NCEP–NCAR and ECMWF Reanalysis Surface Water and Energy Budgets for the Mississippi River Basin

JOHN ROADS

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California

ALAN BETTS

Pittsford, Vermont

(Manuscript received 15 March 1999, in final form 12 July 1999)

ABSTRACT

Surface water and energy budgets from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses are compared here with each other and with available observations over the Mississippi River basin, which is a focus of the Global Energy and Water Cycle Experiment Continental-Scale International Project. There are a number of noticeable differences and similarities in the large-scale basin averages. The NCEP–NCAR reanalysis seasonal precipitation and runoff are larger than the available observations; presumably, evaporation and surface water variations also are too large. The ECMWF reanalysis precipitation is much closer to the observations, whereas the corresponding surface runoff and seasonal surface water variations are too small. The NCEP–NCAR and ECMWF reanalysis seasonal energy components are more similar to each other. The NCEP–NCAR and ECMWF interannual variations also are comparable, indicating that these reanalyses probably can be used to begin to study interannual variations. Nonetheless, improved land surface parameterizations are needed to depict surface water and energy processes and, in particular, variations in seasonal surface water and runoff better.

1. Introduction

The process of optimal combination of short-term model predictions with observations, known as four-dimensional data assimilation, is a critical element of weather prediction and climate analysis systems. No observational network can provide, by itself, the comprehensive gridded information needed to initialize numerical models and to develop adequate water and energy budgets. Even those budget quantities that are observed, such as precipitation, are not measured very well, and comparisons between analyses and measurements can yield new insights. Utilization of observed precipitation as part of the analyses also is under development.

Analyses are imperfect, however, since they must rely on imperfect models to augment the scarce observations. One of the major problems for climate studies is that these imperfect models constantly are being improved. For example, previous global analyses now are being supplemented by regional analyses (see Berbery et al. 1996; Yarosh et al. 1996). Despite the documentation of improvements in the analysis scheme, discontinuities in the operational record (associated with model changes) impair its usefulness for the study of climate variations. For this reason, data from the recent past are being reanalyzed using current, frozen models to develop a climate record, even though the quality of the data inputs varies with time. Two of the most well-known global reanalyses come from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP–NCAR; see Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF; see Gibson et al. 1997).

Examination of these global reanalyses can highlight characteristic features of the water and energy budgets and point out some of the serious issues that still affect the ability to develop adequate regional budgets. A key objective of the Global Energy and Water Experiment (GEWEX) Continental-Scale International Project (GCIP) was to assess the ability of forecast models to estimate the energy and hydrological balances for the Mississippi River basin, using observations of precipitation and runoff as evaluation data. Studies of the

---

Corresponding author address: Dr. John Roads, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0224.
E-mail: jroads@ucsd.edu

GCIP water and energy budgets have been carried out previously by Betts et al. (1998c, 1999) using the ECMWF reanalysis (hereinafter referred to as ERA) and by Roads et al. (1999) using the NCEP–NCAR reanalysis (hereinafter referred to as NRA). Here these disparate efforts are combined and the large-scale average reanalysis surface water and energy budgets are compared explicitly with each other and with available observations for the Mississippi River basin, which is the focus of GCIP. There are a number of notable differences and similarities in the surface water (section 2) and energy (section 3) budgets, which are discussed below.

2. Surface water

a. Model formulation

The surface water budget can be written as

$$0 = -\Delta W/\Delta t + P - E - N + U. \tag{1}$$

The temporal change in surface water $\Delta W/\Delta t$ (including both soil moisture and snow) is equal to precipitation P minus evaporation (and dew) E and runoff N (which includes the surface and subsurface flow). The last term U is a residual and is discussed below. The surface water includes all subsurface water in the various soil moisture layers and the water in lakes and rivers, which usually is assumed to be a small component of the total surface water component. Model soil moisture actually is archived in nondimensional volumetric format (with the maximum volumetric soil moisture being 0.47), which can be converted easily to total water per unit area by multiplying each volumetric component by the depth of each layer and by the density of water. Lower-level soil moisture turns out to be the dominant component in NRA [which has two soil layers with thicknesses of 10 and 190 cm, respectively (Mahrt and Pan 1984)] for seasonal and interannual variations. ERA has four soil layers with thicknesses of 7, 21, 72, and 189 cm (Viterbo and Beljaars 1995). Since the soil moisture in different model layers in both reanalyses is highly correlated on monthly timescales, and since soil moisture provides the bulk of the surface water in the Mississippi River basin, the moisture in the soil is integrated, the water in the snowpack (which is small) is added and only the total surface water is shown.

