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Basin-scale surface water and energy budgets for the Mississippi from the ECMWF reanalysis

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Abstract. This paper compares with observations the energy and water budgets for the subbasins of the Mississippi (the Arkansas-Red, the upper Missouri, the upper Mississippi, the Ohio, and the lower Mississippi and Tennessee Rivers), which were computed on-line with an hourly time scale from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis from 1985 to 1993. The model has a significant precipitation spin-up between the analysis cycle and the 12-24 hour forecast, ranging from 24% to about 40% for the drier Missouri basin. The spin-up of the model "large-scale" precipitation ranges from 30 to 50%, roughly double that of the spin-up of the model "convective" precipitation. The model has an erroneous peak in convective precipitation near local noon, but on 2 day and monthly timescales, the 12-24 hour forecast precipitation is only 10 to 20% higher than the observed precipitation for most of the subbasins. The model runoff, which is all deep runoff from the base soil layer, is low on an annual basis, primarily because the model has very little Spring runoff. The nudging of soil water in the analysis cycle, based on 0-6 hour forecast errors in low-level humidity, plays a major role in the model liquid hydrology. The nudging term has a large annual cycle, positive in summer and negative in winter. Although nudging prevents the downward interannual drift of soil water, associated with a shortfall of precipitation in the analysis cycle, it also attempts to compensate for other errors in the model, such as errors in the seasonal cycle of evaporation and runoff, and may damp the variability of soil water. The model frozen hydrology in winter is not conservative and snowmelt is probably too small. Overall, the ECMWF reanalysis gives a valuable description of the surface energy and water balance of the Mississippi River subbasins on timescales longer than the diurnal, and at the same time, it is clear that improvements in the model physics are needed.

1. Introduction

Basin-scale averages of the surface energy and water budgets for the Mississippi subbasins cannot be determined with any reliability from the few scattered timeseries measurements of the surface radiation budget and the surface sensible and latent heat fluxes. These flux site measurements are representative of rather small areas, less than 1 km^2, and are not uniformly distributed across the diverse vegetation classes and climatic regimes of the Mississippi basin, which covers a total drainage area of 3.16×10^6 km^2. Consequently, one of the objectives of the GEWEX (Global Energy and Water Experiment) Continental International Project (GCIP) was to assess the ability of our forecast models to estimate the energy and hydrological balances on river basin scales [*Coughlan and Avissar*, 1996] and to use observations of precipitation and stream flow as evaluation data. This evaluation can also help identify surface processes that are poorly represented in the forecast model and thus lead to improvements in the modeling of the surface evaporation and hydrological response, which in turn have a significant positive impact in medium-range to seasonal-scale prediction [e.g., *Beljaars et al.*, 1996]. The European Centre for Medium-Range Weather Forecasts (ECMWF) recently completed its reanalysis project, which used a frozen version of their analysis/forecast system, at a triangular spectral truncation of T-106 with 31 levels in the vertical, to perform data assimilation using past data from 1979 to 1993 [*Gibson et al.*, 1997]. The ECMWF reanalysis has a 6 hour analysis cycle, and from every analysis short-term forecasts are run. The standard global grid-point archive contains the meteorological state variables and averaged surface fluxes every 3 hours. In addition, meteorological and averaged surface flux variables for selected grid points and averaged quadrilaterals of grid points were archived at an hourly time resolution as single-column data sets. For the last nine years of the reanalysis from 1985 to 1993, average quadrilaterals were included for the five main subbasins of the Mississippi, and here we analyze the surface water and energy budgets from these. Figure 1 shows the physics gridpoints (shaded dots) of the ECMWF T-106 reanalysis model for the United States: superimposed are the outlines of the five major Mississippi subbasins and their approximation in the reanalysis model by quadrilaterals. In clockwise sequence, basin 1 comprises the Arkansas-Red Rivers, basin 2 the upper Missouri, basin 3 the upper Mississippi, basin 4 the Ohio, and basin 5 the lower Mississippi and Tennessee Rivers (rather more poorly represented than the others because the on-line integration scheme could handle only a few simple quadrilaterals). Note that there is one water gridpoint in Lake Michigan in the upper Mississippi basin 3, which is excluded from our land average for this basin. This on-line domain integration capability is a unique aspect of the ECMWF data assimilation system. An ongoing archive from the current

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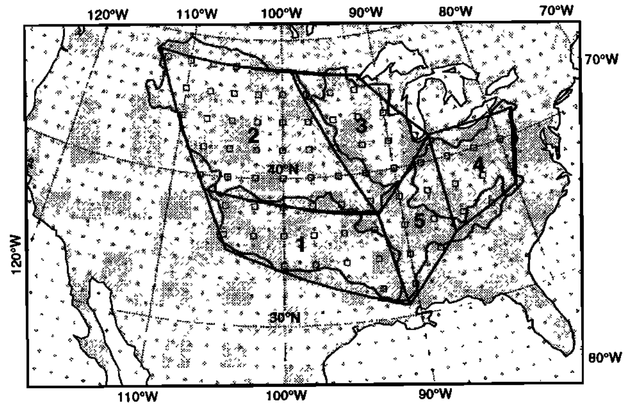

Figure 1. Five major Mississippi subbasins and their approximation in the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis model. Physics grid points are shaded dots, and small squares are the data points for the *Higgins et al.* [1996a] gridded rainfall set.

higher-resolution operational model exists from 1996 for these same domains. We will analyze only the surface water and energy budgets, not the atmospheric moisture budgets, although of course the surface fluxes are consistent with the atmospheric budgets. In this regard, our approach differs somewhat from many of the recent studies using other operational models, which have related surface fluxes to the atmospheric moisture budget [e.g. *Berbery et al.*, 1996; *Berbery and Rasmusson*, 1998; *Gutowski et* al., 1997; *Higgins et al.*, 1996b; *Rasmusson and Mo,* 1996; *Roads et al.*, 1998; *Yarosh et al.*, 1996, 1998]

Our first analysis was of the Arkansas-Red River basin [*Betts et al.*, 1998c], where we evaluated the basin-averaged model fields on diurnal, 5 day, monthly, seasonal, and interannual timescales and made comparisons with the observed basin-scale precipitation and stream flow. We found that the model precipitation had a significant spin-up in the first 24 hours, which spanned the observed precipitation from recording rain gages. This paper also noted that the ECMWF model has a near-noon peak in the diurnal cycle of summer precipitation, rather than the late afternoon and nighttime peaks characteristic of this basin. Model runoff, on the other hand, was only about half the observed stream flow on an annual basis, and the model, which had only drainage from its deepest soil layer, lacked the spring runoff maximum seen in the Arkansas-Red River basin. We were able to explore in detail the structure of the soil water nudging term in the ECMWF model, which was included in the model to control long-term drifts of soil water, resulting from underestimates of precipitation in the analysis cycle. This nudging term plays a major role in the model hydrology, and for the Arkansas-Red River basin, it has an unexpectedly large seasonal (positive in summer and negative in winter) and diurnal cycle (negative at local noon and positive in the evening and at night). We concluded that while it provided a net source of water, the nudging was also compensating for other errors in the model, such as in evaporation (no seasonal vegetation cycle, for example), or the model diurnal boundary layer evolution.

Two other recent studies of the ECMWF reanalysis model [*Betts et al.*, 1998a, b] used average data from the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) for the summer season of 1987 and the Boreal Ecosystem-Atmosphere Study (BOREAS) during 1996 to assess the land-surface interaction of the ECMWF reanalysis at single grid points, where supporting surface flux measurements are available. They found that the model bias in the incoming solar radiation is small. The evaporative fraction (EF) over the season for a grassland location in Kansas is now generally quite good, where soil water is a significant control on transpiration, because the root zone is recharged satisfactorily after major rain events in the four-layer soil water model [*Viterbo and Beljaars*, 1995]. In comparison with the data however, the model has a low bias in EF in June and a high bias in October, which is probably due to the absence of a seasonal cycle in the model vegetation. EF also appears too high in the model just after rainfall. Two noticeable errors can be seen in the surface diurnal thermodynamic cycle. The temperature minimum at sunrise is too low, because the surface uncouples and cools too much at night under the stable boundary layer (BL). The model has also an unrealistic diurnal cycle of mixing ratio, q, with too strong a midmorning peak and too large a fall during the day to a late afternoon minimum that is biased low. The morning peak is partly related to the strong inversion at sunrise, which slows the deepening of the boundary layer. The middle to late-morning peak in precipitation found in the work of *Betts et al.* [1998c] may be related to this midmorning peak in mixing ratio.

Over the boreal forest the ECMWF reanalysis model has a large albedo error in winter and spring, because it assigns the same albedo (of the order of 80%) to snow under the forest canopy as to snow-covered grassland [*Viterbo and Betts*, 1999]. Consequently, net radiation and sensible heat flux are biased low over forests, particularly in spring. In contrast in summer, evaporation is generally overestimated in the ECMWF model over the boreal forest [*Betts et al.*, 1998b]. Observations show that in summer, stomatal controls on evapotranspiration are large, and variations in the water stored in the surface moss layer affect evaporation for wet conifers more than soil water variations [*Betts et al.*, 1999].

