Intercomparison of water and energy budgets for five Mississippi subbasins between ECMWF reanalysis (ERA-40) and NASA Data Assimilation Office fvGCM for 1990–1999

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[1] Using monthly means for 1990–1999, we assess the systematic biases in temperature and humidity and the surface energy and water budgets of both European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) and the of the NASA Data Assimilation Office atmospheric finite-volume general circulation model (fvGCM) for five Mississippi subbasins. We compare ERA-40 and the fvGCM with basin averages of surface observations of temperature, humidity and precipitation, the river basin estimates for the hydrological balance from *Maurer et al.* [2002], and the International Satellite Cloud Climatology Project (ISCCP) retrieved skin temperature and surface radiation fluxes. We show the role of the soil water analysis in ERA-40, which generally supplies water in summer and removes it in winter and spring. The ERA-40 snow analysis increments are a significant contribution to the (smaller) frozen water budget. Compared with National Climate Data Center (NCDC) observations of screen temperature, ERA-40 generally has a relatively small ($\leq$1 K) positive temperature bias in all seasons for the Mississippi basins, while the fvGCM has a large cold bias in temperature in winter. The ISCCP skin temperature estimate is generally high in winter and a little low in summer, compared to ERA-40 and the NCDC screen level temperature. For the western basins, summer precipitation is high in the fvGCM, while for the eastern basins it is high in ERA-40 (in 12–24 hour forecasts after spin-up). Summer evaporation is higher in the fvGCM than in ERA-40, while winter evaporation has a high bias in ERA-40, leading to a corresponding high bias in specific humidity. Net shortwave radiation probably has a high bias in the fvGCM in summer. The seasonal cycle of incoming shortwave is much flatter in ERA-40 than the ISCCP data, suggesting that the reanalysis may have too much reflective cloud in summer and too little in the cooler seasons. The temperature biases at the surface in both the fvGCM and the ISCCP data clearly have a negative impact on the surface long-wave radiation fluxes, although the bias in the net long-wave flux is rather less. *INDEX TERMS:* 1818 Hydrology: Evapotranspiration; 1854 Hydrology: Precipitation (3354); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; *KEYWORDS:* precipitation, surface energy budgets, Mississippi basin budgets, reanalysis

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1. Introduction

[2] The European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) is proceeding in several streams [*Simmons and Gibson*, 2000], and the most recent period, the 1990's, is already complete. The analysis system uses a recent version of the model physics, including the land-surface scheme described by *van den Hurk et al.* [2000], and a 3-D variational assimilation system. The horizontal resolution of the spectral model is triangular truncation at T_L-159, and there are 60 levels in the vertical, including a well-resolved boundary

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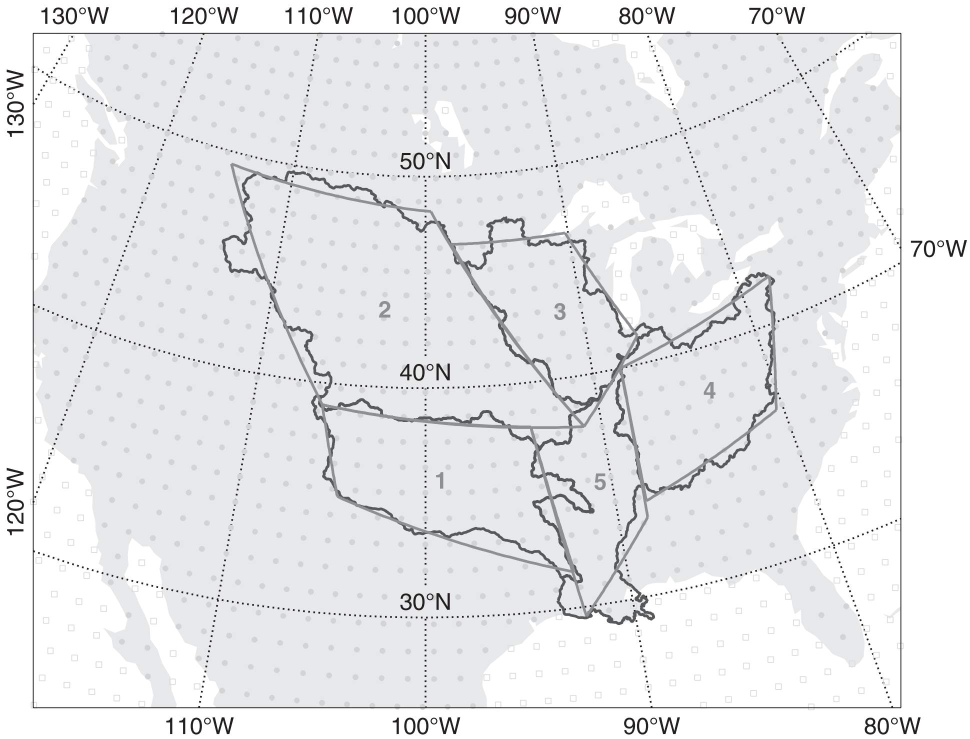

Figure 1. River basin budgets in ERA-40 for the Mississippi. See color version of this figure in the HTML.

layer and stratosphere. Documentation of the Integrated Forecast System (IFS), cycle 23r4, and a summary and discussion of the observations available at different times during the 40-year reanalysis can be found at http://www.ecmwf.int/research/era/. Surface energy and water budgets, and near-surface and subsurface variables averaged over river basins, are computed and archived during the analysis cycle at an hourly timescale. In this paper, using monthly means, we assess the systematic biases in temperature and humidity, and the surface energy and water budgets of both the ECMWF reanalysis, and the National Aeronautics and Space Administration Data Assimilation Office (NASA DAO) atmospheric finite-volume general circulation model (fvGCM) for five Mississippi subbasins. The fvGCM was run with $1 \times 1.25°$ horizontal resolution for the 15 years, 1986–2000, using observed varying sea surface temperatures. The DAO fvGCM results from a collaboration between NASA and the National Center for Atmospheric Research (NCAR). It uses DAO's finite-volume dynamical core [*Lin*, 1997; *Lin and Rood*, 1996]. The atmospheric physics and land-surface model are taken from NCAR Community Climate model (CCM3) in which the land-surface scheme is from *Bonan* [1998], the deep convective parameterization is from *Zhang and McFarlane* [1995] and the shallow convection scheme is from *Hack* [1994].

[3] Earlier budgets of the Mississippi derived from the first ECMWF analysis, ERA-15, and the National Centers for Environmental Prediction (NCEP) model and reanalysis are described by *Betts et al.* [1998, 1999], *Roads et al.* [1997, 1999], and *Roads and Betts* [2000]. S. I. Seneviratne et al. (Inferring changes in terrestrial water storage using ERA-40 reanalysis data: The Mississippi river basin, submitted to *Journal of Climate*, 2003) derive the terrestrial water storage for the same five Mississippi basins from the atmospheric convergence of water vapor in ERA-40, and the observed streamflow from the river basins.

[4] Our basic methodology is to compare the mean monthly annual cycle from short-term forecasts of ERA-40 for the ten years, 1990–1999, with the corresponding mean from the same ten years extracted from a 15-year atmospheric GCM run (initialized on 1 January 1986 in free-running mode with specified 'observed' sea surface temperatures). Thus it can be regarded as a comparison of the fvGCM model's climate with the reanalysis. We evaluate these model products from ERA-40 and the fvGCM using basin averages of surface observations of temperature, humidity and precipitation, the river basin budgets from *Maurer et al.* [2002], and the International Satellite Cloud Climatology Project (ISCCP) retrieved skin temperature and surface radiation fluxes. Some comparisons use a shorter time period.

