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Eta model estimated land surface processes and the hydrologic cycle of the Mississippi basin

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[1] This article discusses the water and surface energy budgets over the Mississippi River basin and subbasins using NCEP's Eta model forecasts. It also discusses the relation between surface states (soil moisture) and other variables that affect the surface energy balance, potentially interacting with precipitation processes. The Eta model is NCEP's operational mesoscale model and therefore has been subject to changes and upgrades over the period of this evaluation. While the atmospheric water cycle is analyzed here using a 7-year long (June 1995 to May 2002) data set, the research focusing on surface processes is based on a 4-year period (June 1998 to May 2002) after substantial upgrades to the land surface component were performed. On the 7-year average the Eta model 12–36 h forecast precipitation averaged over the Mississippi basin differs from the observed precipitation by 2%, while the estimate of evaporation computed as a residual of the water balance equation differs by 5% from the evaporation estimate resulting from a data set of land surface fluxes prepared with the macroscale hydrologic variable infiltration model (VIC). However, the difference between the model parameterized evaporation and VIC's is about 17% due to excessive bare soil evaporation in the Eta model. Notably, the long-term average of moisture flux convergence also estimated from the 12–36 h forecasts is 0.54 mm day^{-1} over the Mississippi basin, while streamflow observations at Vicksburg average 0.50 mm day^{-1}. This agreement within 10% is a strict test of the quality of the hydrologic cycle estimates; therefore these are promising results for estimates of the water cycle from regional analysis or future regional reanalysis. Subbasins of the Mississippi have diverse land surface-atmosphere interactions at monthly timescales. In the western half of the Mississippi basin, feedbacks can be described as follows: increased soil moisture is associated with a slight increase of net radiation at the surface; latent heat also increases with soil moisture while sensible heat decreases, resulting in an almost linear increase of the evaporative fraction. Increased soil moisture is also associated with a lower lifting condensation level and an increase of observed precipitation (though not statistically significant). The overall results support the concept of a positive feedback in which increased soil moisture affects surface fluxes in such a manner that increased precipitation results. However, toward the east (e.g., the Ohio basin), there are no well-defined land surface-atmosphere interactions, suggesting that other effects, like the advection of moisture, may be more relevant for precipitation processes. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 1866 Hydrology: Soil moisture; 1878 Hydrology: Water/energy interactions; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); *KEYWORDS:* hydrologic cycle, land-atmosphere interactions, regional models

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1. Introduction

[2] The water cycle is a key component of the Climate System, and the quality of its representation is intimately linked to the adequate simulation of seasonal and interannual climate variability. For this reason it is important in climate change studies and scenarios, and consequently it can also be used to evaluate a model's performance. Multiple estimates of the Mississippi water cycle have been presented in the literature as a result of efforts supported by the Global Energy and Water Cycle Experiment (GEWEX) Continental-scale International Project (GCIP). Now, a comprehensive description that resulted from the water and energy budget synthesis (WEBS) is presented by *Roads et al.* [2003] and complemented online at http://ecpc.ucsd.edu/gcip/gcipwebs.html. That initiative summarizes the estimates of different regional and global models, together with global reanalyses and a Land Data Assimilation System (LDAS) data set. Collectively, they characterize the water cycle and provide a measure of the resulting uncertainties, which has been called the "closure of the budget".

[3] The surface energy balance is closely related to the water cycle and is an integral part of the interactions between the atmosphere and land surface (soil, vegetation, snowpack). In its most basic form and dismissing some minor magnitude terms, the surface energy responds to a simple balance between the net radiation energy gained at the surface and the losses due to sensible and latent (evapotranspiration) heat fluxes. On an annual basis over the Mississippi basin, minor components of the balance are the ground heat flux and the energy consumed during snowmelt. Soil moisture is known to have a strong control on the partition between the sensible and latent heat fluxes, known as the Bowen ratio. In addition, the link between surface states and the atmospheric hydrologic cycle intrinsically involves the atmospheric boundary layer. *Betts and Ball* [1995, 1998] showed that the boundary layer variables, like equivalent potential temperature and specific humidity, depend at least in part on the underlying soil moisture. Wet soil conditions force larger equivalent potential temperature, greater cloudiness and precipitation potential [*Entekhabi*, 1995]. These links obviously involve complex nonlinear feedbacks, since precipitation and its infiltration affect the multiple processes that take place in the subsurface (runoff, drainage, etc), which in turn affect evaporation and consequently the Bowen ratio and the boundary layer structure [*Beljaars et al.*, 1996; *Betts et al.*, 1996; *Eltahir*, 1998]. Positive feedbacks between these surface and atmospheric states may lead to persistent wet or dry spells [*Betts et al.*, 1996], while negative feedbacks precisely oppose such persistence. *Eltahir* [1998] acknowledged the complex nature of these interactions, and identified a large number of processes that relate soil moisture with precipitation.

[4] Regional features of the hydrologic cycle and the surface energy balance over the Mississippi basin using the National Centers for Environmental Prediction (NCEP) Eta model and its Eta Data Assimilation System (EDAS) have been discussed by *Berbery and Rasmusson* [1999] and *Berbery et al.* [1999]. Despite the advantages of computing moisture budgets from mesoscale regional analyses, those studies were constrained due to the limited amount of data available at that time. Our systematic processing of data sets from NCEP has now exceeded seven years (1995–2002), including a diverse set of surface variables that have become more realistic throughout the years as a result of changes in model parameterizations. On the other hand, because this is the operational version of the Eta model, its changes throughout the years may have affected other output variables. It could be argued that the future products of the NCEP Eta/EDAS-based Regional Reanalysis project (now underway) are better for this purpose, but in fact it is studies based on operational analyses that help motivate those reanalysis efforts.

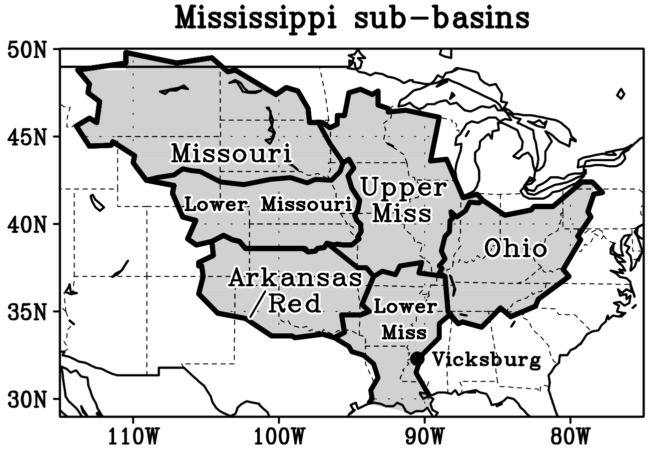


Figure 1. The Mississippi basin and its subbasins. Area averages in the text do not include the lower Mississippi due to unreliable streamflow observations below Vicksburg (marked by a solid circle).