Note that there is an artificial surface water forcing term U in the surface water budget that includes both what usually is referred to as a soil water nudging term U_M and a residual U_S in the frozen hydrological budget. As previously discussed by Kanamitsu and Saha (1996), Schubert et al. (1993), and Roads et al. (1998, 1999), there is a tendency for every analysis model to move toward its own climate, which may be unrealistic. The insertion of observations such as atmospheric and surface parameters, or the artificial forcing of parameters toward a specified climate can prevent this drift to an unrealistic climate, but often at the expense of having an unrealistic budget. As discussed by Roads et al. (1998), not only should good analyses have small differences with respect to the available observations, they also should have realistic budgets.

The forcing term U_M was needed in both the NRA and ERA because there was a tendency for the land surface models' soil moisture to dry out. Since drier soil moisture would have an impact on the precipitation and surface temperature [as noted previously by Betts et al. (1996a) and Beljaars et al. (1996)], an adjustment toward an assumed soil water climate (W_c) was made for the NRA reanalysis (as well as for the current NCEP operational analysis). As discussed by Roads et al. (1999), the NRA surface water relaxation time constant is 60 days [$U_M = (W_c - W)/60$] and the assumed soil water climate is the Mintz and Serafini (1992) soil moisture transformed to the volumetric formulation used in the reanalysis model (M. Kanamitsu and H. L. Pan, 1997, personal communication).

Since the reanalyses had a separate snow analysis, it might seem that it would be useful to understand the contribution of U_S to the total U. Since snow only made a minor contribution to the surface water budget in the Mississippi River basin, however, and therefore also to the artificial forcing term, its contribution can be ignored in this location. It may be more important in other places or in future reanalyses that have less of a contribution from the major U_M term.

As discussed by Betts et al. (1998a,c), a somewhat tighter control was developed for the ERA by adding soil water to the model based on the atmospheric moisture analysis increment and the vegetative fraction according to the formula

$$U_W = K\Delta q, \tag{2}$$

where Δq is the atmospheric near-surface moisture analysis increment, and K is related to the inverse time constant multiplied by the vegetative fraction. The correction is taken to be zero over desert regions. If Δq is 3 g kg^{-1} for a completely vegetated surface, then this nudging process adds 0.15 m of water to the first three soil layers (the root zone) in 12 days (Betts et al. 1998a). The ERA surface water budget also is affected by the insertion of a separate snow analysis, which largely is independent of the frozen hydrological tendencies of the ERA model. This analysis introduces a second frozen residual contribution to U for ERA, which is small for the Mississippi basin.

Comparisons of the monthly mean surface hydrologic components for nine years (1985–93) are shown below. Although additional reanalysis years eventually will be available, only these years were readily available from ERA for this comparison; given all the potential NRA and ERA differences, it is important at least to compare consistent time periods. Monthly anomalies from this nine-year mean annual cycle, calculated by subtracting the monthly mean climatological values from the value for each individual month, also were compared. Table

TABLE 1. NCEP–NCAR (NRA) and ECMWF (ERA) reanalyses and observed (OBS) GCIP annual means (1985–93) for the Mississippi basin, and correlations between NCEP–NCAR and ECMWF reanalyses (⟨NE⟩), between NCEP–NCAR reanalyses and observations (⟨NO⟩), and between ECMWF reanalyses and observations (⟨EO⟩). Correlations are calculated from time series that have the climatological mean removed. Shortwave radiation is SW, longwave radiation is LW, sensible heating is SH, latent heating is LH, and Residual is the ground or residual heating. Surface ground temperature is T_S. Precipitation is P, runoff is N, evaporation is E, the artificial surface water forcing term is U, atmospheric moisture convergence is Moist. conv., and the surface water tendency is $\Delta W/\Delta t$. Total surface water W is composed of soil moisture and snow equivalent water.