2. River Basin Intercomparisons

[5] For ERA-40, averages over selected basins are output for hourly time intervals (accumulated from the full time resolution data) for selected river basins. We analyze here the subbasins of the Mississippi labeled 1 to 5 in Figure 1, representing respectively the Red-Arkansas, the Missouri, Upper Mississippi, Ohio-Tennessee, and the lower Mississippi. The ERA-40 averages are over all grid points, indicated as dots, inside each polygon, which are approximations to the actual river basin boundaries shown. We averaged the hourly data up to one month. For the fvGCM, we similarly averaged over grid points (from the 1×1.25 grid) within the same polygons, and averaged the archived

daily means (derived from 30-min time steps) up to one month. We shall show a ten-year mean annual cycle: 1990–1999, where all the data is available.

2.1. Validation Data

[6] We have three data sets, based on observations, for validation. For temperature and specific humidity, the station data, which were daily means (derived from hourly data) of temperature and dewpoint from the National Climate Data Center (NCDC) on-line archive (only available from 1994], were gridded to the GCM's 1 × 1.25 grid, and then area averaged over the basins. On average, there is about one station per square degree. Although the distribution is not uniform, the coverage is reasonable for all the subbasins. For the hydrological balance (precipitation, evaporation, runoff and surface water change), we used basin averages from the variable infiltration capacity (VIC) model of *Maurer et al.* [2001, 2002]. In this model, the primary driver field is the observed precipitation, and runoff is routed and validated against observed streamflow, so that the model evaporation and changes in soil water and snow amount are linked quite closely to observed parameters. For radiative fluxes, basin averages were derived from ISCCP [*Rossow and Schiffer*, 1999] and other satellite data sets in a revised version of the approach used by *Zhang et al.* [1995] and *Rossow and Zhang* [1995]. This has a fixed 2.5° grid in latitude, with the longitude grid starting at 2.5° at the equator, and increasing poleward to keep an equal-area grid. The ISCCP satellite data give uniform coverage of the basins, and have a 3-hourly time resolution.

2.2. Overview of the Mississippi Water Budget

[7] We first compare the mean water budget for the whole Mississippi basin from the *Maurer et al.* [2002] analysis, with that from ERA-40, and the fvGCM (for which we have only two terms archived). This gives insight into the water budget closure in ERA-40. Figure 2 shows the mean annual cycle for the five years, 1995–1999. We only have the full water budget of the ERA-40 6-hour analysis cycle, starting with 1995, because the basin budgets for the 6-h forecasts from the intermediate 06 and 18 UTC analysis times were not archived for 1990–1994. Figure 2a shows the *Maurer at al.* [2002] analysis using the VIC model. This uses precipitation, derived from gauge observations with corrections for undersampling in regions of complex terrain (but not for gauge undercatch), temperature and wind from NCEP-NCAR reanalysis, and derives dewpoint, and incoming radiation fluxes using established relationships (see *Maurer et al.* [2002] for details). The surface energy and water fluxes are calculated, together with the soil and snow hydrological balances; runoff is routed through a defined river channel network, and gives a reasonable comparison with observed or naturalized streamflows. *Maurer et al.* [2002] conclude therefore that the derived evapotranspiration (labeled ET in Figure 2) is realistically estimated on timescales long enough that changes in surface water storage are small compared to accumulated precipitation or ET. It would be fair to say, however, that ET from this model is likely to be underestimated, since precipitation is not corrected for gauge undercatch, which may be 5–10% (or larger for snowfall). Figure 2a shows the annual cycle of the VIC model runoff and the change of the storage of

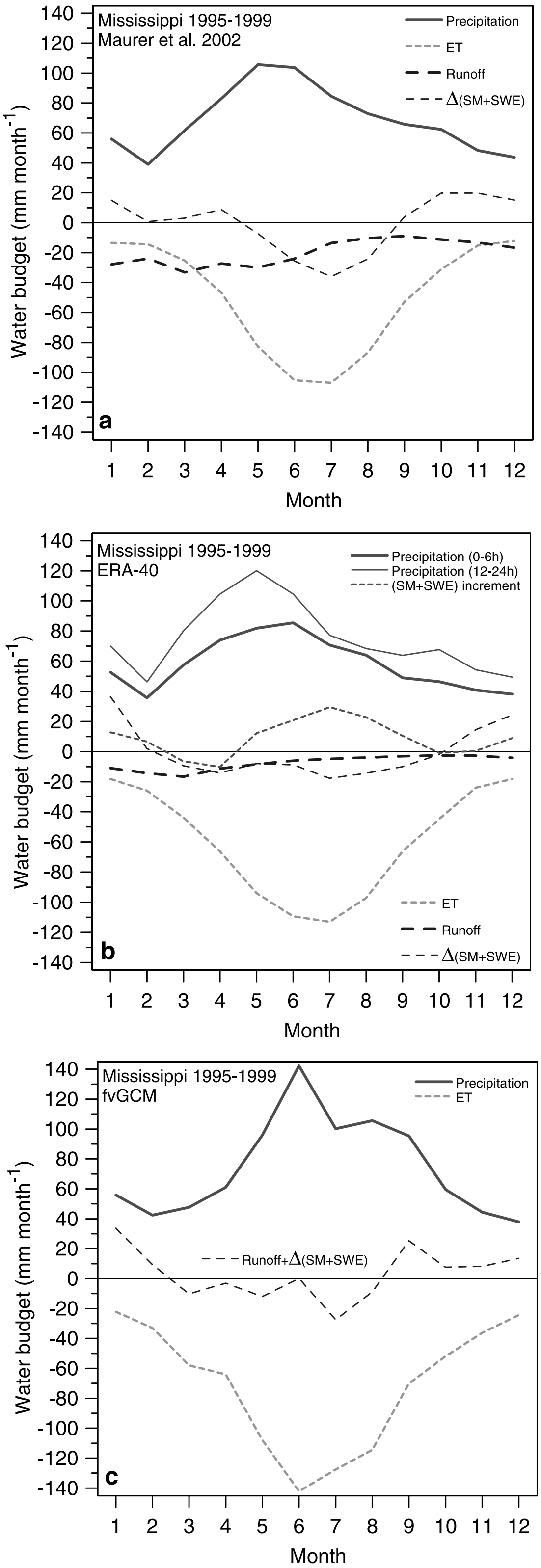

Figure 2. Water budget annual cycle for the Mississippi basin from (a) *Maurer et al.* [2002], (b) ERA-40, and (c) fvGCM for 1995–1999. See color version of this figure in the HTML.

surface water, the sum of changes in the soil moisture (SM) reservoir and the snowpack, as snow water equivalent (SWE). The surface water reservoirs are recharged in winter and fall in the summer.