This paper extends the surface water and energy analysis of *Betts et al.* [1998c] to all five subbasins of the Mississippi. This expands our results and conclusions to include a wider climatic range, including basins with significant cold season snowfall and those with a much larger runoff fraction.

2. Model and Observed Data Sets

2.1. ECMWF Reanalysis Model

We have subbasin averages for the hourly meteorological and subsurface variables and the surface energy and water fluxes accumulated for each hour. The hourly archive includes both the short-term forecasts (hourly to 6 hours) used in the reanalysis cycle and twice-daily 24 hour forecasts from 0000 and 1200 UTC (also archived hourly) so that issues relating to the diurnal cycle and the spin-up in the precipitation field can be addressed. We shall show model precipitation for the same verifying times from both the 0-6 hour analysis cycle (hereinafter referred to as analysis precipitation), and the 12-24 hour sections of the twice-daily 24 hour forecasts (hereinafter referred to as 12-24 FX precipitation). The model has a significant initial spin-up of precipitation from the analysis to the 12-24 hour forecast, and we shall find that the observed precipitation generally lies between these two model estimates in summer.

Model precipitation is subdivided into convective and large-scale rain and convective and large-scale snowfall. The northern basins have significant snowfall in the winter months (about 40% of precipitation). The ECMWF reanalysis model handles liquid and solid precipitation differently. It is the liquid phase that refills the soil reservoir (and also runs off). The frozen phase is treated as a snow layer on the surface [*Viterbo and Beljaars*, 1995], which can melt or evaporate to the atmosphere, but its hydrology is not conservative, since an independent snow analysis is introduced at every analysis time. Consequently, our analysis of the model frozen hydrology will be somewhat limited (section 3.6). When comparing with observations, which are total precipitation (although they underestimate snowfall more than rain), we shall show total model precipitation.

Because precipitation in the analysis cycle in biased low, long-term drifts in soil water were controlled in the reanalysis model by adding soil water nudging to the analysis cycle, based on the q analysis increment in the short-term 0-6 hour forecast for the lowest model level mixing ratio. This nudging is a significant component in the subsurface hydrological budget, with a different signature in summer and winter. The total addition of soil water, $\Delta(SW_R)$, to the root zone of 1 m depth (the top three layers) in a 6 hour analysis interval is calculated from

$$\Delta(SW_R) = C_v\, D\, \Delta t\, (q_a - q_g) \tag{1}$$

where C_v is the vegetation fraction (included so that there is no nudging over deserts). In the reanalysis model, the coefficient D is set so that if the moisture analysis increment (q_a - q_g) =3 g Kg^{-1}, then 0.15 m of water is added to the soil in 12 days. In our hourly data set, the nudging increments were not explicitly stored, so in the work of *Betts et al.* [1998c], we recalculated them from the change in soil water at analysis times. However, this recomputation is approximate for two reasons. There are a few missing analysis times in our hourly data set (when the archiving failed), and the archive program stored soil water for only the near-surface 0-7cm layer and an average for the remaining three layers 7-289 cm (because the software dated from an earlier model version with only two prognostic layers). Normally, the nudging is applied uniformly to the first three layers in the 1 m root zone (0-7, 7-28, and 28-100 cm), but there is in addition a constraint for each individual layer that the field capacity and the permanent wilting point thresholds are never crossed by the nudging. Whenever this occurs in layers 2 or 3, we cannot exactly recompute the nudging. Consequently, for this paper we recomputed the nudging as a residual from the surface flux terms and the column soil water change. In the liquid hydrology budget, the change of total column soil water (SW_T) is determined by

$$\Delta(SW_T) = \text{rain} + \text{melt} + \text{runoff} + \text{evaporation} + \text{nudging} \tag{2}$$

Because we know the other five terms, we can compute the nudging as a residual. This value agrees with the direct but approximate calculation to within 2-16 mm yr^{-1} for the different basins. On the basin scale, it appears that the nudging is compensating not only for the spin-up of precipitation but also for other errors in evaporation and the model diurnal cycle of mixing ratio [*Betts et al.*, 1998c, *Douville et al.*, 1998], as well as in runoff.

2.2. Validation Data

Our validation data for precipitation comes from the *Higgins et al.* [1996a] hourly gridded precipitation data set. We extracted the data for 1985-1993 and calculated simple basin averages from the 2° x 2.5° data, using the grid points that have centers within each ECMWF averaging quadrilateral. The points are shown as small squares in Figure 1. Gauge estimates of precipitation tend to be underestimates [*Groisman and Legates*, 1994; *Groisman et al.*, 1996]. The hourly precipitation data are mostly from Fisher and Porter gauges, which P. Y. Groisman (unpublished manuscript, 1997) estimates to have a 10% low bias for rainfall and a larger low bias for snowfall. Our primary concern is the model liquid hydrology, so we assign a nominal 10% low bias to this precipitation data in summer. The northern basins have significant frozen precipitation in winter, when the Higgins data will have a larger underestimate.

Our validation data for model runoff comes from the daily stream flow records, compiled by the U.S. Geological Survey. Table 1 lists the gauging stations and the corresponding basin drainage areas. We made estimates for four of our subbasins. Our basin 1 is a combination of the Arkansas and Red Rivers. We estimated the upper Mississippi, our basin 3, by differencing the daily stream flow at St. Louis and Kansas City, Missouri, ignoring issues of timing. The ECMWF model does not include a runoff routing model, so we shall only compare model runoff and observed stream flow per unit area on a monthly basis. We do not have runoff comparisons for our basin 5. We have also the measured stream flow at Vicksburg, Mississippi, which is representative of almost the entire Mississippi basin.

Table 1. Stream Flow Basins Used for Comparison

River Basin	Gauging Station	Basin Area km^2	Model Area km^2 (basin)
Arkansas	Van Buren, Arkansas	389,913	
Red	Index, Arkansas	124,397	
Arkansas-Red	*(sum)*	514,210	677,700 [1]
Missouri	Kansas City, Missouri	1,256,656	1,285,700 [2]
Upper Mississippi-Missouri	St. Louis, Missouri	1,805,213	
Upper Mississippi	*(difference)*	548,557	567,700 [3]
Ohio	Metropolis, Illinois	525,765	351,400 [4]
Mississippi Basin	Vicksburg, Mississippi	2,953,996	3,273,000 [1,2,3,4,5]

3. Key Terms in Model Hydrology

On the basin scale, only the model estimates of precipitation and runoff can be validated against measurements, and we will begin with these. The model handles liquid and frozen precipitation differently, so we will use a northern basin to illustrate features of the model frozen hydrology. For the other key processes of evaporation and soil water storage, we have no corresponding basin average observations, so the inferences we make concerning them will necessarily be indirect. We shall find that the model nudging of soil water in the analysis cycle plays a key role in the model liquid hydrology, and it attempts to compensate for other errors in the model.

3.1. Precipitation

We shall show that the model has an erroneous diurnal timescale of precipitation, but that on timescales of 2 days and longer, the model 12-24 FX precipitation matches the observations quite well on the basin scale. We shall use the diurnal cycle to illustrate the model spin-up between the 6 hour analysis cycle and the 12-24 hour forecast.

3.1.1. Diurnal timescale. *Betts et al.* [1998c] showed for the Arkansas-Red River basin that on the diurnal timescale the ECMWF summer precipitation matches the observations poorly, because the model has a convective precipitation maximum near local noon.

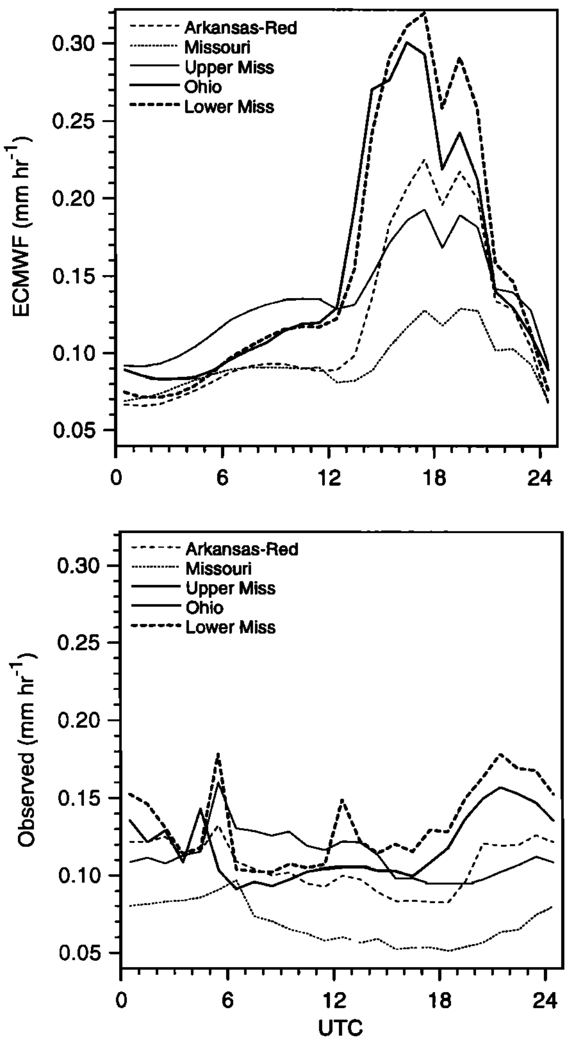

Figure 2. Diurnal cycle of precipitation in warm season (March to September): (top) ECMWF model 12-24 FX; (bottom) Higgins observations.