[5] The WEBS article by *Roads et al.* [2003] focuses on a model intercomparison to assess the uncertainties in water and energy budgets from 1996 to 1999. However, the Eta model had important improvements in its physical parameterizations and initial states, some of them as a result of the early analysis of the water and energy cycles. The objective here is to analyze the multiyear water cycle at the surface and atmosphere from NCEP's Eta model products over the Mississippi river basin (Figure 1). Likewise, the surface energy balance and land surface-atmosphere processes are investigated. Therefore this research aims to produce a 'long-term' regional climatology of the water and energy cycles and relate them to land surface-atmosphere processes. The model data sets and observations are discussed in section 2. Sections 3 and 4 address the three parts in which this research is divided: section 3 describes the atmospheric water cycle and its variability for the 7-year period June 1995–May 2002. As will be discussed later, one of the most significant advances with the Eta model was achieved with the implementation of soil moisture cycling in the EDAS in early June 1998. The analysis of the surface energy balance and the surface water cycle are based on four years (June 1998–May 2002) of data and is also included in section 3. Section 4 inspects the relationships between the land surface states and the fluxes at the surface as well as the

Table 1. Significant Eta Model Changes During May 1995 to December 2001

Number	Date	Description
1	12 Oct. 1995	A 12-h Eta model-based Data Assimilation System (EDAS) is introduced (four 3-h cycles) replacing initialization the atmospheric states of the Eta forecast from the NCEP Global Data Assimilation System (GDAS). The 0-h initial atmospheric states of the 12-h EDAS are taken from the GDAS. An explicit cloud microphysics scheme for precipitation and cloud water/ice was added, to replace the simple super-staturation physics, new treatment of roughness length for heat added in surface layer physics.
2	31 Jan. 1996	Major generational upgrade made to the land surface physics. Old bucket model with temporally invariant initial conditions was replaced with a new 2-layer soil model with explicit vegetation physics (with seasonal cycle) and snowpack physics. Initial conditions for soil moisture and temperature at beginning of the 12-h EDAS taken from GDAS Substantial upgrades were implemented in the PBL physics.
3	18 Feb. 1997	The global ISLSCP I database for monthly green vegetation fraction was replaced with a new monthly green vegetation fraction database from NESDIS. The empirical adjustment of the initial soil moisture taken from the global GDAS at the beginning of the 12-hour EDAS was changed. Improvements were made to the physics of melting snow and the treatment of direct surface evaporation from bare soil. Refinements were implemented in the radiation physics to reduce the high bias in surface solar insolation.
4	9 Feb. 1998	Spatial resolution was increased from 48 km to 32 km and from 38 to 45 vertical levels. The number of soil layers was increased from two (10 and 190 cm) to four (10, 30, 60, 100 cm), in both the forecast model and Eta Data Assimilation System (EDAS). The Optimal Interpolation (OI) approach in the EDAS analysis/update step was replaced with a 3-D Variational approach (3DVAR), including the assimilation of GOES satellite-based three-layer precipitable water estimates for the first time.
5	3 June 1998	Fully continuous cycling of all EDAS atmospheric states (including cloud water/ice) and land states (including soil moisture) was implemented, such that the EDAS is no longer restarted every 12-hours from the global data assimilation system (GDAS). The initial snow cover fields in the Eta model started being initialized once daily from the new NESDIS "IMS" daily 23-km N. Hemisphere snow cover analysis.
6	3 Nov 1998	A number of changes were made to the 3DVAR to improve the low-level moisture analysis and to improve the 3DVAR analysis fit to both radiosonde data and surface observations in general (including surface air temperature and surface winds)
7	28 Sept. 1999	The NCEP mainframe CRAY computer caught fire and was destroyed. For the next three months until early January 2000, the operational Eta/EDAS system was executed in a degraded mode of reduced resolution and reduced volume of assimilated observational data, including some breaks in the continuous assimilation system.
8	26 Sept. 2000	The model spatial resolution was increased to 22 km and to 50 levels in the vertical. Direct assimilation of GOES and TOVS-1B satellite radiance data was implemented in the EDAS, and further refinements to the 3DVAR analysis fit to radiosonde moisture data were done. Vertical advection of cloud water/ice and minor modifications to the Betts-Miller-Janjic cumulus convection scheme were added. The horizontal diffusion was further reduced.
9	24 July 2001	The EDAS began operational assimilation of the hourly, national, 4-km "Stage IV" radar/gage precipitation analyses. Frozen soil physics was introduced into the land physics, as well as a substantially upgraded treatment to the physics of snowpack and ground heat flux. Snowpack density was added as a new state variable. Vegetation canopy resistance treatment was refined and the bare soil evaporation scheme was improved.
10	27 Nov. 2001	The horizontal resolution was increased to 12 km and to 60 vertical levels. The cloud and precipitation microphysics were substantially upgraded, including the addition of several new cloud water/ice state variables. The 3DVAR analysis scheme was improved.

atmospheric water cycle. Summary and conclusions are presented in section 5.

2. Eta Model Products and Observational Data Sets

[6] The Eta model is the operational model being executed at NCEP for short-range continental forecasts over North and Central America. The initial conditions are prepared by its own assimilation system, EDAS. Being operational, both components (model and assimilation system) have been modified during this analysis period, therefore their products are not uniform. We have employed Eta products for the period June 1995 to May 2002, and the main changes during this period are summarized in Table 1. A log with all modifications is provided online at http://www.emc.ncep.noaa.gov/mmb/research/eta.log.html. As shown in Table 1, resolution in the Eta model has been increased from an initial 48-km grid spacing in 1995 to 12-km at present. The model physics has also been modified at different opportunities, including major upgrades to the land surface physics. In January 1996 the old bucket model was replaced by a 2-layer soil model [*Chen et al.*, 1996], and in February 1998 the number of soil layers was increased to four. Other upgrades involved parameterizations of surface evaporation, cloud physics, vegetation, and snow. The most recent significant upgrade to the Eta-model land physics occurred on 24 July 2001, with the inclusion of (1) the frozen soil and snowpack physics discussed by *Koren et al.* [1996] and 2) the upgrades to the soil thermodynamics, bare soil evaporation, and ground heat flux components presented by M. Ek et al., (Implementation of the upgraded Noah land-surface model in the NCEP operational mesoscale Eta model, submitted to *Journal of Geophysical Research*, 2003) (hereinafter referred to as Ek et al., submitted manuscript, 2003). With the latter upgrades, the Eta model land component is now referred to at NCEP as the "Noah" land surface model. The evolution of the Noah land model physics over the past 5 years is provided by the following references: *Chen et al.* [1996, section 1.1, 1997], *Betts et al.* [1997], *Koren et al.* [1999], and Ek et al. (submitted manuscript, 2003).