[8] Figure 2b shows the corresponding water budget terms in ERA-40. All the terms, except one, are from the sum of the 0–6h forecasts of the analysis cycle, made from the four daily analyses at 00, 06, 12 and 18 UTC. The exception is precipitation, which has a significant spin-up in the first 24 hours, so we show both the analysis cycle precipitation, which balances the other water budget terms, and also the precipitation calculated from two 12–24h forecasts from the 00 and 12 UTC analyses. The *Maurer et al.* [2002] precipitation from Figure 2a lies between the two ERA-40 curves, except from July to September, when it is a little higher than both the ERA-40 curves. The ERA-40 ET is greater than the Maurer et al. estimate in all seasons, by about 5 mm month^{-1} in summer and mid-winter, and about 15 mm month^{-1} in spring and fall. In all months, the ERA-40 runoff (annual total 90mm) is much less than the Maurer et al. runoff (annual total, 240mm), which is consistent with the observed streamflow. The drying of the soil water reservoir in July and August in ERA-40 is less than in the VIC analysis. The analysis cycle water budget in Figure 2b is closed by an extra term, the sum of the analysis cycle increments, which are the corrections the analysis makes at the four analysis times to the 6-hourly forecasts (from the preceding analysis) to produce each new analysis. There is an increment in the snow analysis, and in the soil water analysis, and Figure 2b shows their sum. This term is a significant part of the model water budget, reaching nearly 30 mm month^{-1} in July, and contributes over 100mm of water to the annual mean budget. It will be discussed further in Figure 3 below, which separates the liquid and frozen water budgets in ERA-40.

[9] Figure 2c shows precipitation and ET (the other terms in the water budget were not archived in this run) and their residual for the corresponding five-year mean extracted from the 15-year fvGCM run, initialized on 1 January 1986 in free-running mode with specified 'observed' sea surface temperatures. Both P and ET are larger in summer than in Figure 2a. The residual, the sum of runoff and the change of the surface water reservoirs, is small, and the comparison with the sum of the corresponding terms in Figure 2a suggests that it is likely that runoff is too small.

2.3. ERA-40 Liquid and Frozen Water Budgets

[10] Figure 3 separates the liquid and frozen water budgets for ERA-40 for the same five years, showing only the terms that balance in the analysis cycle. In the liquid budget, the sources terms are rain and the melting of snow, which are comparable in size in winter. The ERA-40 soil water analysis modifies soil water in the first three soil layers (0–7, 7–28 and 28–100 cm), subject to certain constraints, based on analysis increments of 2-m temperature and humidity [*Douville et al.*, 2000]. The soil water analysis increment is clearly significant in the liquid water budget, supplying water in summer and removing water in winter and early spring, when melt is largest. The runoff, as seen in Figure 2, is small, and the soil moisture storage is generally positive in winter and negative in summer (there are differences among the subbasins, especially in spring, not shown). In the frozen budget (lower panel), the snowfall and SWE analysis increment are comparable (note the scale differs from the liquid budget). The snow analysis [*van den Hurk et al.*, 2000], which uses snow-depth observations where available, and in addition a nudging toward climatology (with a 12-day timescale) is clearly a significant source term in the frozen water budget. Because frozen evaporation is small, the source from the snow analysis increases the size of the melt term, which in turn contributes to the liquid budget, especially in winter and spring. The melt in nature runs off, but since run-off is too low in ERA-40, it appears that it is the soil water analysis that removes the excess water.

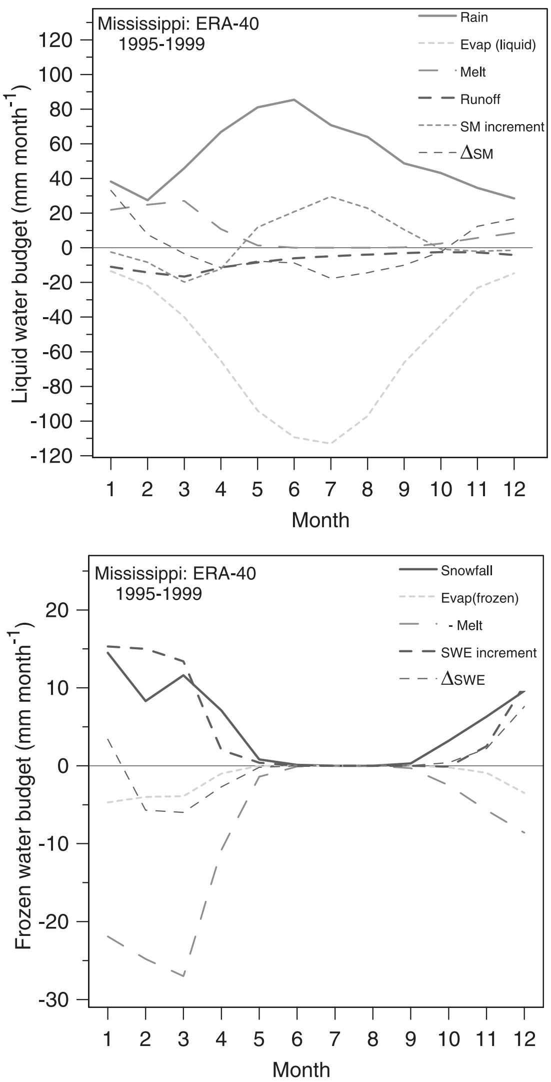

Figure 3. Mean annual cycle of liquid and frozen water budgets for ERA-40 for 1995–1999. See color version of this figure in the HTML.

3. Subbasin Comparison

[11] We shall now show, for the five subbasins of the Mississippi, a more detailed comparison of the mean monthly annual cycle from 12–24 h short- term forecasts from ERA-40 (and in addition 0–12 h for precipitation to show the model precipitation spin-up), the corresponding

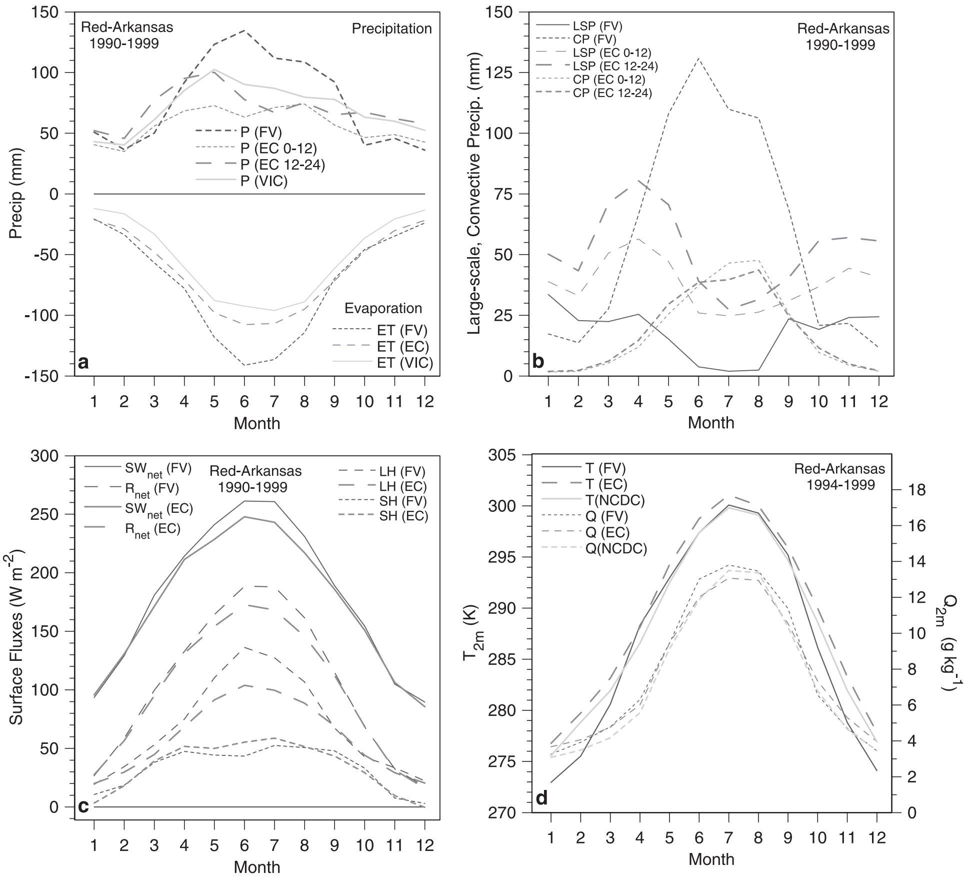

Figure 4. (a) Precipitation and evaporation for ERA-40, fvGCM climate and observations, (b) large-scale and convective scale precipitation, (c) fluxes in energy budget, and (d) 2-m temperature and specific humidity. See color version of this figure in the HTML.