Figure 2 shows that this is true for all basins in the warm season, defined here as March to September. The top panel shows the diurnal cycle of the model 12-24 FX precipitation (we have repeated the 0.5 UTC value at 24.5 UTC for convenience). All basins have a peak near 1800 UTC (close to local noon), exactly the time when the observed precipitation is near a minimum. The observed warm season diurnal cycles, from the Higgins data shown below, are quite different. Most basins have a late-afternoon convective precipitation peak as well as peak near midnight (0600 UTC), and some basins have another peak near sunrise [*Higgins et al.*, 1996a], none of which are reproduced by the model. We believe this model convection peak near local noon is linked to an erroneous late-morning maximum (1600-1700 UTC) in the diurnal cycle of boundary layer mixing ratio [*Betts et al.*, 1998a]. Despite this large diurnal error in the model, on timescales longer than a day, the bias between the model 12-24 FX precipitation and the observations is quite small for all basins (see Figures 6 and 7 later).

Figure 3 shows that in the cold season, defined here as October to March, when large-scale precipitation dominates, the diurnal cycle in the model agrees much better with the observations, although the model does not capture the sharp precipitation maxima observed near local midnight. The Higgins observations from recording rain gauges greatly underestimate snowfall in winter, and not surprisingly, the model precipitation in winter is much larger than the observations for the Missouri and upper Mississippi. To assess this snow fraction, we also show model rainfall for these two northern basins, labeled R; which agree much more closely with the observations. Here it is likely that the model gives the better estimate of total winter precipitation for these northern basins, when about 40% falls as snow (see section 3.6 later).

3.1.2. Model precipitation spin-up. Figure 4 shows the average diurnal cycle for the large-scale precipitation in the analysis cycle (dotted) and the 12-24 FX for the five basins for the cool season, October to February. The dotted curves for the analysis cycle all show large falls at the analysis times of 0000 and 1200 UTC, when there is the most upper air data contributing to the analysis. (We have repeated the 0.5 UTC value at 24.5 UTC to show the 0000 UTC fall at 2400 UTC.) At 0600 and 1800 UTC, when there is less upper air data, the forecast correction is smaller. For each basin, rainfall increases at all times between the 0-6 hour analysis cycle and the 12-24 hour forecast as the model spins up. In the 12-24 hour forecast the drops at 0600 and 1800 UTC disappear, and the drops at 0000 and 1200 UTC are reduced but not eliminated, suggesting that the spin-up of the model large-scale dynamic fields is not complete.

Convective-scale precipitation has a somewhat different spin-up signature (not shown) The spin-up is most visible at 1200 and 1800

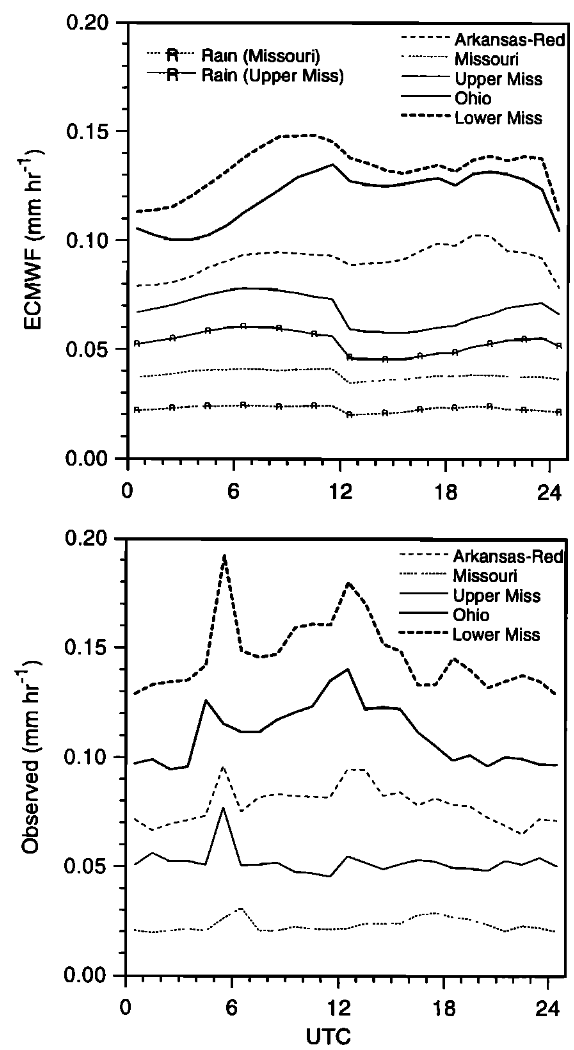

Figure 3. As Figure 2 for cool season precipitation (October to March).

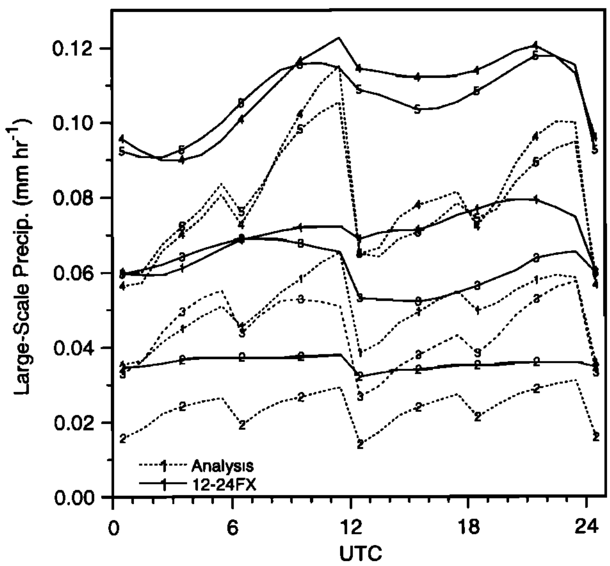

Figure 4. Spin-up of model large-scale precipitation between analysis cycle and 12-24 hour forecast for the cool season (October to February).

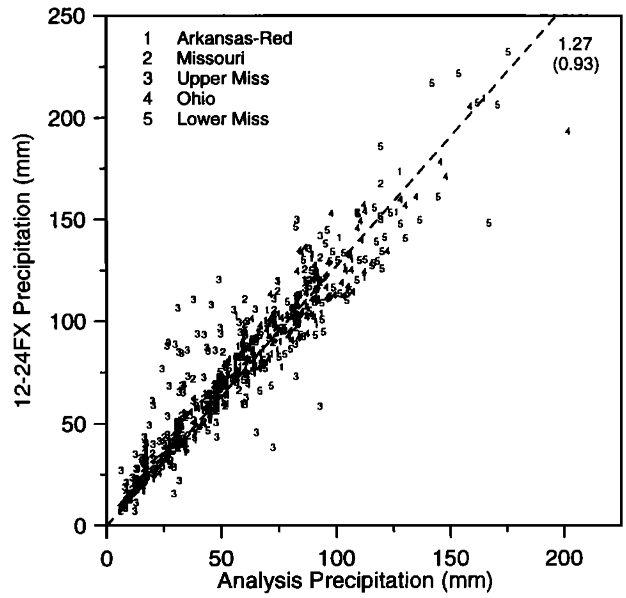

Figure 5. Monthly 12-24 FX total precipitation plotted against the analysis precipitation.

UTC, the time of the spurious model peak of convective precipitation shown in Figure 2. The 1200 UTC drop disappears in the 12-24 FX precipitation, while that at 1800 UTC remains (as in Figure 2) but is reduced in magnitude.

Table 2 summarizes this spin-up in the convective, large-scale, and total precipitation in the model in terms of the ratio of the 12-24 FX precipitation to the 0-6 hour analysis cycle precipitation for the annual average precipitation. The spin-up of large-scale precipitation is significantly larger (a mean of 1.38) than the convection spin-up (1.19), so the spin-up of the total precipitation is 1.30 in the mean. The spin-up is largest for the most northwestern and driest basin, the Missouri, and least for the lower Mississippi, basin 5. In the cool season, most model precipitation is large scale. In contrast, in the warm season, convective and large-scale precipitation is comparable for all basins. Consequently, the spin-up of the model precipitation is greater in winter than in summer.

Figure 5 shows the relatively small scatter of the monthly 12-24 FX total precipitation against the analysis precipitation. The dashed line is the regression fit through the origin to all the data from all basins. It has a slope of 1.27 and an R^2 coefficient of 0.93. In the following sections we will compare the 12-24 FX precipitation with the Higgins observations on the 2 day and monthly timescales. On these timescales longer than the diurnal, model and observed precipitation have a closer relationship, but there are some noticeable interbasin and seasonal differences.