	NRA	ERA	OBS	⟨NE⟩	⟨NO⟩	⟨EO⟩
SW (W m^{-2})	158.15	154.47		0.82		
LW (W m^{-2})	−71.99	−71.65		0.91		
−SH (W m^{-2})	−10.14	−23.93		0.66		
−LH (W m^{-2})	−72.38	−58.75		0.68		
T_S (K)	282.65	283.20		0.91		
Residual (W m^{-2})	−3.64	−0.14		0.71		
P (mm day^{-1})	2.47	1.86	1.99	0.81	0.74	0.94
N (mm day^{-1})	0.52	0.23	0.55	0.49	0.48	0.79
E (mm day^{-1})	2.50	1.91	1.44	0.68		
U (mm day^{-1})	0.53	0.27		0.44		
W (mm)	558.82	754.07		0.58		
$-\Delta W/\Delta t$ (mm day^{-1})	0.01	0.01		0.48		
Moist. conv. (mm day^{-1})	0.47					

1 provides the annual means for the same variables and also provides the correlation between the monthly time series for the two reanalyses, and those between the precipitation and stream flow observations and each reanalysis. Table 1 also shows that the evaporation in ERA (NRA) is 33% (74%) higher than the estimate of 1.44 mm day^{-1} found by taking the difference of the observed annual precipitation and stream flow. If the precipitation observations are negatively biased by 10% (Higgins et al. 1996), then these estimates of model evaporation bias are reduced to 17% and 53% for ERA and NRA, respectively.

b. Comparison of reanalyses

Figure 1 shows the mean monthly cycle of the terms in Eq. (1) in the surface water budget of the reanalyses. For precipitation and runoff, the observations are included as heavy lines: observed precipitation comes from the gridded analysis of Higgins et al. (1996) and observed runoff is the observed stream flow at the gauge at Vicksburg, Mississippi. The observed stream flow is, of course, affected by water management, but presumably this influence is minor by comparison. That ob-

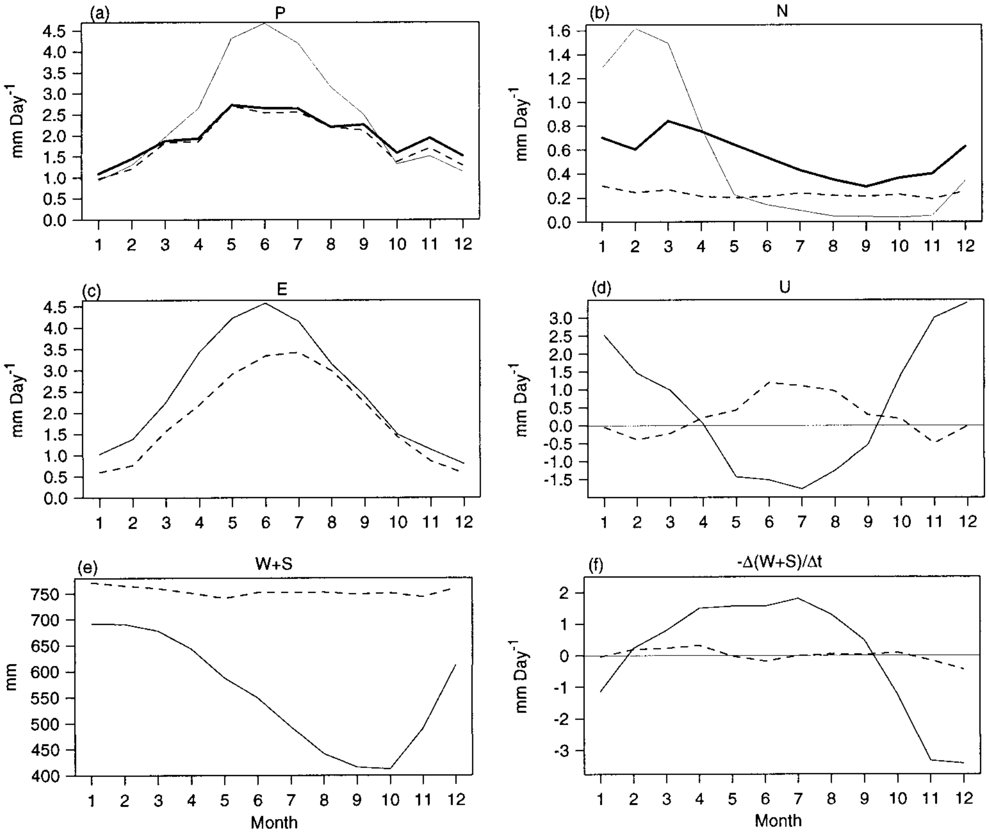

FIG. 1. Seasonal surface water NCEP–NCAR (light solid) and ECMWF (dashed) reanalysis budgets for the Mississippi basin: (a) precipitation (P); (b) runoff (N); (c) evaporation (E); (d) artificial surface water forcing (U); (e) total soil water plus snow (W); and (f) surface water tendency $\Delta W/\Delta t$. In (a) and (b) precipitation and stream flow observations are shown as heavy solid lines.