mean extracted from a 15-year atmospheric fvGCM run, and basin averages of surface observations of temperature, humidity and precipitation, and the river basin estimates of evaporation from *Maurer et al.* [2002].

3.1. Red-Arkansas Basin Means

[12] Figure 4a compares monthly mean precipitation and evaporation for the decade, 1990–1999. The color code is: fvGCM model in blue, ERA-40 in red, and in green precipitation (from observations) and evaporation from the VIC model of *Maurer et al.* [2002]. For ERA-40, two curves are shown for precipitation: from the 0–12 h forecasts (dotted), and from the 12–24 h forecasts (long dashes). As in Figure 2, ERA-40 (using a 3-D variational assimilation system, rather than the 4-D variational assimilation system used currently for operational forecasts) has considerable spin-up of precipitation in the first 24 hours. We see that compared with the data, the 12–24 h ERA-40 precipitation is a little high in winter and low in summer. In contrast, the fvGCM precipitation 'climate' is low in winter and rather high in summer by 25%. Not surprisingly, evaporation is correspondingly higher in the fvGCM in summer than in ERA-40, and both are higher than the Maurer et al. estimate. The VIC model estimate of evaporation could be biased low, because precipitation is not corrected for undercatch (which could be 5–10%). The high evaporation in the fvGCM may be due to an overestimate of canopy interception evaporation, but we do not have the detailed diagnostics to assess this. Both ERA-40 and fvGCM however have too little runoff, compared to streamflow observations (not shown).

[13] Figure 4b compares large-scale (LSP) and convective-scale (CP) precipitation, as produced by the models. There are large differences. The spin-up of ERA-40 is in the large-scale precipitation (LSP), and it has a peak of large-scale precipitation in Spring. Convective precipitation (CP), which has a small spin-down, only exceeds LSP in summer. In contrast, the fvGCM model has much less LSP throughout the year, and almost none in summer, when its CP is very large. Since the models have opposite biases in winter and summer with respect to the precipitation observations, this suggests that in winter the LSP may be a little high in ERA-40 (after spin-up) and low in the fvGCM; while in summer, the CP is low in ERA-40 and rather high in the fvGCM. The two models have different convective parameterizations: the ERA-40 scheme is a mass-flux scheme [*Tiedtke*, 1989] with a convective available potential energy (CAPE) closure for deep convection [*Gregory et al.*, 2000], while this version of the fvGCM uses the *Zhang and McFarlane* [1995] scheme, which adjusts toward a threshold CAPE. ERA-40 uses the large-scale cloud scheme of *Tiedtke* [1993], while the fvGCM has only a diagnostic grid-scale condensation, when mean relative humidity reaches 100%, and no explicit representation of stratiform clouds or their microphysics.

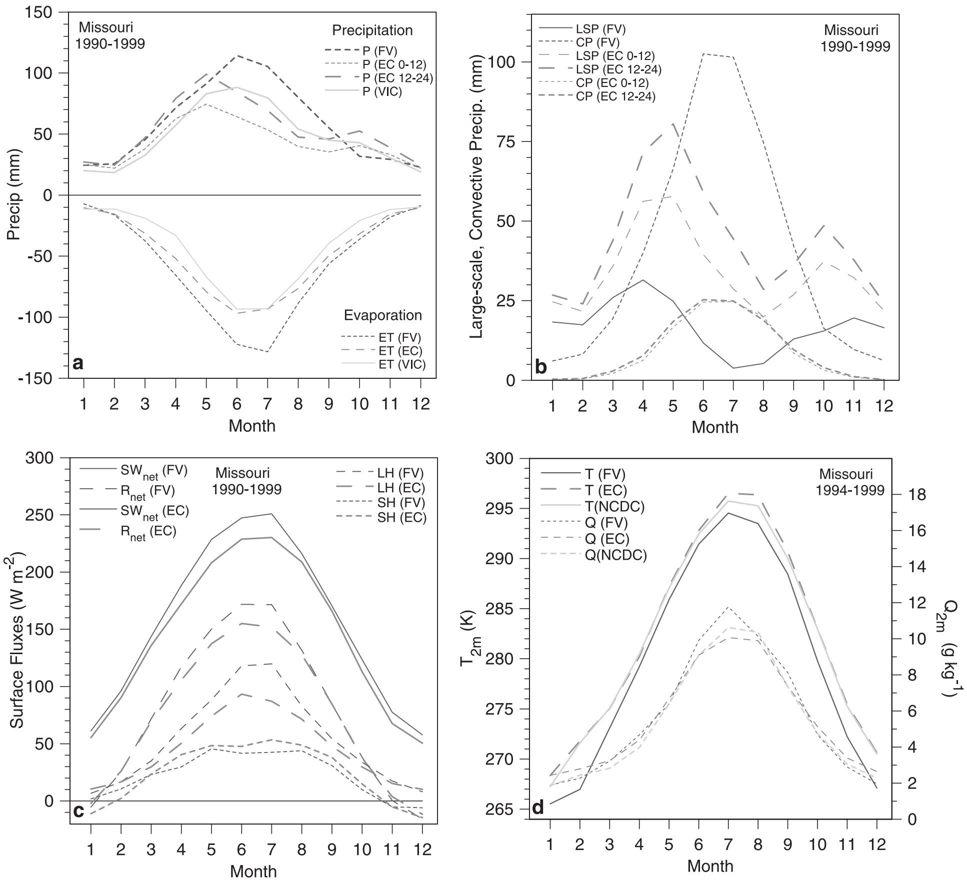

Figure 5. As Figure 4 for Missouri river basin. See color version of this figure in the HTML.

[14] Figure 4c compares the surface energy balance of the two models. Four pairs of curves are shown in descending order: net shortwave (SW_{net}), net radiation (R_{net}), latent heat flux (LH) and sensible heat flux (SH). In summer the fvGCM has more SW_{net} and consequently a larger R_{net} at the surface (the differences in net longwave (LW) flux are small). Comparisons of the ERA-40 radiation model with observations [*Morcrette*, 2002a, 2002b] show that while the LW fluxes have little bias, the incoming SW may have a high bias of order 10 W m^{-2}. This suggests that the fvGCM may have a high bias in SW_{net} as large as 30 Wm^{-2}. The partition of R_{net} at the surface is quite different between the models. The fvGCM has more evaporation (as seen in Figure 4a) in the warm season. The seasonal cycles of the surface SH flux differ, with the fvGCM being lower in spring and greater in late summer and in the Fall. In section 4, we shall compare the model radiation fluxes with the ISCCP fluxes.