Table 2. Ratio of 12-24 FX Precipitation to Analysis Precipitation: Model Spin-Up

Basin	Convective Precipitation	Large-Scale Precipitation	Total Precipitation
Arkansas-Red	1.18	1.39	1 29
Missouri	1.22	1.50	1.40
Upper Mississippi	1.17	1.38	1.30
Ohio	1.24	1.31	1.28
Lower Mississippi	1.15	1.32	1.24
Mean	1.19	1.38	1.30

3.1.3. Two-day precipitation comparison. Figure 6 has six panels, showing the 2 day total 12-24 FX precipitation from the ECMWF reanalysis against the corresponding basin averages from the *Higgins et al.* [1996a] gridded data for the five Mississippi subbasins and the whole Mississippi basin. The regression lines through the origin are shown dashed, together with their slope and R^2 correlation coefficient in parentheses. For three basins the 12-24 FX precipitation is 6-18% greater than the observed precipitation, which probably has a 10% low bias in summer (and a larger low bias for winter snowfall). The drier Missouri basin, which has the largest spin-up (1.40, see Table 1), has the largest slope (1.35), and the wetter lower Mississippi, which has the smallest spin-up (1.24), has the smallest slope (0.93). For the whole Mississippi basin (bottom right) the correlation coefficient is high, and the standard error is quite small, only 1.4 mm for this regression of 2 day data.

3.1.4. Monthly precipitation comparison. Figure 7 shows the corresponding panels for the monthly precipitation, and we have split the data into two subgroups, cold season (October to February, solid circles and solid regression line) and warm season (March to September, open circles and dotted regression line). The cold season correlation coefficients, when large-scale precipitation dominates, are all higher than warm season, when convective precipitation is comparable to large-scale precipitation. For the Missouri and upper Mississippi, which have the highest winter snowfall fraction (see Figure 13, later), the winter slopes are higher than the warm season, which is consistent with the observations having a higher underestimate of snowfall. These basins have less winter than summer precipitation. For the lower Mississippi (and Tennessee) the cold season precipitation, dominated by large-scale precipitation, is considerable. The model forecast precipitation for this basin is less than the observations (slope 0.9), perhaps because the model spin-up of the large-scale fields is not complete at 12 hours (Figure 4). The Ohio shows a somewhat similar structure. In the warm season, 12-24 FX precipitation exceeds observations for

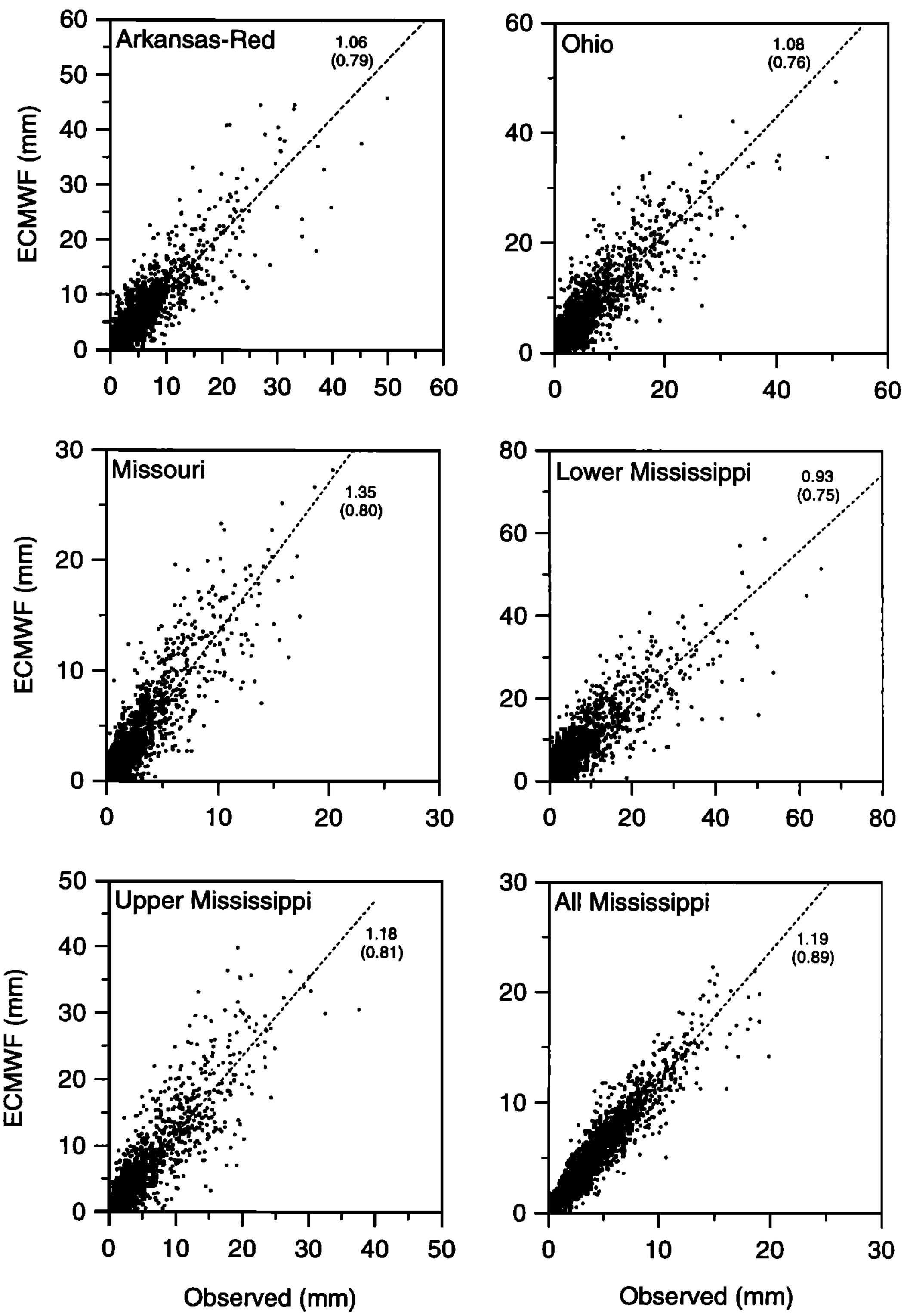

Figure 6. Two-day ECMWF 12-24 FX precipitation for Mississippi and five subbasins against *Higgins et al.* [1996a] gridded observations.

all basins, but the correlation with observations for Ohio and lower Mississippi is poorer than for the western basins. For the entire Mississippi basin the R^2 correlation of monthly forecast precipitation with observations is over 90%, and the standard error is quite small, 4.5 mm in the cold season and 7.6 mm in the warm season. The slopes of 1.25 in the warm season and 1.16 in the cold season, when the model spin-up is probably incomplete, are rather small. Since the Higgins precipitation observations are probably biased 10% low, this means that on timescales longer than the diurnal (Figures 6 and 7) the model 12-24 FX precipitation may only be about 10% high. In conjunction with Figure 5 it also appears that the analysis precipitation is about 20% too low, if