[7] Probably the most significant changes that did not involve changes to the Eta land component physics in the data assimilation system correspond to the change from Optimal Interpolation to a 3-D Variational approach (February 1998), the full and continuous self-cycling of atmospheric and land states including soil moisture and temperature without nudging (June 1998), and the assimilation of observed precipitation that started in July 2001

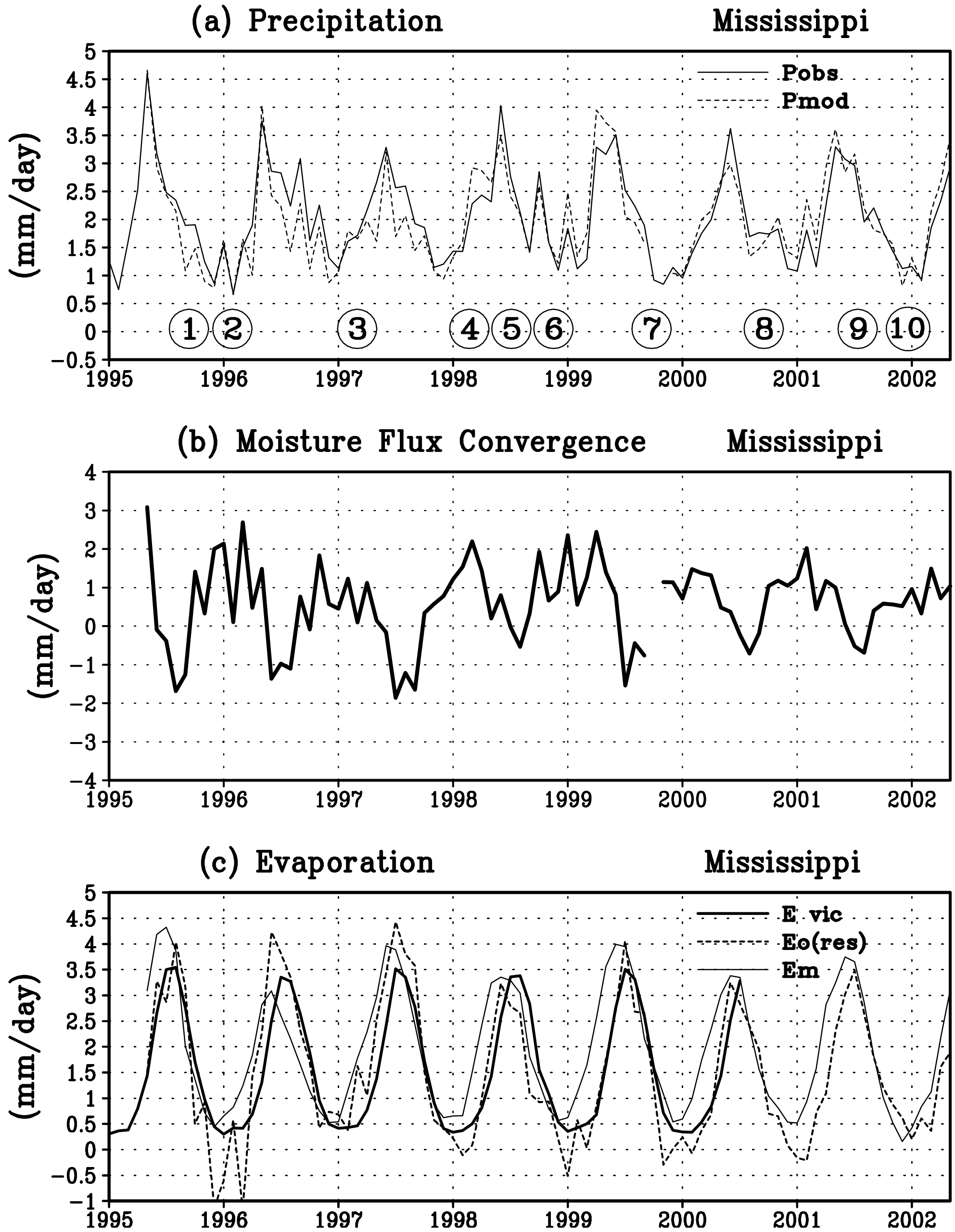


Figure 2. Time series of Mississippi basin area-averaged variables: (a) observed precipitation and Eta model 12–36 h forecast precipitation; (b) Eta model 12–36 h forecast moisture flux convergence; (c) VIC evaporation, Eta model parameterized evaporation, and evaporation estimated as a residual of the water balance equation. Circled numbers in Figure 2a are the model changes presented in Table 1.

[*Rogers et al.*, 2001b]. Within the fully continuous cycling of land states in the EDAS [*Rogers et al.*, 2001a], the soil moisture is the result of (1) the EDAS atmospheric surface forcing fields (downward solar and longwave radiation, wind speed, temperature, humidity, and precipitation; the latter heavily influenced by the EDAS assimilation of radar/gage observed precipitation) and (2) the Eta land model physics, especially the physics of the surface water budget (evaporation, infiltration, runoff, snow melt). Figure 2 presents a time line that associates the model modifications as described in Table 1 with the time series of the Mississippi basin-averaged 12–36 h forecast precipitation, which will be discussed in section 3.

[8] In this study we employ the 12–36 h Eta forecasts to produce a 7-year climatology of the atmospheric water budget, and a 4-year climatology of the surface water and energy cycles. Our decision to use 12–36 h forecasts, rather than the 3-hourly fields of the continuous assimilation timeline, is driven by the fact that the 12–36 h forecast fields manifest notably less spin-up or spin-down than is present in the assimilation fields, which are constantly adjusting to the assimilated observations. Yet the 12–36 h forecast length is still sufficiently short to avoid the model drift and bias that is

commonly known to significantly degrade the long-range forecasts of any coupled land/atmosphere model. Moreover, in this approach there is no need to include analysis increments to compensate for hydrologic cycle imbalances that may arise from observations-based corrections applied by the assimilation scheme to yield the model initial state of analysis fields. In other words, while not exempt of errors, the 12–36 h forecast is the best compromise. Before February 1998 the moisture flux convergence was computed on the model's native grid. Afterward, due to changes in the operational setting, it was computed on an interpolated grid with a 40 k grid spacing. Several tests were done, and the differences between the estimates on both grids are negligible at scales of one month or longer.

[9] Gauge-only observations of daily precipitation are objectively analyzed to a continental United States daily precipitation analysis on a 0.25-degree latitude-longitude grid, as described by *Higgins et al.* [2000]. This daily precipitation analysis was employed for the evaluation of Eta forecast precipitation and to complement the analysis of the water cycle (the observed precipitation component of the atmospheric water budget). Monthly streamflow from 1995–2000 at Vicksburg was employed to measure the discharge of the Mississippi river. The catchment area is 2,964,252 km^2 and does not comprise the delta, where an integrated measure of the streamflow would be extremely difficult.

[10] The variable infiltration capacity (VIC) macroscale hydrologic model was employed by *Maurer et al.* [2001, 2002] to develop a 50-year data set of surface variables at 0.125° grid spacing over the United States and nearby regions. This model is described in detail by *Liang et al.* [1994, 1996] with recent updates described by *Cherkauer et al.* [2002] (although these updates were not included for the current products discussed here). It solves full water and energy balances, and more importantly, has been applied to compute runoff for basins that range from 10^5 to 10^6 km^2. According to *Maurer et al.* [2002], it matches well the observed runoff mean seasonal cycle for the Mississippi basin. The initial data (forcing) consist of observations (e.g., precipitation, surface temperature) and derived data (e.g., downward solar radiation), and by requiring a balance of the surface water and energy budgets, a highly consistent data set is derived. While not exempt from possible systematic errors in physics or forcing, VIC's results from *Maurer et al.* [2002] can be used as a reference for other model computations. Here, in the absence of observations, this data set will be employed to assess the degree of similarity with Eta parameterized variables. Additional comparisons are given by K. Mitchell et al. (The multi-institution North American Land Data Assimilation System (NLDAS) Project: Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system, submitted to *Journal of Geophysical Research*, 2003).

[11] The observed precipitation employed as a forcing by VIC has corrections to reduce biases due to orographic effects [*Maurer et al.*, 2002], while the *Higgins et al.* [2000] data set does not. The differences between the two data sets over the Mississippi River basin typically range between 0.1 and 0.2 mm day^{-1}, but increase over mountainous terrain. Although small, this difference could account for some of the discrepancies between our results and those of VIC.