[15] Figure 4d shows the mean annual cycle of 2-m mean temperature and specific humidity for the two models. The curves in green are from the gridded NCDC screen level observations. Our comparison period is 1994–1999 for which we have the NCDC values, but the differences between the models are largely insensitive to this shorter averaging period of only six years. ERA-40 has a slight warm bias with respect to the NCDC observations, while the fvGCM has a cold bias in mid-winter exceeding 2 K. The warmer temperature in ERA-40 (than the fvGCM) is associated with the larger SH flux, but the cause of the cold bias in the fvGCM in winter is less obvious, as there is little difference in R_{net} between the models, and the other surface fluxes are similar. The lower curves (with scale on the right-hand axis) compare specific humidity. The differences are small, with the fvGCM being a little moister in early summer (presumably because of its higher evaporation), and both models a little wetter than the NCDC data in the winter.

3.2. Missouri Basin Means

[16] Figure 5 shows the corresponding plots for the Missouri basin. There are many similarities to Figure 4, so we will only comment on the differences. Precipitation is a little low in ERA-40 in summer, and correspondingly summer evaporation is close to the VIC estimate. In the spring and fall, ET remains higher in ERA-40 (which has no seasonal cycle in the vegetation) than the VIC estimate. ERA-40 shows no spin-up or spin-down in convective precipitation. The fvGCM again has both higher precipitation and evaporation. Both the temperature and the SH flux are lower in the fvGCM than in ERA-40 throughout the year, and the fvGCM has again a cold bias with respect to the NCDC data. Compared with the specific humidity observations, ERA-40 has a small dry bias in summer and a wet bias in the cooler seasons, while the fvGCM is wet in summer.

3.3. Upper Mississippi Basin Means

[17] For the Upper Mississippi, shown in Figure 6, the spin-up of ERA-40 LSP is larger than for the Missouri

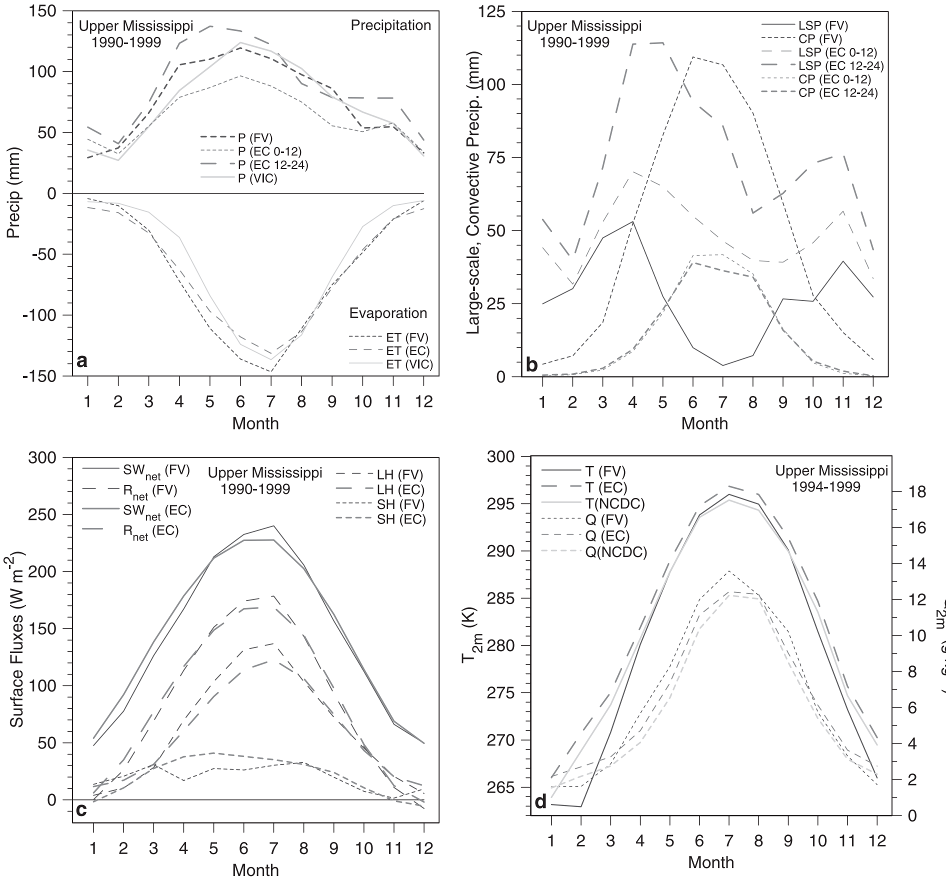

Figure 6. As Figure 4 for Upper Mississippi river basin. See color version of this figure in the HTML.

basin, while the fvGCM has little precipitation bias in summer. This is the only basin where ERA-40 has less evaporation in summer than the VIC model estimate. The fvGCM has a lower R_{net} in winter than ERA-40 and the temperature difference between the models in February has increased to 5 K. However, while the fvGCM is still cold compared to NCDC data, the warm bias in ERA-40 has increased to 2 K in January. A warm bias over snow-covered regions has been seen in operational forecasts (P. Viterbo, personal communication, 2002). Changes to the albedo in the presence of snow, may have slightly over-corrected the large cold bias at high latitudes that was seen in previous versions of the model [*Viterbo and Betts*, 1999]. In specific humidity, the fvGCM is wetter than ERA-40 when its evaporation is higher from May to July, with the reverse from December to March. The comparison with the NCDC data shows that ERA-40 has a small warm wet bias throughout the year, which is a little larger in winter.

3.4. Ohio-Tennessee Basin Means

[18] For the Ohio-Tennessee basin, shown in Figure 7, the 12–24 h precipitation in ERA-40 is higher than the fvGCM, as well as the observations, throughout almost the whole annual cycle: this is quite a different pattern from the Red-Arkansas basin. The annual cycle of evaporation and LH flux is noticeably flatter in ERA-40 than the fvGCM. The wet bias of ERA-40 in specific humidity throughout the year suggests that in all seasons, evaporation is too high. The cold bias of the fvGCM (with respect to NCDC data) reaches 3 K in January, even though the model has a higher upward SH flux than ERA-40 (and much lower evaporation). This suggests a problem with the surface interaction in the fvGCM.

3.5. Lower Mississippi Basin Means

[19] This basin's characteristics are an overestimate of precipitation in ERA-40 in the summer, and rather low precipitation in the fvGCM climate in the cool seasons. Figure 8b shows the low cool season LSP in the fvGCM, and that the difference in CP between the 2 models is smallest for this basin. In October, when precipitation is lowest in the fvGCM, we see SH = LH flux for the fvGCM, in sharp contrast to ERA-40. As in other eastern basins, in summer, both models have a small warm wet bias, but in winter, ERA-40 has a warm wet bias in winter and the fvGCM a cold bias.