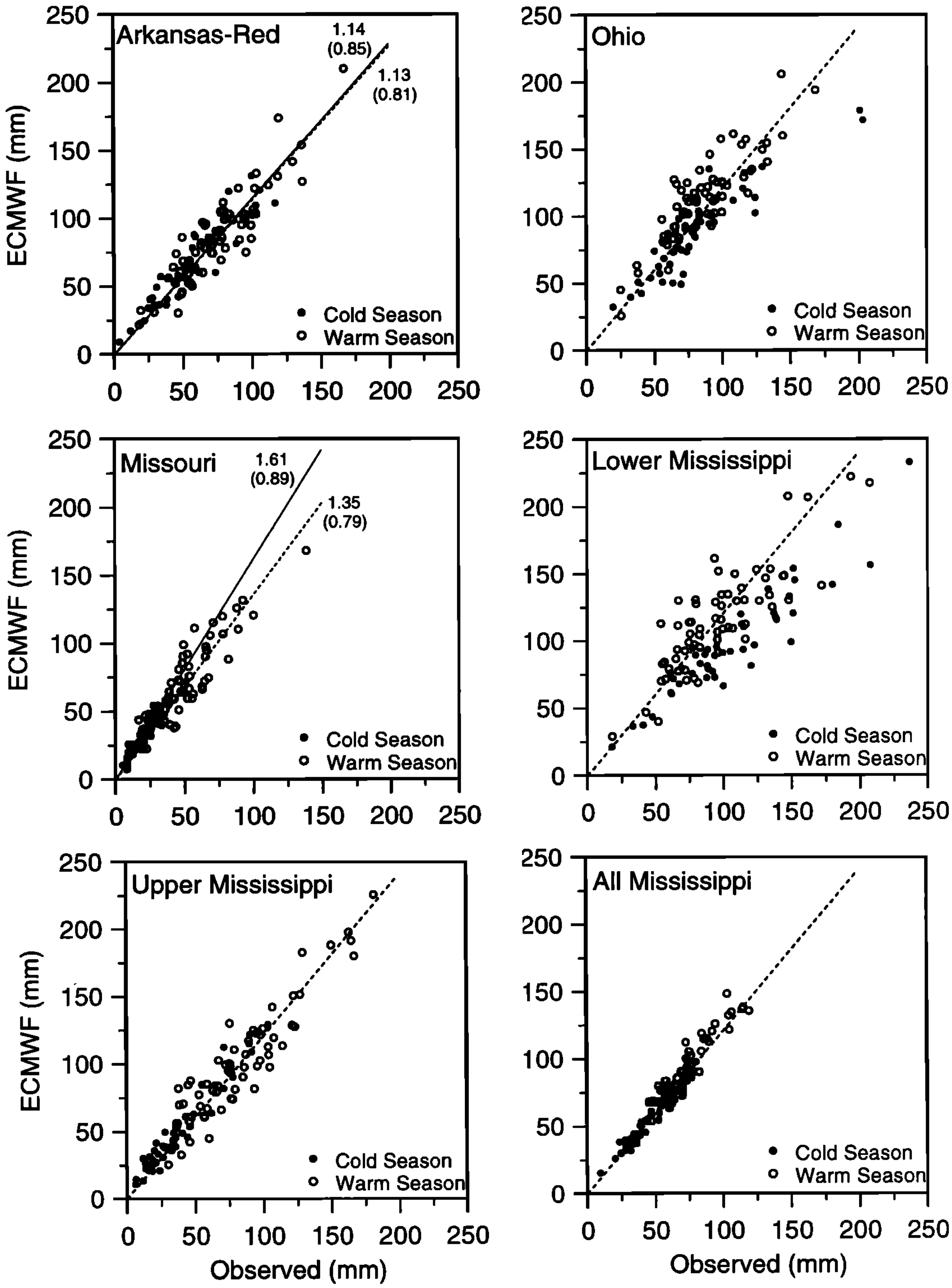

Figure 7. Monthly ECMWF 12-24 FX precipitation for Mississippi and five subbasins against *Higgins et al.* [1996a] gridded observations.

compared to corrected observations. Despite the errors of the model convective precipitation on the diurnal timescale, these comparisons with observations on longer timescales are very encouraging.

3.2. Runoff and Stream Flow

Figure 8 compares the seasonal cycle of the 9 year average model runoff with the corresponding observed stream flow (both in mm month^{-1}) for the Arkansas-Red Rivers, the upper Missouri, the upper Mississippi, and the Ohio. Although the model runoff does increase from the dry Missouri basin to the Ohio, the model runoff has no spring or fall runoff peaks, so on an annual basis, the model runoff is only a third to a half of the observed stream flow. This is a clear model deficiency, which is related to the fact that the model runoff is all drainage from the deep soil layer. This deep runoff increases exponentially as the soil water in the model base layer (100-289 cm)

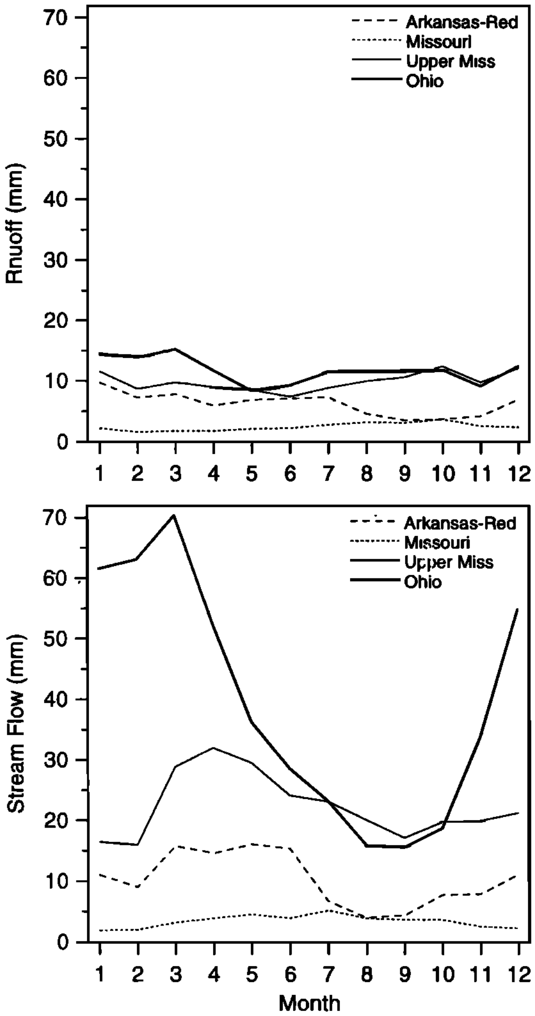

Figure 8. Comparison of monthly average (1985-1993) ECMWF runoff (top) and observed stream flow (bottom) for four subbasins of the Mississippi.

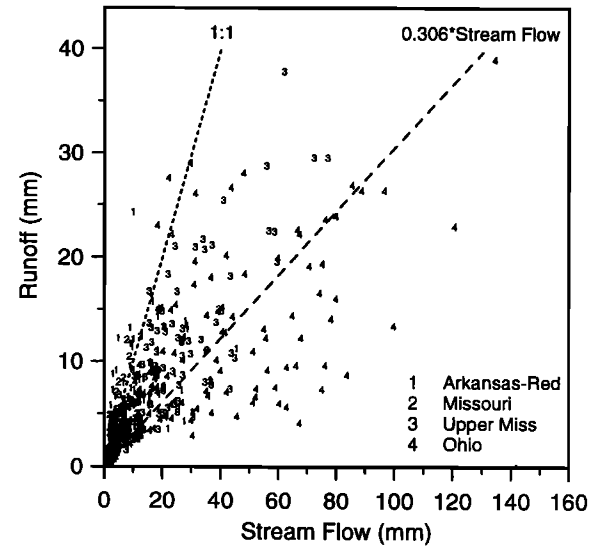

Figure 9. Scatterplot of monthly ECMWF runoff against monthly stream flow.

approaches a threshold value. The surface runoff model is hardly ever activated, because of an inadequate representation of sub-grid-scale precipitation. Figure 9 shows the scatterplot of monthly runoff against stream flow. For reference, the 1:1 line is shown dotted, indicating that in the 9 years of data, runoff exceeds stream flow in very few months. The regression line through the origin with slope equal to 0.31 is shown dashed: it is a poor fit with an R^2 correlation coefficient of only 0.37. The model has no routing scheme for runoff, but runoff does lag surface precipitation by a few weeks, because of the time it takes for the soil water to drain through to the base model layer.

This lack of model runoff is most significant for the Ohio basin, which has the largest cool season stream flow. This error is partly compensated in the model by an increase in the removal of soil water by the nudging scheme in the analysis cycle (see next section).

3.3. Contribution of Nudging to Subsurface Hydrology

The nudging of soil water plays an important role in the model liquid hydrology [*Betts et al.*, 1998c]. Figure 10 shows the 9 year mean seasonal cycle of the nudging term for the five basins, which all show a large summer peak and negative values in winter, early spring, and fall. This nudging was designed to control long-term drifts in soil water and is based on the q analysis increment in the short-term 0-6 hour forecast for the lowest model level mixing ratio, as discussed in section 2. However, it is clear from *Betts et al.* [1998c] and *Douville et al.* [1998] that the nudging attempts to compensate for other model errors, and indeed the mean structure of the nudging is a good indicator of other error signatures. We believe the large annual cycle shown in Figure 10 represents in part a projection of an evaporation error in the model onto the nudging, caused by the lack of a seasonal cycle in the model. In winter, spring, and fall, when evaporation is less than precipitation, evaporation in the model is probably too high, and the nudging is trying to compensate for this by removing soil water. In summer, when precipitation is low, evaporation is too low in the model and nudging supplies a lot of soil water. The large underestimate of cool season runoff for the Ohio, shown in Figure 8, is probably the cause of the negative displacement of the nudging curve for the Ohio (as well as for the lower Mississippi and Tennessee): the nudging is removing part of the water, which in reality runs off. Consequently, the contribution of nudging is near zero on an annual basis for the Ohio, whereas nudging is supplying ~120 mm yr^{-1}

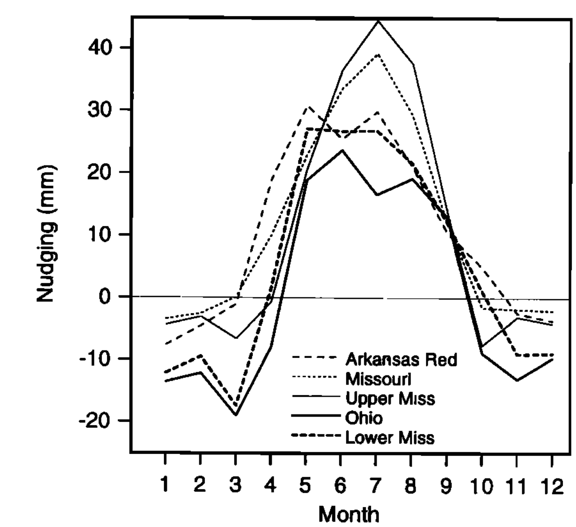

Figure 10. Nine year mean annual cycle of the nudging term for the five subbasins.