3. Water and Energy Budgets

3.1. Atmospheric Water Budget (June 1995 to May 2002)

[12] Figure 1 presents the Mississippi River basin and its subbasins. Because river discharge cannot be measured reliably in the lower Mississippi below Vicksburg (32.3°S, 90.5°W), all area averages exclude this subbasin. In this form, area averages are consistent with the streamflow measured at Vicksburg. [However, for reference, figures in this article will depict the contour of the whole basin.]

[13] The 1995–2002 time series of the Mississippi basin area-averaged Eta model 12–36 h forecast precipitation and observed precipitation (based on the daily analyses of *Higgins et al.* [2000]) are presented in Figure 2a, along with a sequence of numbers that represent the major changes in the model as described in section 2 and Table 1. The two curves depict close similarity in magnitudes and the year-to-year variability, but some changes are noticed over the years. Differences are larger before 1998, as the forecast precipitation (heavy line) tended to have higher month-to-month variability and discrepancies in magnitude. From mid-1998 onward, when atmospheric and land states (including soil moisture) began to be cycled without a dependence from NCEP's global model (indicated by 5 in Figure 2a), the observed and forecast precipitation tend to show a closer agreement. The last part of the record (marked with number 9) shows even closer correspondence. This was the time when the EDAS began to assimilate observed precipitation.

[14] The differences between the early and late periods are manifested in the scatterplots of monthly observed vs. forecast precipitation averaged for the Mississippi basin (Figure 3). During 1995–1997 (Figure 3a) the Eta model had a dry bias during both the cold and warm seasons, particularly in the range 1–3.25 mm day^{-1}. On the other hand, during 1998–2002 (Figure 3b) a more even distribution of points along the symmetric axis is noticed. There appears to be a slight wet bias, particularly for large precipitation during winter, but the magnitude is smaller than the dry bias of previous years. The dry bias during the first years was observed in all subbasins except the Ohio basin (not shown), but it was removed beginning in mid-1998. The slight wet bias during the 1998–2002 winters affects the Missouri and Upper Mississippi basins.

[15] Evaporation was estimated as a residual of the water balance equation, $E_{res} = P_o + \int_p \nabla \cdot qVdp + Q_t$ where P_o is the observed precipitation, $-\int_p \nabla \cdot qVdp$ is the vertically integrated moisture flux convergence, and Q_t is the local change in water content in the column. The last two terms are computed from the Eta model 12–36 h forecast. Q_t, is significantly smaller than the other terms, and plays no role in a long time average as this one. In reality, evaporation estimated this way also includes other potential sources not accounted in the simple balance equation, but the results of *Maurer et al.* [2002] show that this computation has less errors than other estimates. Moisture flux convergence, presented in Figure 2b, ranges between −2 mm day^{-1} and +2 mm day^{-1} most of the time. As with precipitation, the

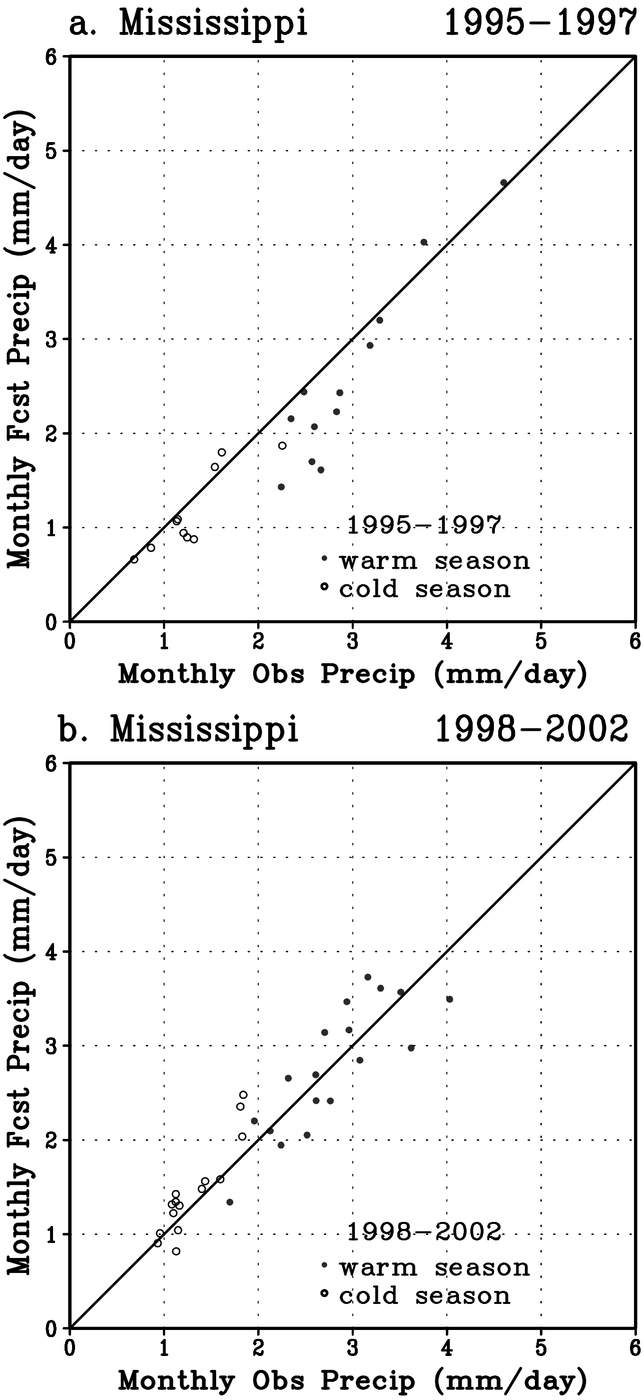


Figure 3. Scatterplots of Mississippi basin area-averaged monthly observed precipitation versus Eta model 12–36 h forecast precipitation for (a) 1995–1997 and (b) 1998–2002. Warm season is defined as May-August, and cold season is defined as November-February.

month-to-month variability seems to be smaller during the second half of the period. These changes may be due to the adjustment of the model to different initial conditions beginning in 2000. According to Figure 2c, the evaporation estimated as a residual of the water balance has larger amplitude, and larger interannual variability than the evaporation estimated with the VIC model, which has a rather uniform annual cycle. The residual evaporation also tends to peak about one month before the VIC estimate. During the winter 1996/1997 and less dramatically during other winters, negative values of evaporation are produced. This may be in part due to the underestimation of observed precipitation during the cold season, and to errors in the estimated moisture flux convergence. The parameterization of the Eta model evaporation, also presented in Figure 2c, was changed several times along the years, nevertheless it continued to have excessive values during spring. This will be discussed later in the article.

[16] Figure 4 presents the annual mean observed and forecast precipitation. The 12–36 h Eta model forecast precipitation (Figure 4a) bears most of the features of the high resolution rain gauge based analysis (Figure 4b). According to the difference field (Figure 4c), the forecast precipitation has a slight negative bias over the Mississippi basin, and positive over Florida and along the southeastern United States coastline (of about 1–2 mm day^{-1}). However, this bias is notably smaller than that depicted in global reanalysis precipitation [*Higgins et al.*, 1996]. Although the maxima and field structure toward the west seem similar in the model and observations (Figures 4a and 4b), the orographic effects are marked and produce large biases (Figure 4c) particularly over the Cascades and Sierra Nevada. The model forecasts over the southern coast of California and central Arizona are slightly drier than observations.