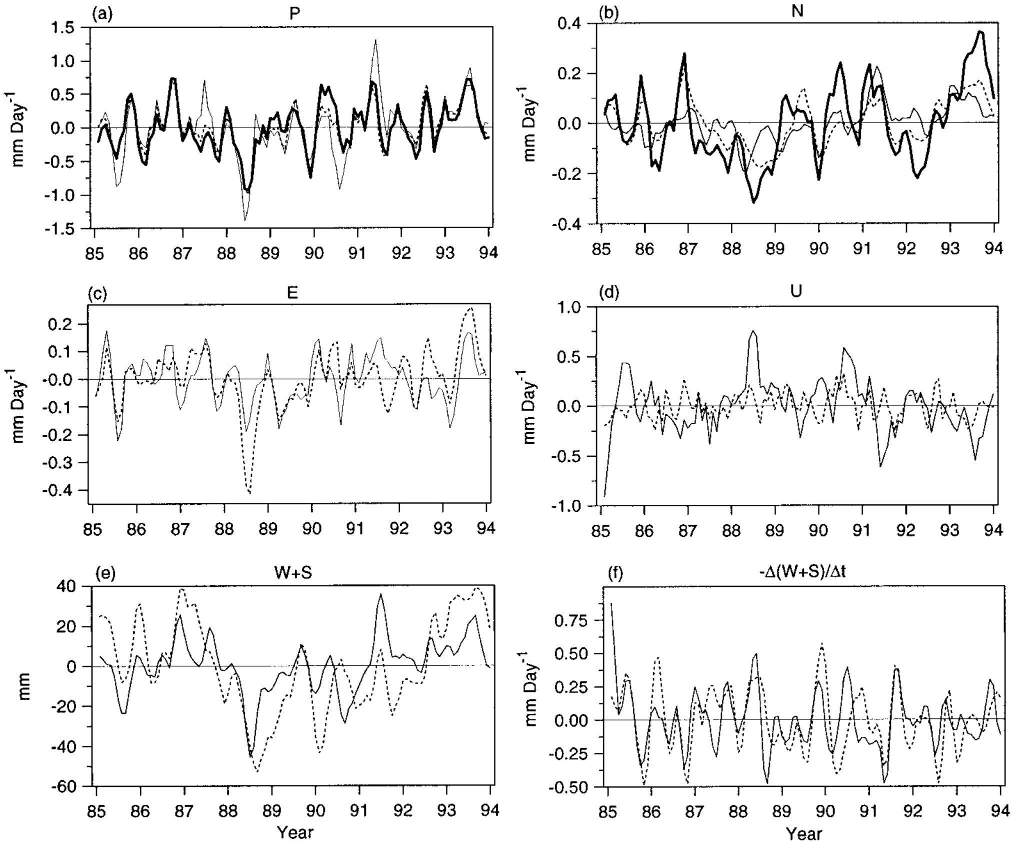

FIG. 2. As in Fig. 1 for monthly anomalies of surface water budget terms (three-month running means for presentation only) for NCEP–NCAR, ECMWF, and observations [(a) and (b) only].

served precipitation also is affected by undercatch is well known. It is our opinion that both of these observed errors are small in comparison to reanalysis errors.