Table 3. Nine Year Mean Hydrology Balance for Five Subbasins

Basin	1	2	3	4	5
Rain (12-24 FX)	918	545	881	1176	1277
Rain (analysis)	712	396	685	919	1029
Melt	3	8	5	2	1
Runoff (-)	-75	-30	-119	-141	-182
$Evap_{liquid}$	-770	-508	-700	-779	-910
Nudging	123	136	124	7	60
Δ(soil water)	-8	2	-5	8	-2
Snowfall (12-24 FX)	33	83	71	52	19
Snowfall (Analysis)	22	53	47	38	13
Melt (-)	-3	-8	-5	-2	-1
$Evap_{snow}$	-8	-30	-44	-29	-11
Residual	11	14	-3	7	2
Precipitation (12-24 FX)	951	628	953	1228	1295
Precipitation (analysis)	735	449	732	957	1042
Higgins	827	434	773	1005	1211
Runoff	75	30	119	141	182
Stream flow	124	41	268	474	--

Units in millimeters year^{-1}.

(about 17% of evaporation) for the Arkansas-Red and upper Mississippi basins, and 136 mm yr^{-1} (27% of evaporation) for the drier Missouri basin (see Table 3).

3.4. Mean Annual Cycle for the Mississippi

Figure 11 shows the 9 year mean annual cycle for the entire Mississippi basin. The top three curves are all precipitation estimates. The dotted curve is from the analysis cycle, the thin solid curve is from the 12 to 24 hour forecast, and the precipitation from the *Higgins et al.* [1996a] gridded data is shown as a thick solid line. The three curves track quite well. If the observed precipitation is corrected for a probable 10% low bias, it lies roughly midway between the model analysis and 12-24 FX precipitation. The small model runoff (with little seasonal variation) and the large total evaporation (of liquid and snow) are both plotted negative. The 9 year mean stream flow at Vicksburg for the Mississippi as a whole (long dashed) exceeds the model runoff in all months. In summer, the nudging (short dashed) is a large positive contribution to the liquid hydrology, supplying about 30% of the evaporation, while in winter the nudging is small and negative, as shown in Figure 10.

3.5. Interannual Variability of Liquid Hydrology

We will now show the interannual variability of the key terms in the model liquid hydrology, given in equation (2). This budget involves rainfall rather than total precipitation: the only contribution of snowfall to the liquid budget is through a snowmelt term. This term is very small even for the northern basins (less than 10 mm yr^{-1} and typically reaching about 5 mm month^{-1} in spring), and we will not show it here.

The top panel in Figure 12 is the time series of monthly rainfall in the analysis cycle. The tick marks on the x axis mark the beginning of each month and the long ticks the beginning of each year; while the monthly data are plotted at points corresponding to the middle of a month. It is clear from Figures 5, 6, 7, and 11 that the ECMWF model gives a realistic interbasin and interannual variability of precipitation and summer rainfall, although the analysis precipitation is biased low because of the model spin-up. The dry year of 1988 is clearly visible, as is the following wetter year of 1989, and the high summer rainfall in 1993 on the upper Mississippi and Missouri Rivers. The second panel shows the model runoff, which too has a considerable interannual variability, coupled to the rainfall, although as we have shown earlier, considerably less than the observed stream flow. The middle panel is the model (liquid) evaporation, which appears to vary in a realistic way between dry and wet basins, and dry and wet years. We would like to be able to assess both the absolute accuracy and the relative variability of the model evaporation, but this is not easy, because of the magnitude of the model nudging, shown in panel 2 from the bottom. The nudging also has significant interannual variability, as well as the annual cycle shown in Figure 10. The nudging is greater in the dry year of 1988 than the wet summer of 1993. In fact, in dry summer months, more than half the evaporation is being supplied by the nudging term, which was certainly not anticipated when nudging of soil moisture was introduced into the analysis cycle to constrain long-term drifts. Contrast, for example, the upper Mississippi and Missouri Rivers for the dry year of 1988 and the wet year of 1993. Runoff is low in 1988 for both basins in summer, and the nudging is comparable to rainfall. In the extreme month of June 1988 for the upper Mississippi, the nudging is supplying two thirds of the water used for evaporation, which is clearly unrealistic. The evaporation may of course be too high, but it is also likely that the model has insufficient reserves of soil water (or does not draw sufficiently on its deep soil water) to provide evapotranspiration during extended droughts. In contrast in the wet summer of 1993, evaporation increases to about 120 mm month^{-1} for the upper Mississippi, runoff

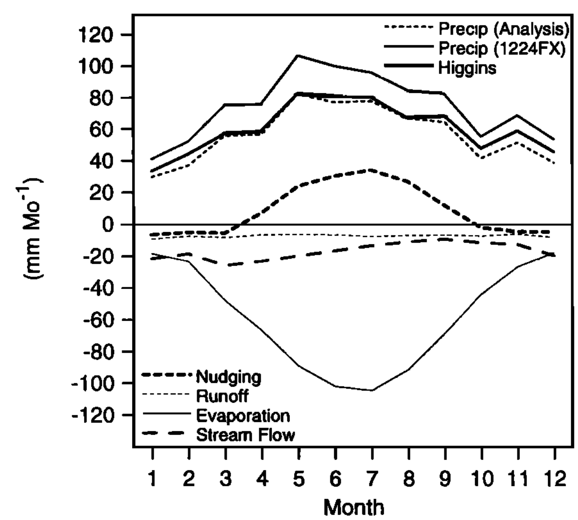

Figure 11. Nine year mean annual cycle of precipitation, total evaporation, runoff, stream flow, and nudging term for the entire Mississippi basin.

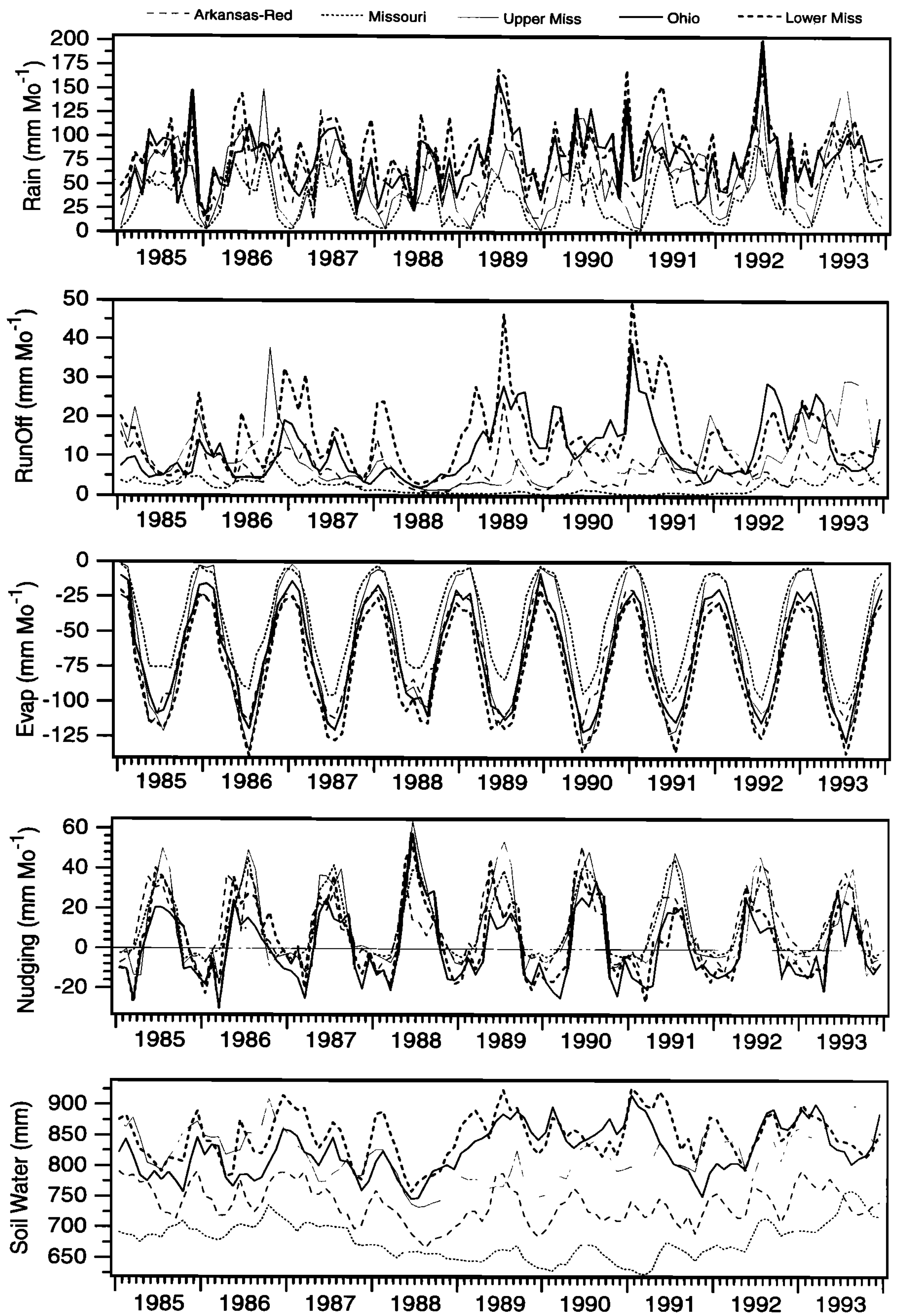

Figure 12. Interannual variability of the model liquid hydrology, showing rainfall, runoff, evaporation, nudging, and total column soil water.

