth and Giorgi [1998] concluded that large domain sizes were essential to reduce the impact of lateral boundary condition specification on the model sensitivity to internal processes. We agree with Seth and Giorgi [1998], although we would go further to suggest that the study of continental-scale soil moisture feedbacks probably requires a global model.

2. Forecast Ensembles and Precipitation Validation Data

Table 1 summarizes the ensembles of July forecasts (at T-106 triangular truncation, corresponding to a spacial resolution of approximately 120 km) used to assess the impact of soil water on

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% availability

a) July 79-93 ERA soil wetness

0-1 10-20 20-30 30-40 40-50 50-80 60-70 70-80 80-90 90-100100-110



Plate 1. ECMWF Reanalysis (ERA) soil wetness (% of availability) for 15 year July mean, July 1, 1993, and June 1988 (left). (top right) Soil wetness difference of idealized (wet-dry) simulations of *Belgaars et al.* [1996]. (center right) Soil wetness difference of ERA July 1, 1993, from July ERA-15 mean. (bottom right) Soil wetness difference of ERA July 1, 1993, from ERA June 1988.

July 1993 precipitation. We used three initial dates, July 1, 2, and 3, and averaged the forecast days for the rest of July as representative of July 1993. Although the length of these three forecasts are 31, 30, and 29 days, respectively, we will refer to them generically as July integrations to distinguish them from the ERA 12-24 hour forecasts. The first set A used the ERA soil water for the respective initial dates. The second and third ensembles in Table 1 were also initialized on July 1, 2, and 3, but the soil water fields for set B were taken from the 15 year July ERA mean and for set C

from June 1988, when soil water was a rather low, following a period of drought over the central United States.

-35--25-25--15-15--5 5-15 15-25 25-35 35-45 45-55 55-65 65-75

d) July 93 CY 48 wet-dry: Soil wetness difference

% availability

The forecast model used (cycle 15R7) has a few revisions from the earlier reanalysis model: including a new stable boundary layer parameterization and the addition of soil water freezing [*Viterbo et al.*, 1999] and a change of the albedo of the boreal forests with snow [*Viterbo and Betts*, 1999], of which the latter two changes have no impact in summer.

We also use precipitation from the ensemble of short-term





Plate 2. (top) U.S. 1979-1993 July mean precipitation, observed [*Higgins et al.*, 1996] and 12-24 hour forecast precipitation from ERA. (bottom) Precipitation anomaly fields for July 1993 for observations and ERA.

forecasts produced by ERA-15. In the reanalysis there are two estimates of precipitation. The first is from the four 0 to 6 hour forecasts of the reanalysis cycle. These are known to be biased low over the central United States [*Betts et al.*, 1998b, this issue], because the model has significant spin-up in its dynamic fields. The second is from the 24 hour short-term forecasts, which are run twice daily from the 0000 and 1200 UTC analyses. Of these two, a composite of the precipitation from the two 12 to 24 hour forecasts is considered the better model estimate of precipitation. We will show these here and we will refer to them as 12-24FX precipitation.

For validation of the precipitation fields, we will use the gridded

Table 1. July Forecast Ensembles

Initial Dates in 1993		Initial Soil Water	Forecast Length (Days)
A	July 1, 2, 3	July 1, 2, 3, 1993	31, 30, 29
В	July 1, 2, 3	ERA-15 July mean	31, 30, 29
С	July 1, 2, 3	June 1988 mean	31, 30, 29

precipitation over the continental United States from *Higgins et al.* [1996], which has a resolution of $2.0^{\circ} \times 2.5^{\circ}$. This hourly precipitation data come mostly from Fisher and Porter gages, which *Groisman and Legates* [1994] estimates have a 10% low bias. *Betts et al.* [1998b, this issue] evaluated ERA precipitation over five subbasins of the Mississippi River for a 9 year period. They found that the 12-24FX precipitation was about 10 to 30% higher than the Higgins precipitation.

3. Results

3.1. Soil Wetness

The left three panels in Plate 1 are percent soil wetness availability, and the right three are percent soil wetness difference fields. Top left is the 15 year ERA July average soil wetness, which was used to initialize ensemble B in Table 1. Mean values are as low as 10-30% over much of the western United States and 75% over sizable areas in the East. Underneath is ERA soil wetness on July 1, 1993, which was used to initialize the July 1 forecast of ensemble A. Soil wetness is close to 100% over parts of the central United States, following heavy rain in June, but is slightly drier in the Southeast and in the West than in the 15-year ERA mean. The



Plate 3. (top) Precipitation anomaly field for July 1993 from ensemble A of forecasts from July 1, 2, 3 for the month of July. (middle) Precipitation difference of month-long forecasts for July 1993 between set A, using early July 1993 soil wetness, and set B, using July mean soil wetness. (bottom) Precipitation difference of month-long forecasts for July 1993 between set A, using early July 1993 soil wetness, and set C, using July 1988 soil wetness.