The mean seasonal cycle of precipitation is accurately described by ERA, while mean precipitation has a high bias in NRA. This excessive precipitation in NRA is a well-known bias (e.g., Betts et al. 1996b, 1998b) that may have multiple causes related to excessive surface evaporation from an overly wet surface and the particular convective and planetary boundary parameterizations used. These parameterizations have been updated since (e.g., Hong and Pan 1996). There also are large differences in the surface runoff. Note that the NRA runoff is too high during the winter and too low during the summer when compared with the observed stream flow. By contrast, ERA runoff (which is all ''drainage'' runoff from the deepest model layer) has no annual cycle, unlike observed stream flow, so that model runoff is too low during the winter and remains low during the summer, despite the realistic precipitation. Consistent with the larger precipitation, total evaporation is larger in the NRA, even though the total surface water is considerably lower. There are indeed large differences in the surface water amounts and variations between the models. The ERA surface water is much larger than that of the NRA but has a very small seasonal cycle. This large difference is caused in part by the larger soil depth in the ERA, which may be irrelevant to seasonal variations. On the other hand, the NRA surface water has an exaggerated seasonal cycle, because of the nudging (the ''artificial source'' term *U*) toward an imposed climatic seasonal cycle of soil water, which adds surface water in winter and removes it in summer. By contrast, the ERA soil water nudging term has the opposite seasonal cycle; soil water is added in summer to maintain evaporation and is removed in winter, when the model runoff has a low bias. This cycle acts to damp the ERA seasonal change in water storage (Betts et al. 1998b, 1999). The time constant in the ERA surface water forcing is much faster than the 60-day time constant used in the NRA, although the nudging methods are not strictly comparable.

Figure 2 shows the variations of the monthly anomalies in the surface hydrologic cycle: these show greater similarity in amplitude and variation than do the corresponding means, which provides some renewed faith in the value of the reanalyses. In particular, precipitation has similar interannual variations in both reanalyses. Note, however, that the NRA has some more extreme years than does ERA, and thus NRA has a lower overall

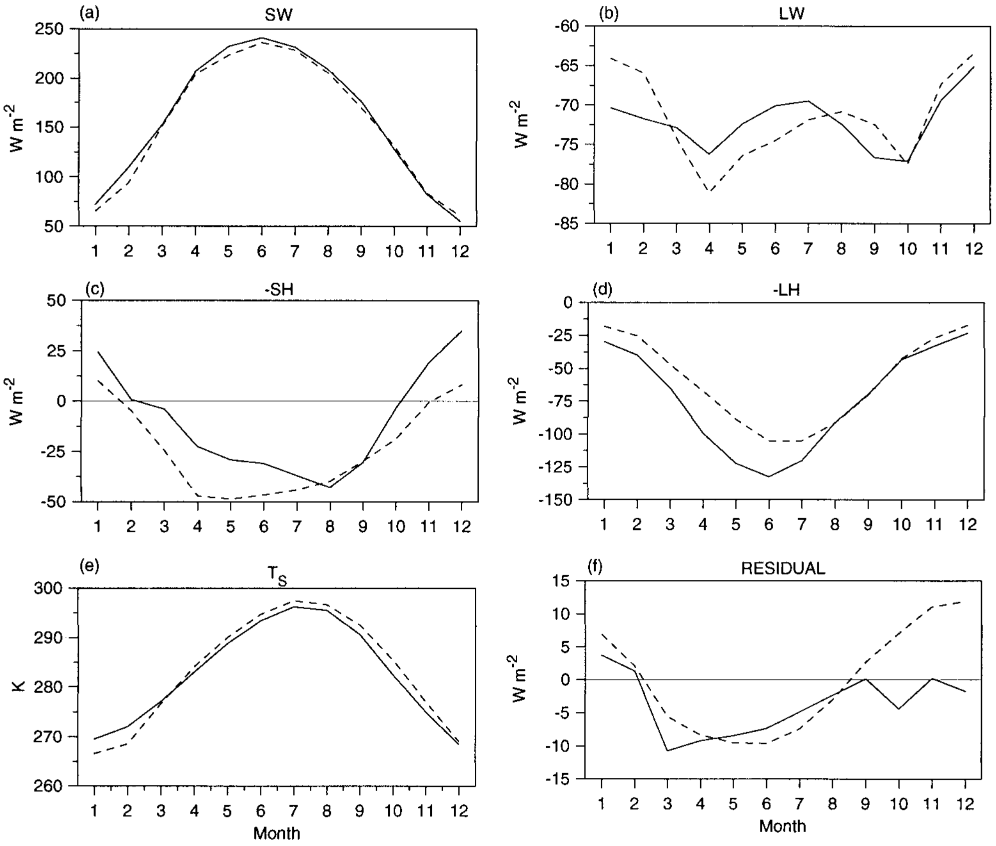

FIG. 3. Seasonal surface energy NCEP–NCAR (light solid) and ECMWF (dashed) reanalysis budgets for the Mississippi basin: (a) Net surface solar radiation (SW); (b) net surface longwave radiation (LW); (c) sensible heat (SH); (d) latent heat (LH); (e) surface temperature (T_S); and (f) residual.