[17] Other components of the atmospheric water cycle are presented in Figure 5. The moisture flux convergence (Figure 5a) is positive over most of the Mississippi basin and particularly over the Ohio basin, where annual values achieve a maximum of about 2 mm day^{-1}. Slightly negative values between -1 and 0 mm day^{-1} (divergence) are found over a narrow band of the Central U.S. in the western part of the Mississippi basin. A second region of divergence in the southeastern U.S. runs along the coastline, which is associated with the dominant moisture flux divergence over the oceans. To the west, patterns are more difficult to interpret and large values of either sign are found over the complex terrain of the Rockies, Sierra Nevada, and the Cascade Mountains. These kinds of patterns are typically produced in mesoscale model simulations where the moisture flux divergence can achieve larger magnitude and gradients than typical estimates from global reanalyses.

[18] Evaporation computed as a residual of the atmospheric water cycle equation is largest in the eastern part of the country, toward the coasts of the Gulf of Mexico and the Atlantic Ocean (Figure 5b). Values progressively decrease toward the north, and mostly range between 1 and 4 mm day^{-1}. The Eta model parameterized evaporation (from the 12–36 forecasts; Figure 5c) presents a much smoother field, and its magnitude over the eastern part of the basin is larger. Largest differences between the two evaporation estimates are found in the western part of the country, most prominently over California, and in particular the Central Valley, where the evaporation estimated as a residual from the Eta model exceeds 5 mm day^{-1}. The large values in this region result from the moisture flux convergence term (Figure 3d) in the balance equation. Because of the nonexistence of evaporation observations, these fields are compared to VIC's evaporation, which responds to the surface water

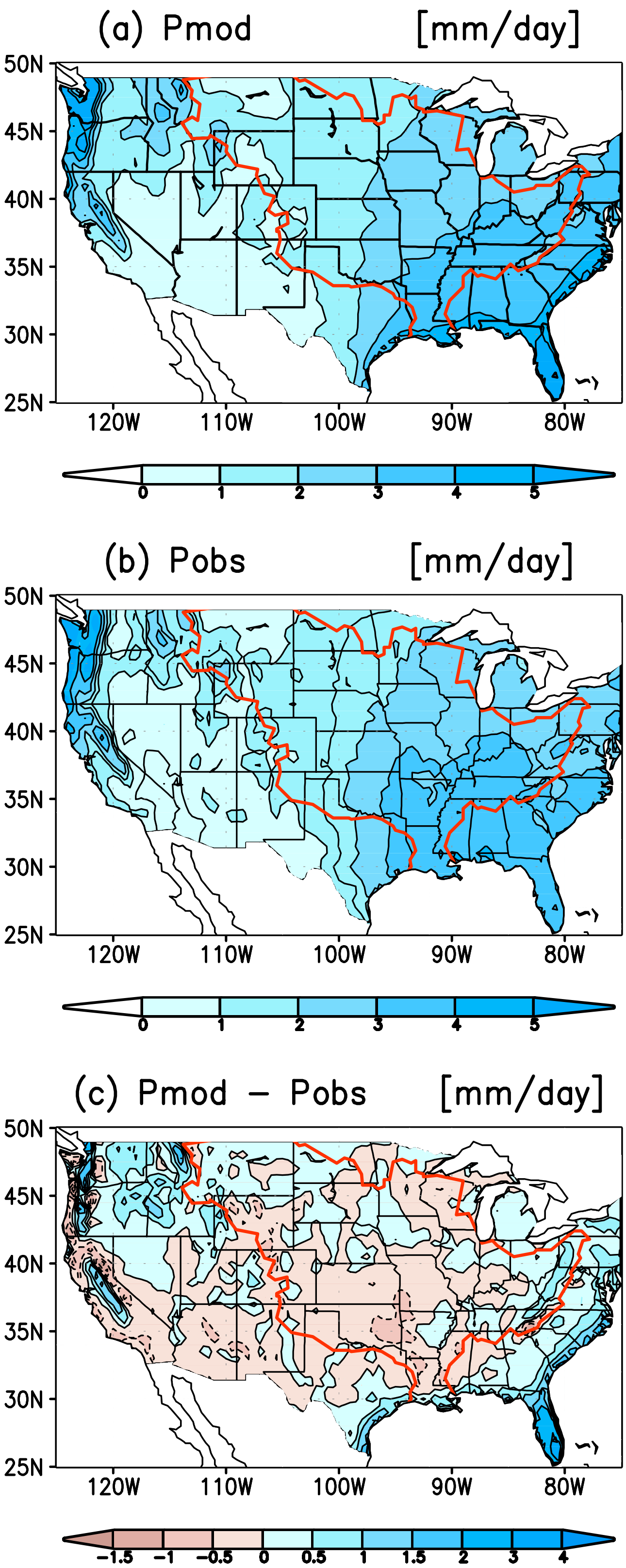


Figure 4. June 1995 to May 2002 annual mean fields of (a) Eta model 12–36 h forecast precipitation, (b) observed precipitation, and (c) their difference.

balance equation forced with observations or parameters derived from observations. Figure 5d shows that the VIC's evaporation field is also more uniform and smoother than the one estimated as a residual of the water balance. Values within the Mississippi basin range from somewhat less than 1 mm day^{-1} over the northwestern sector of the Missouri subbasin to near 3 mm day^{-1} over the lower Mississippi subbasin. VIC's evaporation along the Gulf of Mexico coast has lower values than the two Eta estimates. In all these cases the reader is reminded that VIC data sets are not available after July 2000, so that differences may also be due to the difference in the averaging period.

[19] The June 1995 to May 2002 mean annual cycle of the atmospheric water cycle averaged over the Mississippi basin is presented in Figure 6a. Observed precipitation achieves a maximum during May–June and smoothly decays to a minimum in December. Moisture flux convergence tends to remain constant at about 1 mm day^{-1} from October to May of the next year, when it begins to decrease and in fact converts to divergence from June to September, with largest divergence values near −1 mm day^{-1} during August. The divergence of moisture flux during summer is a typical feature of the Mississippi basin [see, e.g., *Berbery and Rasmusson*, 1999]. The local change of precipitable water is small at all times, and does not measurably contribute to the estimate of evaporation.

[20] The evaporation estimated as a residual of the water balance equation is consistent with previous results, including the Eta-based 2-year estimate by *Berbery and Rasmusson* [1999]. During winter, values are small and positive although, as previously shown, individual years may achieve negative values. Evaporation increases rapidly during spring achieving a maximum of 3.5 mm day^{-1} in July. The decrease of evaporation during the second half of the summer may be associated with the drying of the soil moisture, in addition to the browning (senesence) of the vegetation. As will be shown later (Figure 8), by August the soil moisture dry-down has reached a sufficiently dry state as to contribute to vegetation transpiration stress—that is, decrease of evaporation through the plant canopy owing to the increasing soil moisture deficit of late summer (August–September).