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bottom left panel shows the ERA soil wetness for one of the driest summer months in the 15 year record, June 1988, which was used to initialize ensemble C. This was a drought month over the central United States, and much of the eastern United States has ERA soil wetness values in the 40-50% range. Over the western United States, these reanalysis soil wetness fields are all relatively dry and show little variability.

Beljaars et al. [1996] showed that the precipitation difference between two ensembles of July 1993 integrations (initialized on July 1, 2, 3), using wet and dry initial soil water, resembled the observed precipitation anomaly for the month. Having no soil water analysis, they used $A_w = 100\%$ for vegetated areas for their "wet" soil water ensemble and $A_w = 25\%$ for vegetated areas for their "dry" soil water ensemble. Nonvegetated areas, which are small, were given no soil water. The top right panel shows the difference of these two idealized soil wetness fields. It is 60% over most of the western United States and 70% over much of the East. It is rather uniform because it mirrors the vegetation fraction map of ERA, which has little variability, ranging from 80 to 90% cover over much of the United States, exceeding 90% in the Southeast and falling below 70% only over the deserts of the western United States. This simplified vegetation fraction is derived following the biome distribution of Wilson and Henderson-Sellers [1985], with a correspondence table, relating each vegetation type to a fixed cover, based on Warrilow et al. [1986].

Below it, middle right, is the anomaly field for July 1, 1993, differenced from the 15 year ERA July average soil wetness. Over the central United States the wet anomaly ranges from only 10% to a maximum around 40%, and the dry anomalies elsewhere are in the 10-20% range. These are small differences, when compared with the panel above of the idealized (wet-dry) soil wetness differences, used by Beljaars et al. [1996]. The bottom right panel shows the difference in ERA soil wetness between July 1, 1993 and June 1988. Comparing this with the top right panel (which has the same color scheme), we see that the (July 1, 1993 to June 1988) ERA soil wetness difference is barely half that of our earlier idealized (wetdry) difference over much of the eastern United States, reaching only 60% in limited regions of the central United States. Over the western United States, differences in ERA soil wetness are much smaller and do not resemble the soil wetness difference used by Beljaars et al. [1996], shown in the top right panel.

3.2. July 1993 Precipitation From ERA and Higgins Data Set

Plate 2 shows the 15 year July mean (1979-1993) for the Higgins data in the top left panel (available only over the continental United States) and the 12-24FX precipitation in the top right. Although the Higgins data have a 10% low bias, it is clear that the ERA precipitation probably has a high bias, which is largest over the eastern United States. To partly eliminate these bias issues, we will compare anomaly fields.

The bottom two panels of Plate 2 show precipitation anomaly fields for July 1993: the bottom left panel is the difference of the Higgins data from its 15 year mean (top left), the lower right panel is the ERA 12-24FX precipitation, differenced from the corresponding 15 year ERA mean (top right). These anomaly patterns show that ERA and the data both have low precipitation over the southeastern and southwestern United States. However, the one striking difference is that the wet anomaly in ERA, which has roughly the right amplitude, is shifted 4°N of the observed location centered on 40°N.

This northward shift in the 12-24FX ERA precipitation is surprising, because it differs from *Beljaars et al.* [1996]. Their Figure 2, which shows 2-3 day forecasts in the model cycle "CY48"

(which became the new operational model in August 1993), correctly gave a precipitation maximum centered on 40°N. The reanalysis model has the same land surface parameterization as CY48 (although there are updates to other model physical parameterizations, including a prognostic cloud scheme [Tiedtke, 1993] and a sub-grid-scale orography scheme [Lott and Miller, 1997]. However, the soil wetness fields are very different between the two studies. Soil wetness in the work of Beljaars et al. [1996] for the then-new CY48 was initialized in late June 1993 with uniformly high values (A_w =100%) for vegetated areas, since no global soil water fields were available. Over the western United States the ERA soil wetness fields shown in Plate 1 are much drier. This is significant because Beljaars et al. [1996] concluded that it was increased evaporation over the southwestern United States and the Mexican plateau (their Figure 3b) that was responsible for the improved location of the precipitation maximum in the CY48 forecasts. In that study, increased evaporation upstream improved the structure of the elevated boundary layer and reduced the strength of the capping inversion overlying the moist southerly flow from the Gulf of Mexico, which permitted a more southerly onset of precipitation. In contrast, soil water in the reanalysis is low over the western United States.