correlation with respect to the observations (Table 1). The major NRA discrepancies occur during the summer months, especially during the summers of 1990 and 1991. Evaporation anomalies are somewhat consistent during the early part of the record, the one exception being 1988 when the ERA evaporation was reduced noticeably. The differences that result later probably are related to the surface water variations. Like surface water, runoff has a clear interannual signal, which appears in both reanalyses, but with reduced amplitude. Again, the ERA reanalysis variations have a higher correlation with observations (Table 1), despite having too little runoff in the mean. In addition, interannual variations in the surface water and the surface water tendencies are comparable in both reanalyses, despite their large seasonal differences. Unfortunately, the artificial forcing and tendency terms are large, especially in the NRA, which limits the ability to discern cause and effect for particular seasonal anomalies.

3. Surface energy

The corresponding surface energy balance can be written

$$0 = \mathrm{SW} + \mathrm{LW} - \mathrm{SH} - \mathrm{LH} + (G + Q_{\mathrm{melt}}). \quad (3)$$

The surface energy balance is maintained by the net shortwave solar heating SW, the net longwave cooling LW, the sensible heating SH, the latent heating LH, the flux into the ground G, and a small contribution due to snowmelt. Here the ground heating and snowmelt are combined to provide only a net residual heating ($G + Q_{\mathrm{melt}}$). The reanalyses in fact calculate a surface skin temperature diagnostically from the surface energy balance. On monthly timescales, variations in the surface 2-m air temperature closely mirror variations in the surface skin temperature and the near-surface soil temperature.

As shown in Fig. 3, there is almost a complete seasonal energy balance. Solar radiation provides a large positive input; this input is slightly larger in NRA than in ERA. This solar flux is balanced in part by net longwave radiation, sensible heating, and latent heating (including the evaporation of snow), all of which act to cool the surface, especially during the summer. Sensible heating also helps to warm the surface during the winter, especially in the NRA, although the stable boundary layer transfer coefficients may be too high in that model

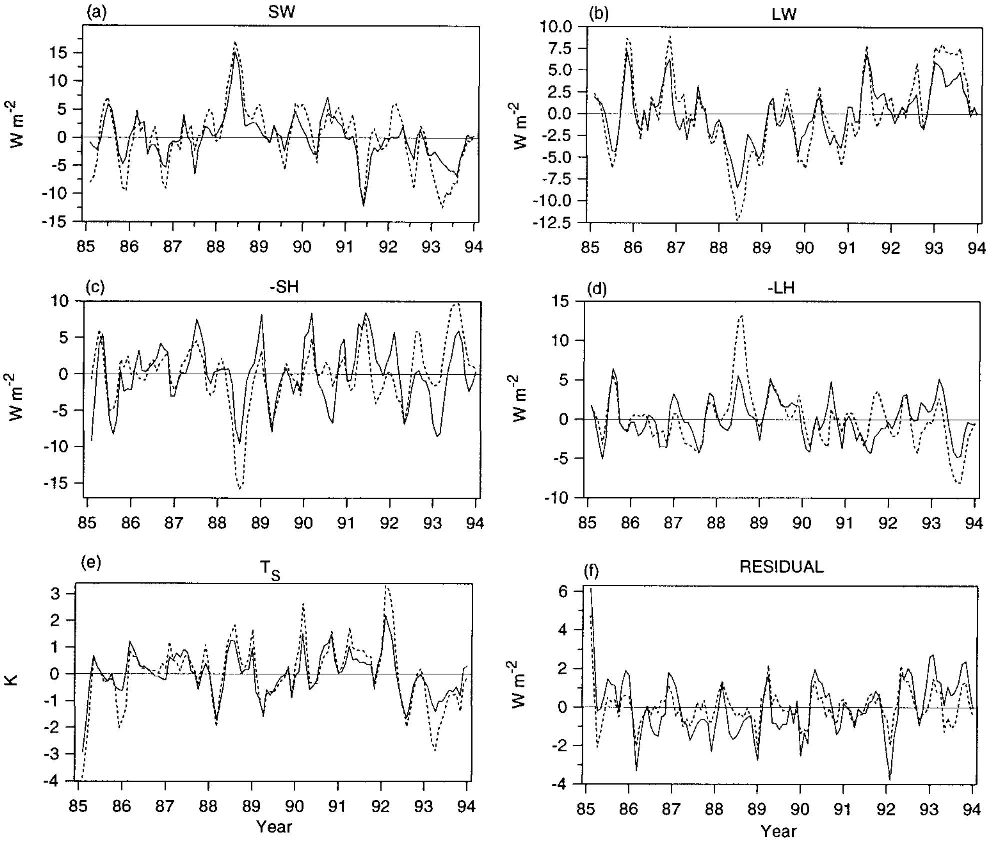

FIG. 4. As in Fig. 3 for monthly anomalies of surface energy budget terms (three-month running means for presentation only).