[21] The difference between the 12–36 h forecast Eta precipitation over the Mississippi basin and observations is not uniform along the year (Figure 6b). During the warm season, the model tends to produce less precipitation than suggested by observations. During winter and early spring, the model produces slightly more precipitation (at most 0.5 mm day^{-1}), and this does not necessarily mean an erroneous forecast, since others have shown the winter underestimation of solid and liquid precipitation [e.g., *Groisman and Legates*, 1994]. Similar biases were found by *Adam and Lettenmaier* [2003] not only at regional scales but even on the mean annual global terrestrial precipitation. This emphasizes the need to have more studies in this area given the implications it has for model performance evaluation.

[22] Figure 6c presents the two estimates of evaporation, as a residual of the water balance equation and the model parameterized evaporation. The first aspect to be noticed is that although their magnitude is close to the VIC's estimate, they are larger during spring and smaller during autumn, causing a one month shift with respect to VIC's, which

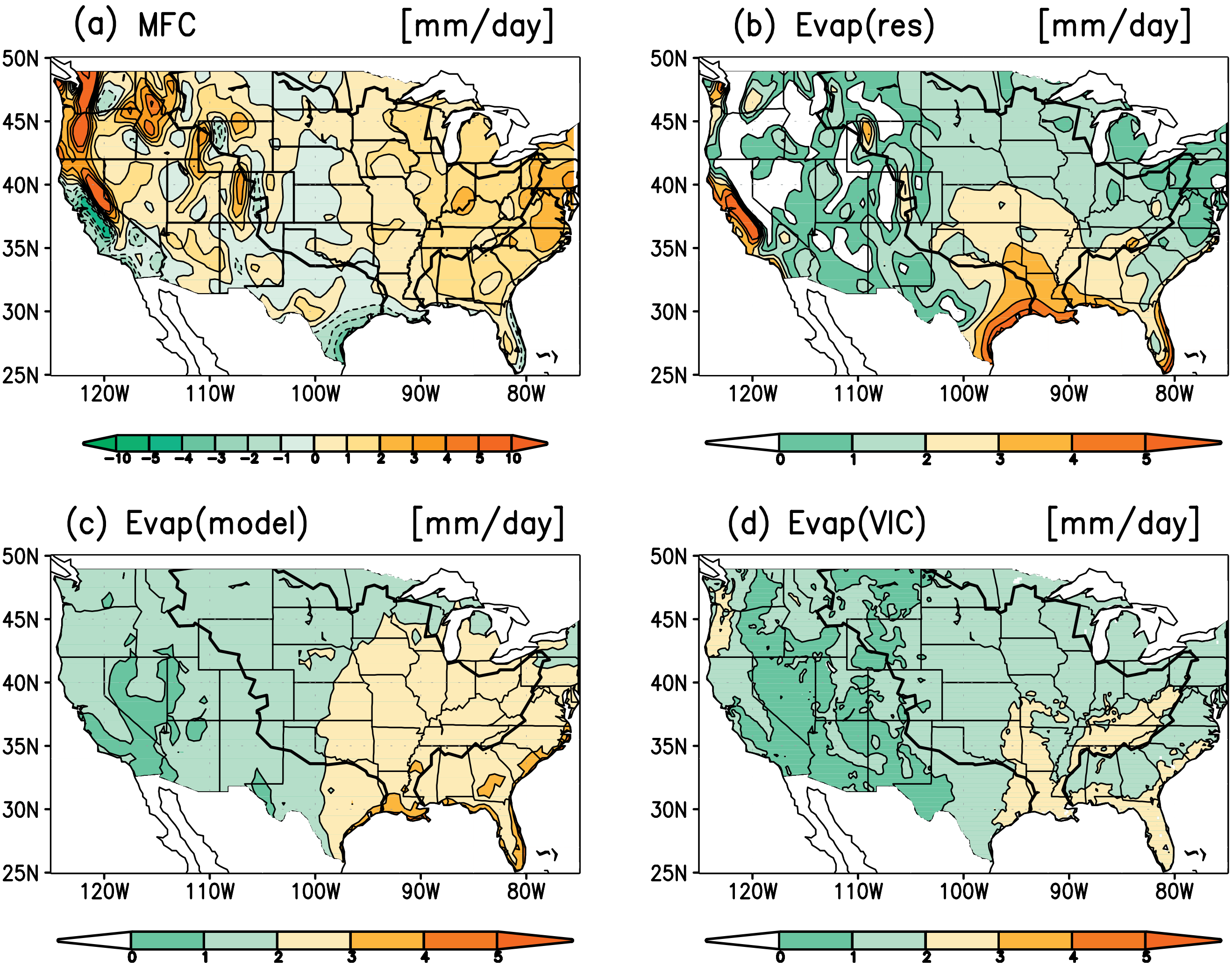


Figure 5. June 1995 to May 2002 annual mean fields of (a) vertically integrated moisture flux convergence, (b) evaporation as a residual of the water balance equation, (c) Eta model parameterized evaporation, and (d) VIC estimated evaporation.

achieves a maximum during July–August. The excessive model evaporation during spring causes a shift in other variables as well: as a result of the Eta land surface parameterizations producing too much evaporation in spring, by August the Eta soil moisture is sufficiently more depleted than VIC (not shown), and consequently the Eta surface evaporation in August becomes more stressed than that of VIC. The bare soil evaporation in the Eta scheme was improved in the 24 July 2001 implementation (see Table 1) to greatly reduce the Eta bias of surface evaporation over relatively moist "bare" soils (meaning sparse green vegetation; this situation is most pervasive in spring over the Mississippi Basin). Hence, until the 24 July 2001 implementation, the Eta had a low-level near-surface air temperature cool bias that arose as a result of the land surface evaporation being too high and the Bowen Ratio being too low over moist bare soils over the eastern two thirds of the U. S. during spring (before the emergence of crops and before significant early-summer green-up of natural vegetation) [*Mitchell et al.*, 2002].

[23] Table 2 presents the 7-year means of the water cycle components, and the observed streamflow at Vicksburg is added for comparison. Two estimates of observed precipitation are presented, the first one from *Higgins et al.* [2000] and the second one that was used as a forcing for VIC. The latter has a correction due to orography effects, but over the Mississippi basin their difference is about 0.1 mm day^{-1}. The difference between the long-term average of the Mississippi basin-averaged observed and forecast precipitation is about 2%. Differences are larger between evaporation estimates; the residual evaporation is about 5% lower than VIC's, but the parameterized evaporation is about 17% larger. The implied magnification of the residual evaporation with respect to the difference in precipitation is due to the nature of the computation, since the moisture flux convergence is about an order of magnitude less than precipitation.