3.3. Impact of Soil Water on Precipitation Anomaly Fields for July Integrations

The top panel of Plate 3 is the July precipitation anomaly (differenced from the 15 year ERA mean) for the ensemble of July integrations initialized on July 1, 2, and 3, 1993 (ensemble A in Table 1). It shows a similar anomaly pattern to the ERA 12-24FX precipitation, although the precipitation maximum is underpredicted by perhaps 50%, and its location has exactly the same error, a northward shift. The dry anomalies are forecast quite well on this monthly timescale.

The middle panel of Plate 3 shows the precipitation difference for the July 1993 integrations (the precipitation difference between ensembles A and B in Table 1), coming from the excess soil water at the beginning of the month over the 15 year July ERA-mean, shown in the middle right panel of Plate 1. This precipitation difference field bears no resemblance to the precipitation anomaly for the month, showing that the precipitation anomaly cannot be attributed to the ERA soil moisture anomaly at the beginning of July 1993.

The bottom panel in Plate 3 shows the precipitation difference for the July 1993 integrations (the difference between ensembles A and C in Table 1), coming from a large change of initial soil wetness (July 1, 1993 to June 1988), shown in the corresponding bottom right panel of Plate 1. The precipitation pattern is similar to that observed, with perhaps 30% of the amplitude. However, the soil water anomaly needed to produce this precipitation anomaly is probably the largest observed summer difference in the 15 years in the ERA soil water analyses. This anomaly pattern is qualitatively similar to but has a smaller amplitude than that shown by *Beljaars et al.* [1996, Figure 9c], which used the much larger soil wetness change shown in Plate 1 (top right).

4. Discussion

We are again encouraged at how well the model forecasts reproduce the observed maximum precipitation anomaly pattern for July 1993. However, all the July 1993 model precipitation anomaly fields have the Midwest U.S. maximum too far north in comparison to the observed maximum. This is true for the 12-24 hour forecasts as well as the monthly forecasts. This contrasts with the correct location in the ensemble of 2-3 day forecasts in the work of *Beljaars et al.* [1996], who attributed this to a weaker upper capping layer, which in turn they linked to more upstream evaporation over the southwestern United States and the Mexican plateau. The ERA reanalysis soil water and the corresponding evaporation is low over the southwestern United States, and we believe this is again the reason that the precipitation maximum is too far north. However, there is another model error that might also affect precipitation location. The reanalysis model has a large error in the diurnal cycle of precipitation over the central United States [*Betts et al.*, 1998b, this issue]. The model precipitation maximum is at local noon, rather than as observed during the evening and at night.

Our second conclusion is that the July 1 ERA soil water anomaly does not account for the July 1993, precipitation anomaly. However, replacing the July 1, 1993 soil water with the much drier soil water from June 1988 reduces the July 1993 ensemble forecast precipitation by about 40%. Thus while a significant portion of the precipitation anomaly of July 1993 may be linked to initial soil water anomalies, this requires rather large anomalies, comparable to the extremes shown in the model in the ERA-15 summer record. This is fully consistent with the monthly forecasts of Beljaars et al [1996], who used widely differing, idealized wet and dry soil wetness fields. This raises the question of whether the ERA soil wetness variations (as well as the soil wetness and evaporation over the western United States) are realistic or may have too narrow an interannual range. It was suggested by Betts et al. [1998a] in a comparison against FIFE (First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment) data that perhaps the nudging of soil water might have reduced the amplitude of soil water variations between wet and dry periods. Betts et al. [1998b, this issue] found, in addition, that the soil water nudging has a large annual cycle (negative in winter and positive in summer), which is probably damping the seasonal variation of soil water. Thus it seems probable that the nudging in the ERA model, which was introduced to control long-term drifts of soil water, has significantly reduced the variability of soil water. A new optimal interpolation scheme for soil water has been developed [Douville et al., 1999] for inclusion in the next reanalysis. We remain convinced that as the realism of the land-surface interaction and the model soil water fields are improved in the global model so will the summer precipitation forecast skill.

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