(Betts et al. 1996b). Note that there is stronger sensible heating of the atmosphere in the ERA and less latent heating, which is consistent with the relatively smaller evaporation in the ERA. Note also that the seasonal temperature variation is similar in both reanalyses, although the NRA temperature is a little lower during the summer and fall and a little higher during the winter. The ERA has a clear seasonal cycle of the residual, which is dominated by the ground flux in this model (downward in summer and upward in winter, with a near-zero annual residual, as it has a zero-heat-flux lower boundary condition). The residual in NRA has a less marked annual cycle, with a small net annual residual heating of 3.6 W, presumably because it has a climatological lower thermal boundary condition.

Figure 4 shows the variations of the monthly anomalies in the energy terms, which again have a remarkable consistency between the reanalyses. Note, in particular, the interannual signal in the radiation components, which are anomalously high from the summer of 1988 to the winter of 1991 and then low thereafter. This variation is consistent with the surface temperature variations, perhaps more so than with the latent or sensible heat variations, although that conclusion requires further study. Over the United States, Roads et al. (1997) showed in a previous version of the NCEP operational model, which used a bucket surface hydrological model, that the evaporation had both the largest anomalies and a clear relationship to temperature anomalies. Note further that shortwave and longwave components have almost opposite variations with each other, which probably means that they mirror variations in cloudiness, since less cloud cover gives more incoming shortwave and more outgoing longwave radiation. In fact, the radiation variations are somewhat similar to the surface water variations, a fact which also suggests that increased surface water produces increased cloudiness. This conclusion also needs further study. Note that sensible and latent heating also have opposite variations with each other. Again, the residual heating (which includes ground heat flux and snowmelt), which was small in the seasonal cycle, is now comparable with other components, particularly for NRA, and must be counted when accurately accounting for monthly anomalies. Table 1 shows that the radiation fluxes of the two reanalyses are more highly correlated than are the SH and LH fluxes.

4. Summary

In this paper, two major reanalyses, NRA and ERA, were compared with each other and with available observations for the Mississippi basin for the period 1985–93. There were a number of noticeable differences and similarities. NRA precipitation, runoff, and, probably, evaporation were too large when compared with observations, whereas the ERA runoff was too small. These differences are caused by the limitations of the physical parameterizations in the models, which in some cases already have been revised for subsequent reanalyses (M. Kanamitsu 1998, personal communication). There are large differences in surface water in the reanalyses, since surface water is greatly affected by the residual forcings that were imposed to prevent long-term drifts of the subsurface hydrological behavior. For example, ERA's time constant for soil water nudging probably was too short, which results in too small a seasonal cycle of soil water. On the other hand, the nudging toward a surface water climate in the NRA imposed much too large a seasonal cycle of deep soil water, which may have had an impact on evapotranspiration and precipitation. There is a good balance between the NRA runoff and atmospheric moisture convergence (Table 1). It thus can be deduced that the residual tendency in the atmospheric moisture balance is, on the average, just as large as the artificial forcing by nudging in the surface water balance. If a probable 10% negative bias in the precipitation observations is allowed for, then the model estimates of annual evaporation are positively biased by 17% and 53% for ERA and NRA, respectively.

Despite these seasonal differences, interannual and decadal anomalies were comparable with and highly correlated with each other (Table 1). Unfortunately, the anomalies in the residual (artificial) hydrologic forcing are comparable in magnitude with the annual variability, which still makes it difficult to understand the different hydrologic and energy contributions to temperature and precipitation variations. Thus, current coupled land–atmosphere models need further development. A renewed national focus to improve the modeling of the land–atmosphere interaction would continue to be useful.

Acknowledgments. This study was supported by NOAA Grants NA37GP0372 and NA36GP0377 to John Roads. Reanalysis data were provided by NOAA's Climate Diagnostic Center and by ECMWF. We are grateful for our discussions with M. Kanamitsu at NCEP. Alan Betts acknowledges support from the NOAA Office of Global Programs under Grant NA76GP0255, and from the National Science Foundation under Grant ATM-9505018. We thank E. Yarosh and W. Higgins for providing stream flow and precipitation observations. We thank the editor and reviewers for their help in improving this paper.