[24] Because of the surface water balance equation, in a long-term average the model moisture flux convergence should equal the observed streamflow. Observed streamflow for the period 1995–2000 (observations were not available afterward) is on average 17128 m^3 s^{-1}, which is equivalent to 0.50 mm day^{-1} if the basin area is taken into account, while the Eta model forecast moisture flux convergence is

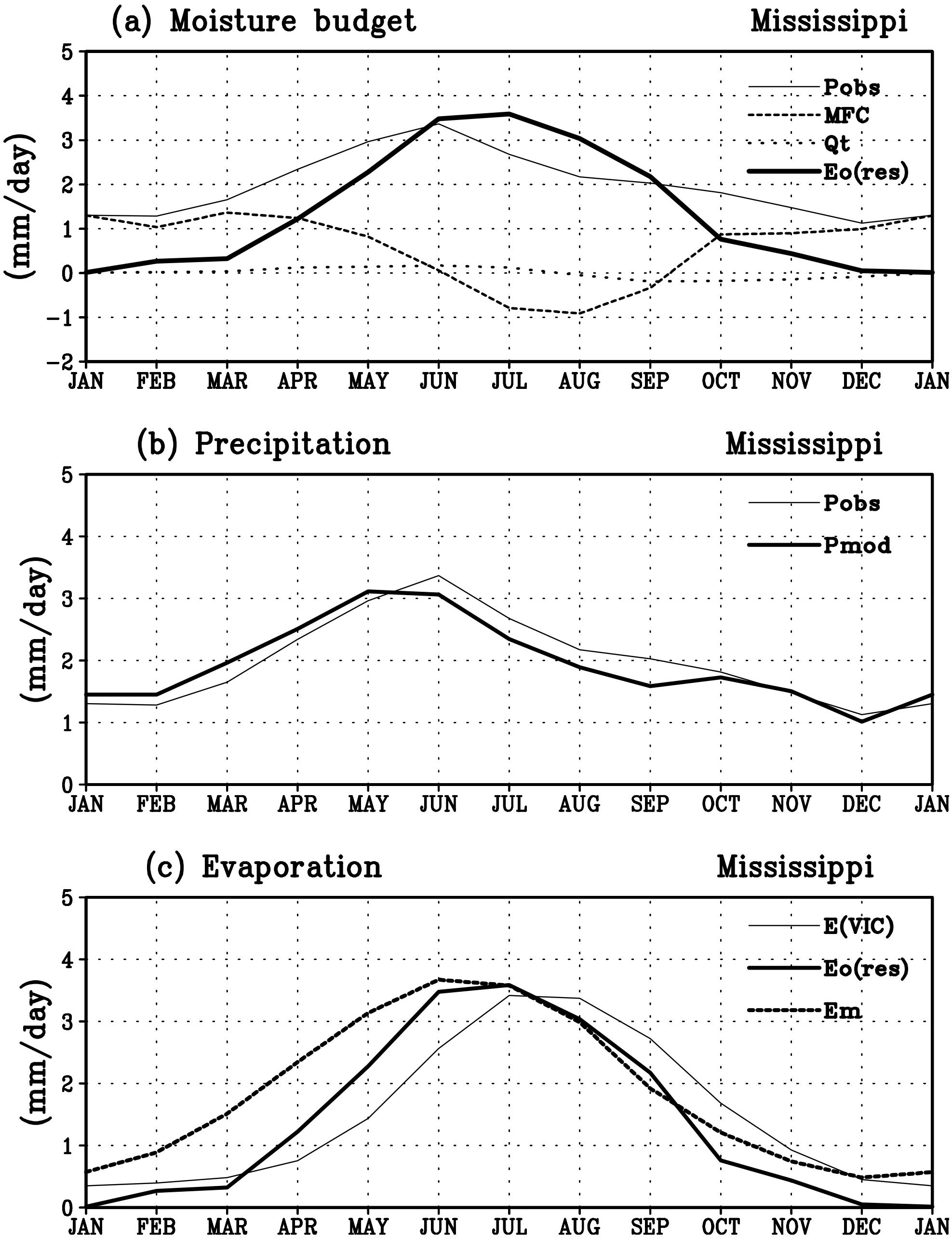


Figure 6. June 1995–May 2002 Mississippi basin area-averaged mean annual cycle of (a) moisture budget components, i.e., observed precipitation, Eta model 12–36 h forecast vertically integrated moisture flux convergence, local change of water vapor content, and evaporation (Eo(res)) estimated as a residual of the moisture balance; (b) the observed precipitation, and the Eta model 12–36 h forecast precipitation; and (c) VIC evaporation, evaporation as a residual of the water balance equation using observed precipitation, and the model parameterized evaporation.

0.54 mm day^{-1}. The difference is less than 10% and represents a notable achievement by the Eta model. The estimate of streamflow as the difference between VIC's precipitation and evaporation is 0.52 mm day^{-1}, despite the record length being about two years shorter.

[25] These estimates do not consider the effect of upstream diversions and reservoir evaporation, which is not accounted for in the Eta model. *Roads et al.* [2003] discusses and applies adjustments and corrections for these two effects. According to Lettenmaier (personal communication, 2003) the "naturalized flows" should be of the order of 8% larger than the measured flows.

3.2. Land Surface Water Budget

[26] Figure 7 presents the annual mean fields related to the surface water as produced by the Eta model parameterizations. In this case, the averages are performed for the period June 1998–May 2002, to avoid the earlier period when surface parameterizations had important changes; we still included several months after the July 2001 upgrade

Table 2. June 1995 to May 2002 Annual Mean Basin-Averaged Precipitation (P), Streamflow (S), Moisture Flux Convergence (MFC), and Evaporation (E)[a]

	Value in mm day^{-1}	Value in m^3 s^{-1}
P_o	2.02	
P_m	1.98	
P_{VIC}	2.11	
S_o (6/1995–5/2000)	0.50	17128
MFC	0.54	18579
$P_{VIC} - E_{VIC}$	0.52	17840
$E_{res} = P_o - MFC$	1.48	
E_m	1.94	
E_{VIC}	1.59	

[a]Subindices are observed (o), Eta model (m), VIC model (vic), and residual of the water balance equation (res). The equivalence between mm day^{-1} and m^3 s^{-1} is obtained taking into account the Mississippi basin's surface area.

(Table 1) to have four complete years. Note that the Eta model estimates reported in *Roads et al.* [2003] are somewhat different to those reported here. The reason is that those estimates were based on the period 1996–1999, thus the first half of the period was not favorable given the model changes explained in section 2.

[27] The water equivalent of accumulated snow depth presented in Figure 7a shows a smooth latitudinal gradient within the Mississippi basin, with values of about 10–20 mm toward the north. Large values of snow accumulation exceeding 50 mm are found over mountainous regions, particularly affecting the western part of the Missouri basin, although the largest values fall outside the basin. The structure of the field is similar to that from VIC (not shown here, but see the WEBS document online at http://ecpc.ucsd.edu/gcip/gcipwebs.html). The total content of soil moisture in the layer 0–2 m is presented in Figure 7b. The western subbasins (Arkansas/Red and Missouri) are the driest, with values between 400 and 500 mm, while toward the east, the Ohio subbasin and the Mississippi delta are the ones with highest soil moisture (600–700 mm).

[28] The Eta model forecast runoff within the basin (Figure 7c) is largest on the eastern part of the basin and the lower part of the Mississippi, and is similar to the estimates from the VIC model (again, see http://ecpc.ucsd.edu/gcip/gcipwebs.html). Runoff achieves large values near the Rockies, the Central Valley in California and the coast of Texas, but no observations are available to verify these features.