4. Comparison With ISCCP Radiation Fluxes and Surface Temperature

[20] In this section we intercompare the radiation flux components and the surface temperature from the models with the ISCCP data. We shall only show two basins, since all have similarities, generally between the two examples shown. Figure 9 for the Red-Arkansas has two panels: the four components of the surface radiation budget above, and below, T_{2m}, and the radiometric skin temperature, T_s, which determines the upward longwave (LW) fluxes. For the SW

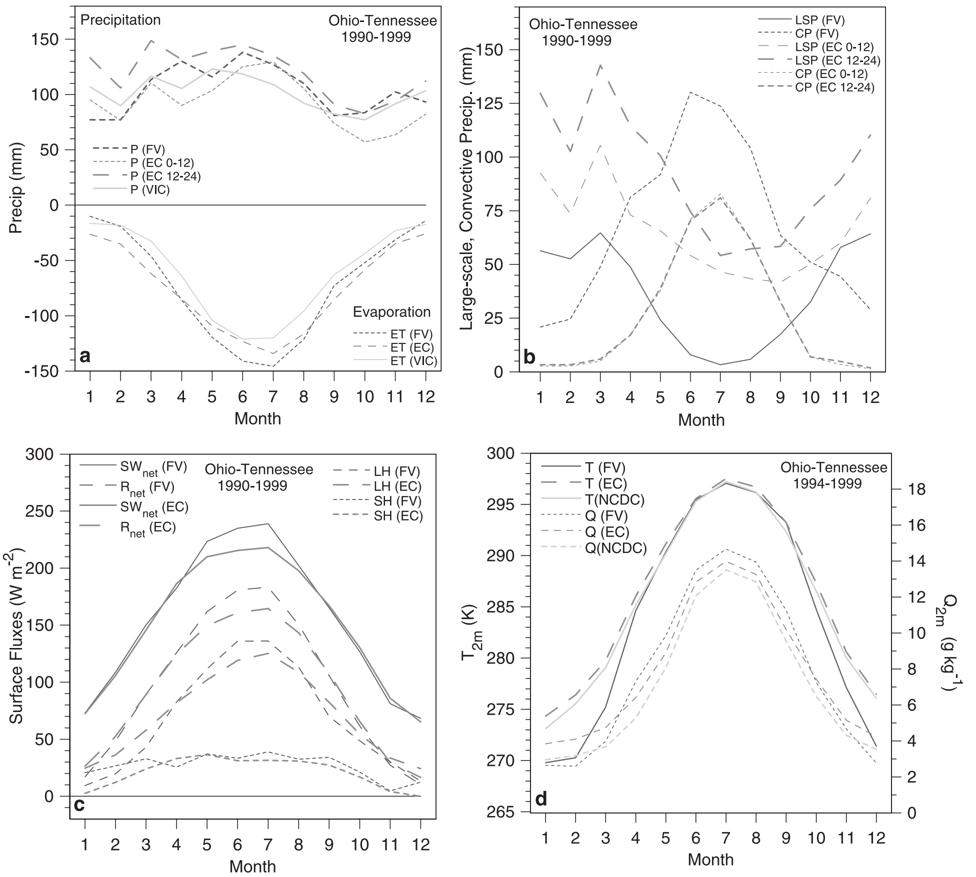

Figure 7. As Figure 4 for Ohio-Tennessee river basin. See color version of this figure in the HTML.

fluxes (upper panel, lower curves), we compare the downward and upward (reflected) SW fluxes for ERA-40 and ISCCP. Two features stand out. ERA-40 has a greater downward SW flux, except in summer, when it is a little lower. This suggests that the ERA-40 cloud field in the cool season is less reflective than the cloud field seen by the ISCCP top of the atmosphere data set. The albedo in ERA-40 is 15% in summer, much greater than the ISCCP albedo of 9%. This albedo difference has an 18 Wm^{-2} impact on the reflected shortwave. In summer, the net shortwave is 25 Wm^{-2} lower in ERA-40, while in mid-winter, the relative bias reverses, with ERA-40 about 10 Wm^{-2} higher than ISCCP. We have already shown that the fvGCM net shortwave is appreciably higher than ERA-40 in the warmer months (Figure 4). However, we do not have the separate SW components for the fvGCM, as they were not archived for this model run (so they are not shown here).

[21] We have however the complete long-wave budget (upper panel, upper curves). These show the upwelling and downwelling LW fluxes for ISCCP, ERA-40 and the fvGCM. The differences between the LW_{up} and LW_{dn} curves are similar, and in general terms reflect differences in the surface and air temperatures. The lower panel shows T_s for ISCCP, ERA-40, and fvGCM; and T_{2m} for ISCCP (a value extrapolated from the TOVS satellite retrieval for the lowest 200hPa layer), ERA-40 and for the NCDC data. Accepting the NCDC data as 'truth,' we see that ERA-40 has only a slight high bias in all seasons (already seen in Figure 4), and therefore we expect the most realistic LW budget. However, in winter, the ISCCP skin temperature has a large high bias of +5 K (for the Red-Arkansas basin), giving LW_{up} fluxes that are too large by 20Wm^{-2}, while the cold bias of fvGCM (already shown in Figure 4) gives LW_{up} fluxes that are too low by about 15 W m^{-2}. Figure 10 shows the corresponding curves for the Ohio-Tennessee river basins. The general pattern of the differences between the models, the ISCCP retrievals and the NCDC data is similar. The ERA-40 temperature bias is a little smaller (<1 K). The fvGCM has no temperature bias in summer, but the cold winter bias is a little larger (already seen in Figure 7). For this basin, the ISCCP T_s has a 3 K cold bias in summer, while the warm bias in winter is much smaller. In comparison with Figure 8, this is a cold shift of the bias of T_s in all seasons. For the other basins (not shown), the ISCCP T_s bias pattern is also cold in summer and warm in winter; with Figure 9 and 10 representing extremes. Both the cold summer and warm winter bias can be associated with cloud contamination. The summer bias may be associated with undetected thin cirrus over summer land areas [*Rossow and Schiffer*, 1999], and the warm winter bias may be associated with the presence of near-surface temperature inversions, which are typically missing from the operational sounder analysis used in the ISCCP retrievals.

[22] In monthly means T_s and T_{2m} should be quite close: models typically also show $T_s > T_{2m}$ in summer and $T_s < T_{2m}$ in winter (as does ERA-40 in Figure 9). If the bias in both T_s and T_{2m} are similar then the bias in the net LW is considerably reduced. The ISCCP extrapolated T_{2m}