REFERENCES

Beljaars, A. C. M., P. Viterbo, M. J. Miller, and A. K. Betts, 1996: The anomalous rainfall over the United States during July 1993: Sensitivity to land surface parameterization and soil moisture anomalies. *Mon. Wea. Rev.,* **124,** 362–383.

Berbery, E. H., E. M. Rasmusson, and K. E. Mitchell, 1996: Studies of North American continental-scale hydrology using Eta model forecast products. *J. Geophys. Res.,* **101,** 7305–7319.

Betts, A. K., J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. Viterbo, 1996a: The land surface–atmosphere interaction: A review based on observational and global modeling perspectives. *J. Geophys. Res.,* **101,** 7209–7225.

——, S.-Y. Hong, and H.-L. Pan, 1996b: Comparison of NCEP–NCAR reanalysis with 1987 FIFE data. *Mon. Wea. Rev.,* **124,** 1480–1498.

——, P. Viterbo, and A. C. M. Beljaars, 1998a: Comparison of the land-surface interaction in the ECMWF reanalysis model with the 1987 FIFE data. *Mon. Wea. Rev.,* **126,** 186–198.

——, ——, ——, H.-L. Pan, S.-Y. Hong, M. L. Goulden, and S. C. Wofsy, 1998b: Evaluation of the land–surface interaction in the ECMWF and NCEP/NCAR reanalyses over grassland (FIFE) and boreal forest (BOREAS). *J. Geophys. Res.,* **103,** 23 079–23 085.

——, ——, and E. Wood, 1998c: Surface energy and water balance for the Arkansas–Red River basin from the ECMWF reanalysis. *J. Climate,* **11,** 2881–2897.

——, J. H. Ball, and P. Viterbo, 1999: Basin-scale surface water and energy budgets for the Mississippi from the ECMWF reanalysis. *J. Geophys. Res.,* **104,** 19 293–19 306.

Gibson, J. K., P. Kallberg, S. Uppala, A. Hernandez, A. Normura, and E. Serrano, 1997: ERA description. ECMWF Re-Analysis Project Report Series 1, 72 pp. [Available from ECMWF, Reading RG2 AX, United Kingdom.]

Higgins, R. W., J. E. Janowiak, and Y.-P. Yao, 1996: A gridded precipitation data base for the United States (1963–1993). NCEP Climate Prediction Center Atlas No. 1, 47 pp. [Available from Climate Prediction Center, NCEP, NWS, Camp Springs, MD 20746.]

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.,* **124,** 2322–2339.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kanamitsu, M., and S. Saha, 1996: Systematic tendency error in budget calculations. *Mon. Wea. Rev.,* **124,** 1145–1160.

Mahrt, L., and H.-L. Pan, 1984: A two layer model of soil hydrology. *Bound.-Layer Meteor.,* **29,** 1–20.

Mintz, Y., and Y. V. Serafini, 1992: A global monthly climatology of soil moisture and water balance. *Climate Dyn.,* **8,** 13–27.

Roads, J., S. Chen, M. Kanamitsu, and H. Juang, 1997: GDAS's GCIP energy budgets. *J. Atmos. Sci.,* **54,** 1776–1794.

——, ——, ——, and ——, 1998: Vertical structure of humidity and temperature budget residuals over the Mississippi River basin. *J. Geophys. Res.,* **103,** 3741–3759.

——, ——, ——, and ——, 1999: Surface water characteristics in the NCEP global spectral model and reanalysis. *J. Geophys. Res.,* **104,** 19 307–19 327.

Schubert, S. D., R. B. Rood, and J. Pfaendtner, 1993: An assimilated dataset for earth science applications. *Bull. Amer. Meteor. Soc.,* **74,** 2331–2342.

Viterbo, P., and A. C. M. Beljaars, 1995: An improved land surface parameterization scheme in the ECMWF model and its validation. *J. Climate,* **8,** 2716–2748.

Yarosh, E. S., C. F. Ropelewski, and K. E. Mitchell, 1996: Comparisons of humidity observations and Eta model analyses and forecasts for water balance studies. *J. Geophys. Res.,* **101,** 23 289–23 298.