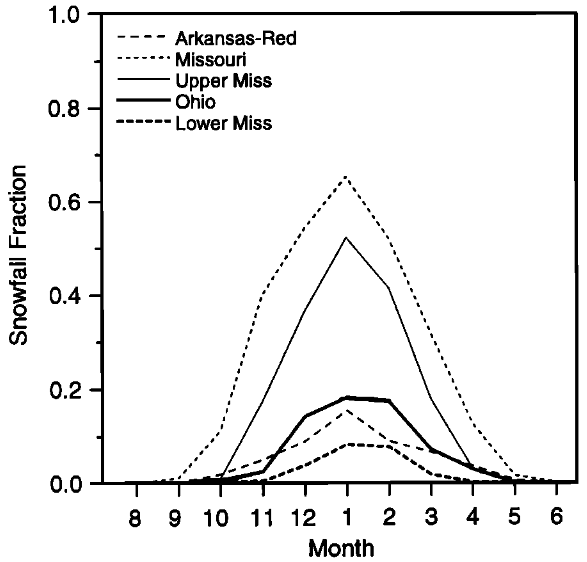

Figure 13. Mean fraction of precipitation falling as snow in the ECMWF model for the five subbasins.

increases to 30 mm month^{-1}, and the model nudging plays a much smaller relative role in the model hydrology.

The bottom panel shows the time series of total column soil water for the five subbasins. The model maintains significant interbasin differences between the dry Missouri and the much wetter Ohio and lower Mississippi, and between wet and dry years. The interannual variability of about 100 mm is as large as any annual cycle. We suspect but cannot prove that the nudging, which itself has a strong annual cycle and an interannual variability, is damping the variability of soil water. If true, this is important because evaporation in the model is strongly coupled to soil water (see section 4) through the evapotranspiration calculation. However, since the nudging both responds to (it is calculated from short-term forecast errors in mixing ratio at the model level about 30 m above the surface) and is linked to errors in the evaporation algorithms [*Betts et al.*, 1998c)], we cannot draw definitive conclusions.

3.6. Frozen Hydrology for the Upper Mississippi Basin

The frozen hydrology budget in the model is distinct from the liquid hydrology budget discussed in the preceding sections. Figure 13 shows the 9 year mean monthly fraction of frozen precipitation in the model 12-24 hour forecast. From December to February it is about 50% for the more northern Missouri and upper Mississippi basins, while it is less then 20% for the other three basins. Given the relative accuracy of the model precipitation estimates, and the difficulty of measuring winter snowfall, these model estimates of snow fraction on the basin scale may be more accurate than any based on observations.

However, as mentioned earlier in section 2, the frozen budget in the ECMWF model is not a closed one, because an independent snow analysis is introduced at each analysis time based on observations of snow cover and snow depth, where available, otherwise on a climatology. Nonetheless, for the northern basins its realism is of interest, as a new snow model is under development. Figure 14, an average for the eight winters from 1985-1986 to 1992-1993 for the upper Mississippi basin, shows the terms in the model snow budget on the left-hand scale. Analysis snowfall (thick solid) is around 10 mm month^{-1} in winter. This is almost balanced by snow evaporation (long dashed), which is much larger than the melt term (short dashed). Both are plotted negative because they

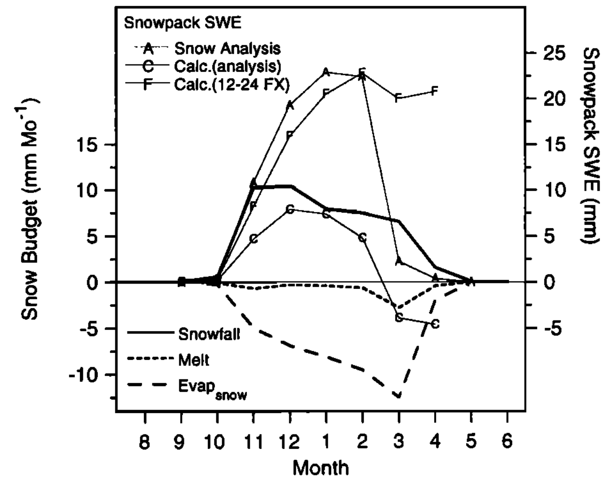

Figure 14. Mean annual cycle of the model frozen hydrology for upper Mississippi basin.

represent a loss of snow. On the right-hand scale we show three estimates of snow pack snow water equivalent (*SWE*) at the end of a month. The thin solid line labeled A is the basin-averaged *SWE* from the independent snow analysis. The similar line labeled C is calculated by accumulating the sum of the model snow budget terms shown (Snowfall(analysis) + $Evap_{snow}$ + Melt]. The *SWE* calculated from this model budget is much less than the independent snow analysis. It also does not close over the season, because the evaporation and melt of snow exceed analysis snowfall over the winter. However, the spin-up of the model winter precipitation is quite large because it is dominated by the large-scale spin-up, which is 38% for this basin (Table 2). The third *SWE* curve labeled F is calculated by summing the terms [Snowfall(12-24 FX) + $Evap_{snow}$ + Melt]. This gives a much greater snow pack, since there is about 25 mm more snow (as *SWE*) over the winter in the 12-24 hour forecast than in the analysis cycle. Again, the budget does not close over the winter, because now 12-24 FX snowfall exceeds evaporation and melt of snow over the season. The difference between the *SWE* curves labeled C and F in spring suggests that a reduction in the model spin-up is needed before the frozen

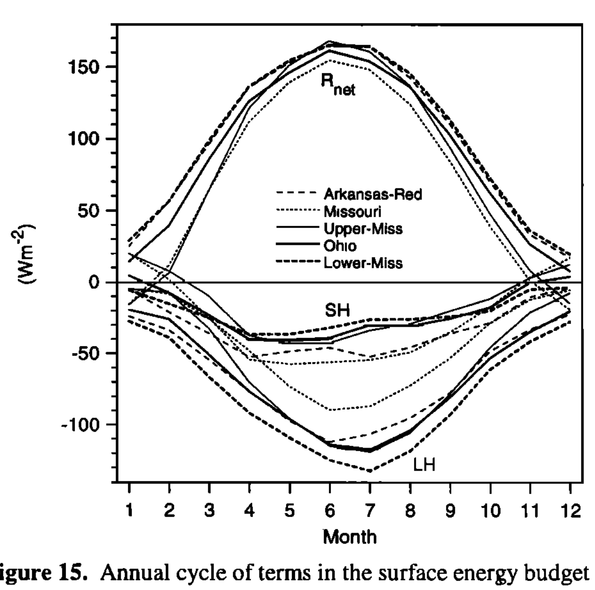

Figure 15. Annual cycle of terms in the surface energy budget for the five subbasins.

hydrology in the model can be satisfactorily closed. Otherwise, some term analogous to the nudging of soil water may have to be introduced into the frozen hydrology to maintain snow depth in winter, or the independent snow analysis maintained. We cannot assess the accuracy of the snow evaporation term. The reanalysis model has a significant error in the albedo of forested regions with snow (see section 4), which may impact this northern basin. The melting of snow, however, contributes only about 5 mm yr^{-1} to the liquid hydrology budget, which seems too low, and another possible cause of the low spring runoff in the model.

3.7. Summary of Liquid and Frozen Hydrology

Table 3 summarizes by basin, for comparison with other model studies, the terms in the 9 year average of the ECMWF model liquid and frozen hydrology, together with the corresponding Higgins precipitation and the stream flow for four of the subbasins. The long-term changes of column soil water are small. The residual in the frozen hydrology budget, which is not closed, is the sum of the snowfall (analysis), melt, and evaporation of snow terms.

4. Seasonal Surface Energy Balance

Figure 15 shows for the five basins the 9 year mean annual cycle of net radiation (net), sensible heat (SH) flux and latent heat (LH) flux, the key components of the surface energy balance. The effect of latitude can be seen as R_{net} goes negative in winter for the two northern basins. We have no basin-scale validation data for the ECMWF radiation fluxes. A time series comparison at a grassland site in Kansas has shown little net radiation bias in summer but a small negative bias in the ECMWF model in the fall [*Betts et al.*, 1998a]. However, a similar comparison over the boreal forest in Canada [*Betts et al.*, 1998b)] showed that while the summer R_{net} bias was small, the ECMWF reanalysis model had a large R_{net} bias in winter and spring, when the ground was snow covered, because the model assigned the same high albedos (of 0.8) to forests as to grassland. We would expect this error to bias the model R_{net} low in winter and spring for the northern basins, which have significant snow and forest cover.