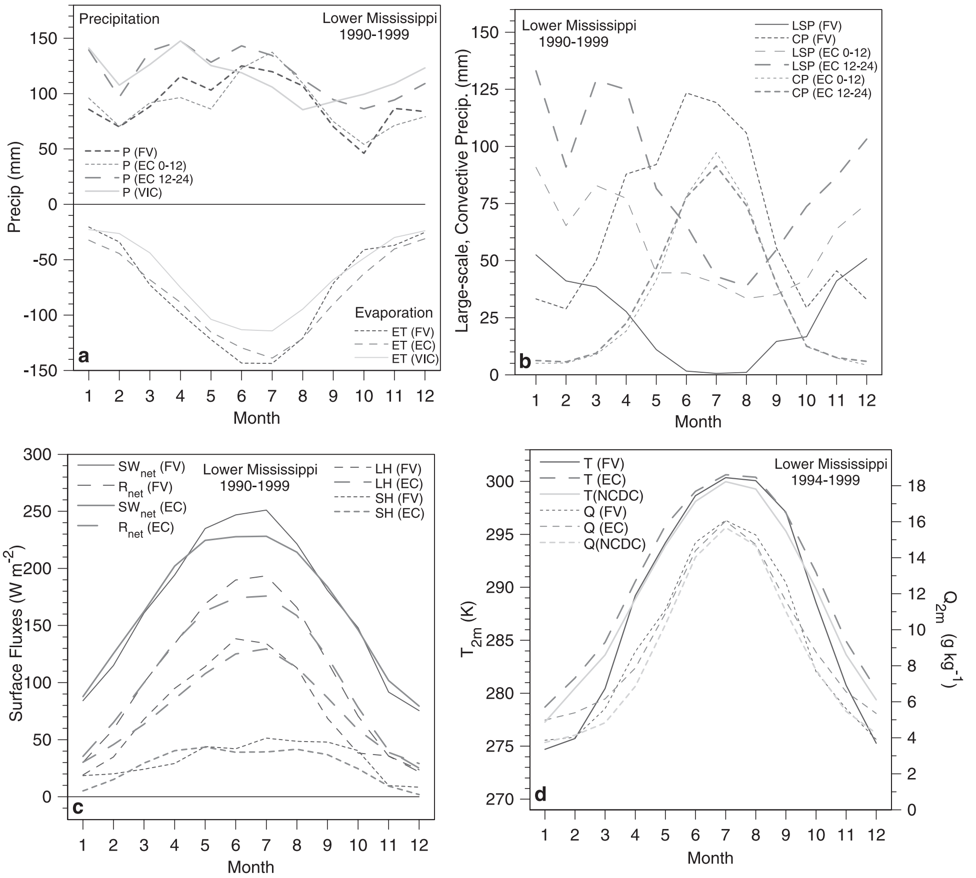

Figure 8. As Figure 4 for Lower Mississippi river basin. See color version of this figure in the HTML.

temperature in Figure 9 is colder than the corresponding skin temperature by about 2 K during much of the year, while in Figure 8, the ISCCP $T_{2m} > T_s$ by a similar amount for most of the year. The LW_{dn} flux is strongly influenced by the near-surface air temperature [*Rossow and Zhang*, 1995], so consequently the LW_{net} bias of the ISCCP data is related to the relative bias of T_s and T_{2m}. For the Ohio-Tennessee, in mid-winter and mid-summer, the ISCCP data has T_s rather less than T_{2m} , which reduces the net outgoing LW flux by 5–10 Wm^{-2} in comparison to ERA-40. A coupled land-surface-atmosphere model in the ISCCP retrieval would give a better representation of the surface energy balance, although this would require additional information about the surface hydrological balance, and in particular precipitation. Because it has a fully coupled land-surface model, and the surface hydrological balance is constrained by the soil water and soil temperature assimilation [*Douville et al.*, 2000], ERA-40, a reanalysis, has at present the better estimate of the surface temperatures, the skin-air temperature difference, and hence the surface LW balance.

[23] The difference in the shortwave fluxes suggests two important issues. The surface downwelling SW flux has quite a different annual cycle in ERA-40 and ISCCP. Although the models differ in their SW schemes, and treatment of aerosols, this difference in annual cycle implies a different annual cycle of reflective cloud cover. Since the ISCCP surface flux is derived from the observed cloud reflectance, it is likely that the cloud scheme in ERA-40 has too little reflective cloud in fall, winter and spring, and too much in summer. *Morcrette* [2002b] made a detailed comparison with cloud and radiation observations from the Atmospheric Radiation Measurement Program Southern Great Plains site in Oklahoma for April and May, 1999 with the ECMWF model (cycle 13r1), and also found a positive short-wave bias in the model for these spring months. They attributed this to an underestimate of the gaseous (clear sky) absorption, errors in cloud amount, and a model-simulated cloud reflectivity that was too small for liquid water clouds. Although this was a comparison for only two months at a single point, it is located within the Mississippi basin. Improvements in the radiation model are under development. The difference in SW albedo between ERA-40 and ISCCP is a reminder that the surface albedo, which is of fundamental importance to the surface energy balance, is still poorly known. The background (snow-free) land albedo for each grid point in ERA-40 is interpolated to the model grid from the monthly mean values of a snow-free albedo produced for the combined years 1982–1990. The albedo for that data set was computed using the method of *Sellers et al.* [1996], but with new maps of soil reflectance, new values of vegetation reflectance and the biophysical parameters described by *Los et al.* [2000]. To obtain a smooth evolution in time, the ECMWF model does a linear interpolation between successive months, assuming that the monthly field applies to the 15th of the month. The ISCCP albedo is constructed by normalizing the visible portion of the spectral albedo, which depends on the vegetation/land type survey used in the Goddard Institute for Space Studies

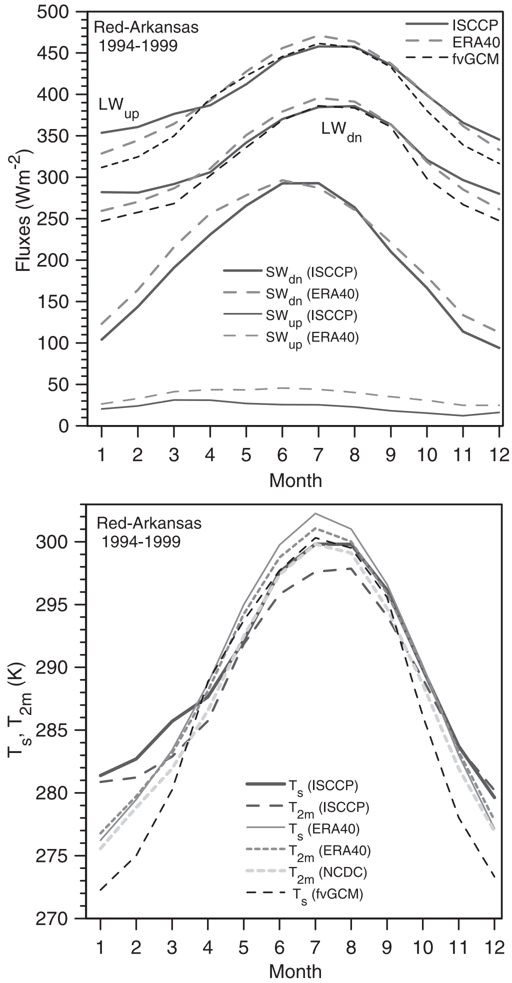

Figure 9. Comparison of surface radiation budget components (above) and surface temperatures (below) for Red-Arkansas basin. See color version of this figure in the HTML.

climate GCM, to the observed ISCCP visible reflectance. In other words, the ratios of the albedos in six wavelength bands are the same as in the model, but the whole spectrum is adjusted to fit the ISCCP measurements.

5. Discussion

[24] ERA-40, is an analysis system, incorporating surface, upper air and satellite observations, while for the fvGCM we have one realization of the model 'climate' for the same 10-year period, so what general conclusions can be drawn from the differences between the basin budgets? The much higher net shortwave in summer in the fvGCM (for all basins) may indicate deficiencies in the radiation and cloud schemes. *Morcrette* [2002b] showed a smaller bias of the same sign in April and May in the ECMWF model over the ARM site in Oklahoma. However, ERA-40 has a much flatter seasonal cycle of surface downwelling SW radiation than the ISCCP surface flux estimate, lower in summer and higher in winter. For this fvGCM run we are missing the separate SW flux components, so we cannot assess the summer bias of SW_{dn} in the fvGCM against the ISCCP data. ERA-40 has significantly higher surface albedo in summer than the ISCCP estimates. This needs further research, since an accurate surface albedo is essential to give a realistic climate.