In summer, LH exceeds the SH flux for all basins in the mean. The trends in summer of the SH and LH appear realistic, from the drier Missouri basin with the highest SH and lowest LH (thin dotted curves) to the wet lower Mississippi basin, with the lowest SH and highest LH flux (thick dotted curves). The SH trend in winter reflects the latitudinal change in R_{net} and the evaporation trend the gradient of temperature (not shown). Again, we do not have basin-scale estimates of the surface fluxes to assess this partition of the surface energy balance in the model. The grassland comparison [*Betts et al.*, 1998a] showed that the ECMWF reanalysis model tracked well the summer daytime evaporative fraction (EF= LH/(LH+SH)), with a small low bias in spring and high bias in fall, perhaps because the model has no seasonal vegetation cycle. The model also had a high EF immediately after rain. However, a similar comparison over the boreal forest in Canada [*Betts et al.*, 1998b] showed that in addition to a large error in spring, resulting from the R_{net} error mentioned above, the reanalysis model had a much higher EF than the dominant coniferous forest species in summer,. The model has only a single unstressed vegetative resistance, with a value which was based on grassland rather than forest data [*Viterbo and Beljaars*, 1995]. Since coniferous forests are one landscape component of the northern subbasins, this bias may be present.

Betts et al. [1998c] found an inconsistency between the surface energy and water budgets, coming from an approximation made in the calculation of the evaporation of intercepted water. The consequence is that the basin-averaged latent heat flux in the atmospheric surface energy budget is higher than the liquid evaporation in the subsurface hydrology. This error is about 4% in winter, rising in summer to 5% for the dry Missouri basin and as high as 10% for the lower Mississippi basin.

4.1. Coupling of EF and Soil Water in Model

Figure 16 (top) shows the close coupling of EF in the model and SW1, the 0-7 cm volumetric soil water. The data points are 5 day averages during the summer months of June to September, 1985-1993. We show the summer months to minimize the impact of the rise of EF with increasing temperature. The partition of the net radiation into sensible heat and evapotranspiration in the model is primarily modulated by the dependence of vegetative resistance on root-zone soil water [*Viterbo and Beljaars*, 1995]. The 0-7 cm soil water variations shown are well correlated with those of the 0-100 cm root zone.

4.2 Coupling of Soil Water and Lifting Condensation in Model

Another consequence of the coupling of EF to soil water in the model is the correlation between the 0-7 cm soil water and the pressure height to the lifting condensation level (P_{LCL}), shown in the

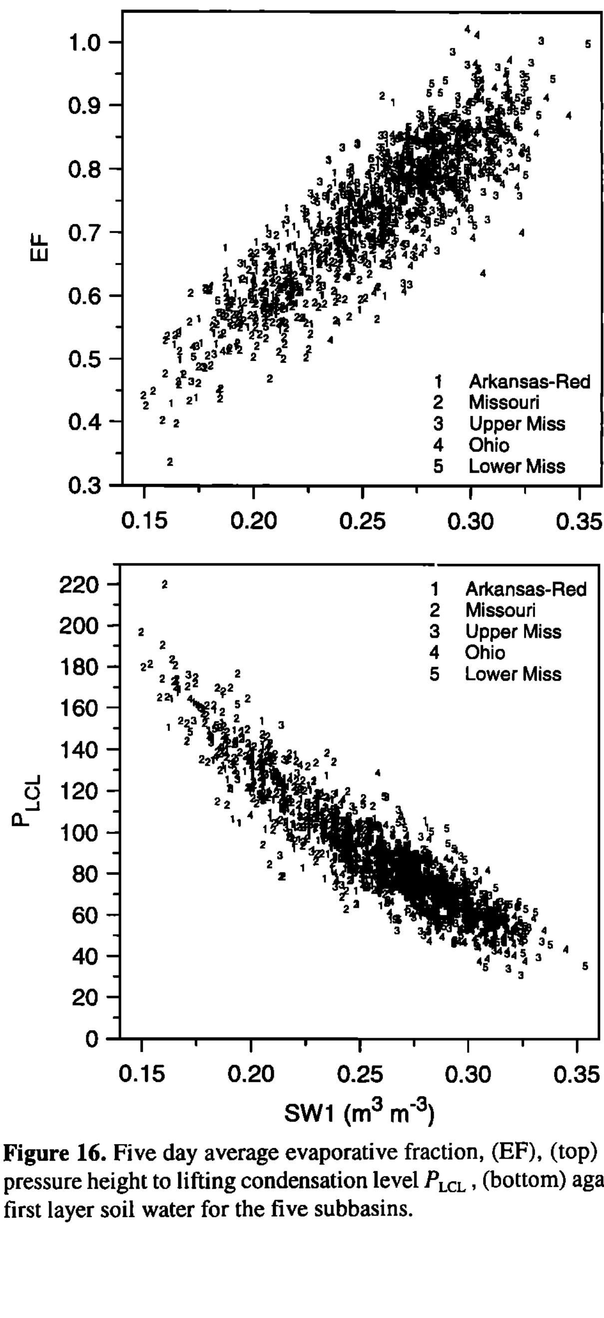

Figure 16. Five day average evaporative fraction, (EF), (top) and pressure height to lifting condensation level P_{LCL}, (bottom) against first layer soil water for the five subbasins.

bottom panel of Figure 16. This relationship, which is not a strong function of temperature (and is therefore a little tighter than the dependence of EF on SW1), is valid across the whole range of soil water from the driest conditions in the Missouri basin (labeled 2) to the wettest conditions in basins 3, 4, and 5. This is an important relationship over land, which arises because the vegetative resistance causes a drop of saturation between the inside of the (model) leaf and the outer surface, which is in contact with the atmosphere. This is the link between surface evaporation and cloud and boundary layer processes. *Betts and Ball* [1998] showed, using field data, that at warmer temperatures, high soil water is correlated both with low P_{LCL} and with high equivalent potential temperature, θ_E, so wet soils favor moist convection.

5. Conclusions

This analysis of the surface hydrologic and energy balance of the five subbasins of the Mississippi River provides basin-scale estimates of the surface energy and hydrologic balance from the ECMWF model and confirms and extends the conclusions of our earlier study [*Betts et al.*, 1998c]. The ECMWF model has a reasonable diurnal cycle of large-scale precipitation in winter but an erroneous diurnal cycle of convective precipitation in summer. The model has a near-noon precipitation maximum in summer and does not show the observed evening and nocturnal rainfall maxima. This error is probably linked to the model error in the diurnal cycle of mixing ratio, which has a spurious midmorning peak [*Betts et al.*, 1998a]. The model has a significant spin-up of precipitation between the analysis cycle (a 0-6 hour forecast) and the 12-24 hour forecast, ranging from 24 to 40% (for the dry Missouri basin). The model spin-up of large-scale precipitation is larger (30-50%) than that of convective precipitation (15-24%), and there is evidence that the model large-scale fields have not reached equilibrium at 12 hours forecast time. The variability of precipitation on the 2 day and monthly timescales, however, is well reproduced by the model. Our main verification, the *Higgins et al.* [1996a] precipitation data, shows that while the model analysis precipitation is low, the model 12-24FX precipitation values generally exceed the observations. If we allow for the observations being biased low by perhaps 10%, it seems likely that the 12-24 hour forecast precipitation is accurate to about 10-20% for monthly averages. In contrast, the model runoff, when compares to observed stream flow, is too low on an annual basis. All the model runoff is deep drainage (there is no surface runoff), and the Spring runoff is almost entirely missing in the model.

The nudging of soil water, which was introduced to control long-term drifts in soil water plays an important role in the model liquid hydrology. It has a large mean seasonal cycle: all five basins show a positive summer peak and negative values in winter, early spring, and fall. It appears that the nudging, while providing water missing because of the low rainfall in the analysis cycle, also attempts to compensate for other model errors, such as in the formulation of evaporation and runoff. Indeed, the mean structure of the nudging is a good indicator of other error signatures.

It is clear that the ECMWF model gives quite realistic interbasin and interannual variability of precipitation and summer rainfall, even though the analysis precipitation is biased low because of the model spin-up. The interbasin differences of soil water appear realistically linked to precipitation, and they feedback on the model evaporation and lifting condensation level height, as these processes are linked to soil water in the model through a soil water dependent vegetative resistance. However, on the basin scale we have no validation data for the model evaporation. Because the nudging of soil water plays such an important role in the liquid hydrology of the model, we cannot assess how much of the variability in model soil water on timescales longer than a month is realistic, as again on the basin scale, we have no validation data.

In winter, when the observations greatly underestimate snowfall, it is likely that the model 12-24 hour precipitation is a better estimate than the observations. The model estimate of the fraction of frozen precipitation may also be useful. However, the frozen hydrology in the model is not conservative and needs improvement. A new snow depth analysis is introduced at each analysis time, based on observations and climatology. The alternative of calculating snow depth from the model snowfall is, however, rather sensitive to the spin-up of the model large-scale precipitation in winter. Snowmelt is very small and contributes very little to the soil water in spring. These processed hourly data sets for the Mississippi subbasins are available from the first author for further GEWEX analyses.

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