[25] The large cold surface temperature bias in winter in fvGCM is a systematic error in this model, and the cause is unclear. Earlier versions of the ECMWF model had a similar error, which was reduced by changes to the stable boundary layer parameterization and the coupling to the ground, as well as the introduction of the thermal impact of soil freezing [*Viterbo et al.*, 1999], and at frozen latitudes by reducing the albedo in the presence of snow [*Viterbo and Betts*, 1999]. ERA-40 now has a small warm temperature bias in winter, which suggests this error may have been slightly overcorrected. Compared with NCDC observations of screen temperature, ERA-40 generally has a relatively small ($\leq$1 K) positive temperature bias in all seasons for the Mississippi basins. The ISCCP skin temperature estimate is generally high in winter and a little low in summer, compared to ERA-40 and the NCDC screen level temperature.

[26] The warm season evaporation in the fvGCM is generally too high, as is precipitation for most basins. This generally leads to a wet bias at the surface in the model in summer. The cool season evaporation in ERA-40 for most basins is clearly too high, as it leads to a marked wet bias in winter in comparison with the screen level dewpoint obser-

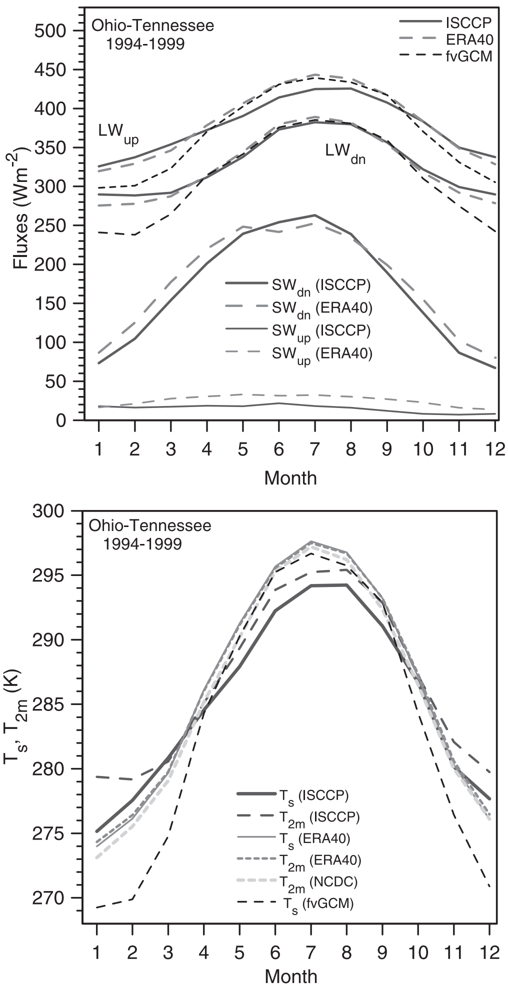

Figure 10. As Figure 9 for Ohio-Tennessee basin. See color version of this figure in the HTML.

vations from NCDC. It probably reflects the lack of a seasonal cycle in the vegetation in that model (that is, the model vegetation continues to evaporate in the cold season). The introduction of leaf area index seasonality into the ECMWF model reduces winter evaporation [*van den Hurk et al.*, 2003]. In summer, ERA-40 has a small dry bias for the western basins, and a small wet bias for the eastern basins, consistent with the higher summer precipitation for the eastern basins.

[27] The large difference in the partition between LSP and CP in the two models is striking. LSP, which dominates the cool season, is much smaller in the fvGCM, and summer CP is higher than in ERA-40. The partition in a model may depend on resolution, since it is simply a projection of a process which occurs over a very wide range of scales, from the cloud scale, frontal and mesoscale, to the synoptic scale, onto the resolved scale and the parameterized deep convection. A quantitative observational basis for this partition depends on the measuring system. The TRMM radar observations [*Schumacher and Houze*, 2003] show that about 40% of the rain in the tropics falls as stratiform rain. ERA-40 has a similar LSP fraction in the summer season, but the fvGCM has essentially no LSP over the summer continents or in the tropics (not shown here). The grid-scale condensation in the fvGCM is determined when mean relative humidity reaches 100%. There is no explicit representation of stratiform clouds or their microphysics, and the *Zhang and McFarlane* [1995] cumulus parameterization does not detrain liquid water to the large-scale environment. The low precipitation bias in the cool season in the fvGCM, when the LSP is low may suggest also a coupling with the large-scale dynamical field, such as weaker cyclone activity.

[28] The larger spin-up of the large-scale dynamics and LSP in ERA-40 makes assessment of its LSP difficult. The hydrological imbalance caused by too little precipitation in the analysis cycle is compensated in summer by the soil water assimilation [*Douville et al.*, 2000], which nudges soil water and temperature using observed surface temperature and humidity biases. For some basins, however, such as the Upper Mississippi and the Ohio-Tennessee, the 12–24 h precipitation in ERA-40 exceeds that observed by 20–30% in some seasons. In spring in ERA-40, negative soil moisture analysis increments compensate for relatively large snowmelt (related in part to positive SWE analysis increments), coupled with low runoff. The model lacks a realistic surface runoff treatment over unfrozen ground. We only show the comparison between the ERA-40 runoff and streamflow for the entire Mississippi, since model runoff was much less than streamflow for all subbasins (as in ERA-15 [*Betts et al.*, 1999]). An improved subsurface hydrology model is still under development.

[29] The comparisons among different basins are interesting as they show the general nature of certain biases. However, the more detailed differences between the basins could have several causes. In ERA-40, there does seem to be a difference in the biases between the western two basins, and the eastern three, with an overestimate of the summer precipitation in the east. The climate in the fvGCM may be significantly different from the observed 1990–1999 climate, which is presumably reasonably represented in the reanalysis. Without the observational constraint (only sea surface temperatures are specified), the fvGCM climate is more sensitive to local land-surface feedbacks, such as precipitation-evaporation feedback, which is quite strong over this region of the United States, at least in the ECMWF model [*Beljaars et al*, 1996]. This could amplify the high precipitation and evaporation in the fvGCM. However, remote forcings and interactions, as well as interactions between the cloud, water vapor and radiation fields, could also impact the model climate for the Mississippi basin.

[30] Comparison of river basin budgets with reanalyses is a useful method of assessing the impact of model changes on the surface energy budget and hydrological balances, and we plan to repeat this work with new versions of the fvGCM using different parameterizations. Some characteristics of the water budget in ERA-40 have changed from ERA-15. The frozen hydrology in ERA-40 is improved (with reduced snow evaporation and larger melt), but the contribution of the snow analysis increments is large, and spring melt may now be too large. A more detailed analysis of the ERA-40 frozen hydrology will be given using the basin budgets for the Mackenzie river [*Betts et al.*, 2003]. The spin-up in ERA-40, using the 3-D variational assimilation system, is larger in winter than in summer. We shall continue to assess the biases in the global reanalyses, since understanding them can lead to improved parameterizations and hence to improved analysis-forecast systems. Reanalyses may give us our best estimate of the global and regional energy and water cycles. However, the goal of the accurate representation of the energy and water budgets in both climate and forecast models, is still a few years in the future.

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