[29] The Mississippi basin-averaged mean annual cycle of surface water variables is presented in Figure 8. For two variables, snow and runoff, the VIC estimates are included for comparison (VIC is available only until mid-2000). Observed streamflow at Vicksburg is also included, and its units have been converted to mm day^{-1} taking into account the basin's surface area. Compared to VIC, the Eta model snow water equivalent (Figure 8f) has a positive bias during winter, and decays faster during spring. Because of

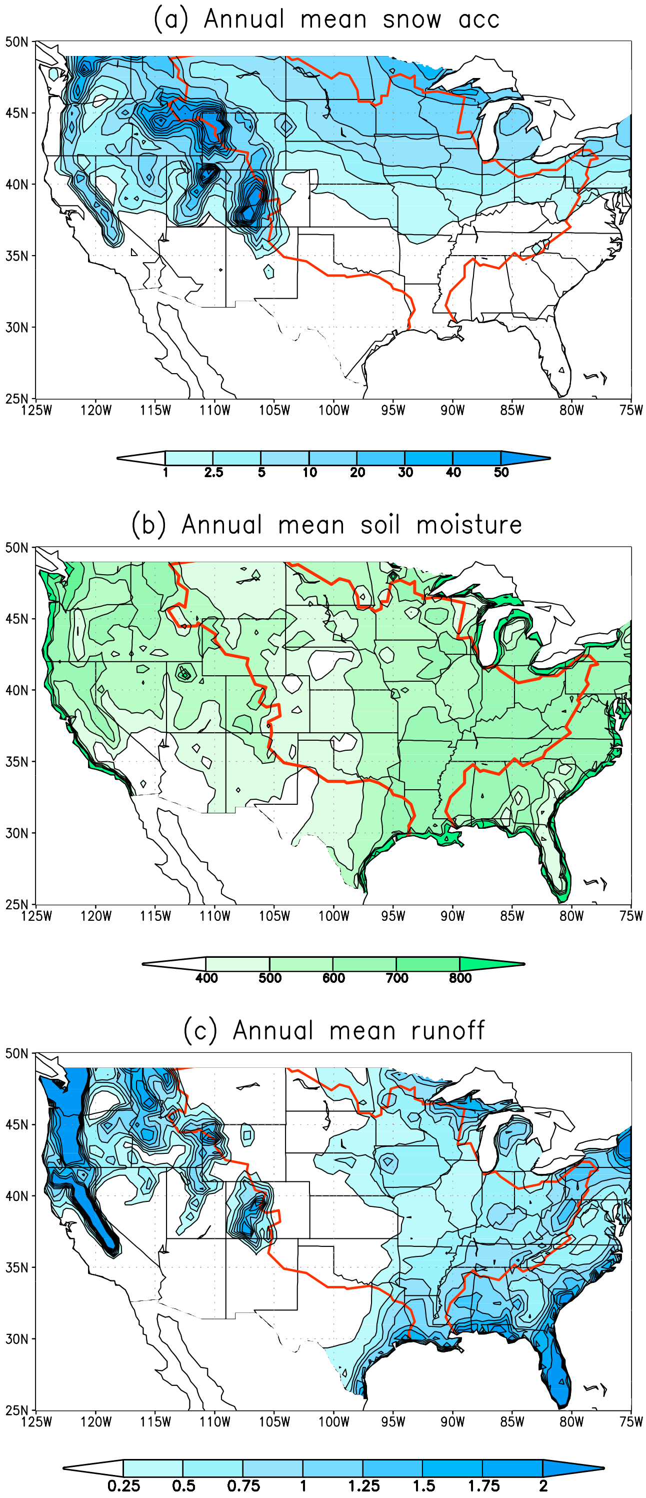
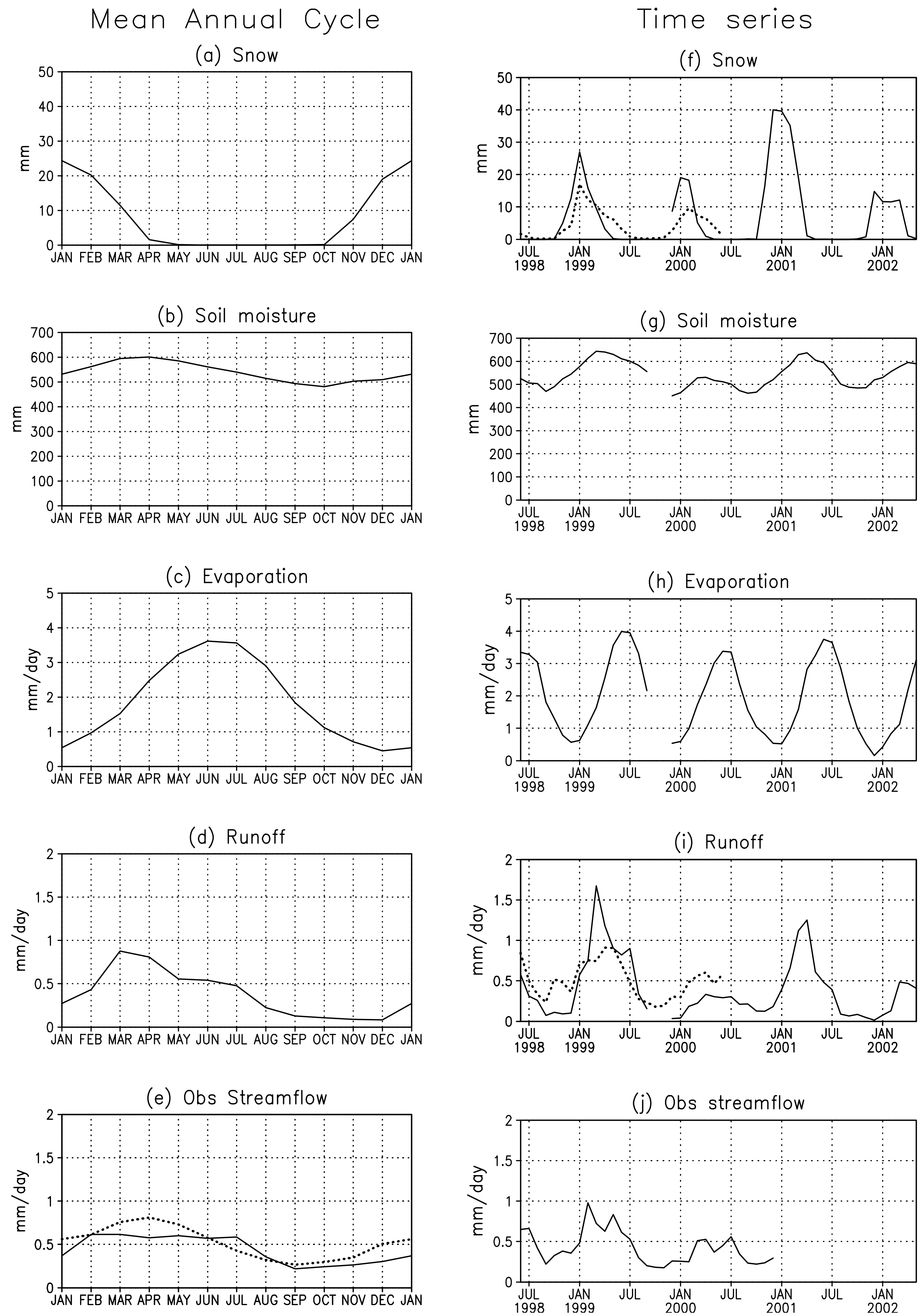


Figure 7. June 1998 to May 2002 annual mean (a) water equivalent of accumulated snow depth, (b) soil moisture for the 0–200 cm layer, and (c) runoff. All fields are computed from the Eta model 12–36 h forecasts.

Figure 8. (opposite) June 1998 to May 2002 Mississippi basin area-averaged mean annual cycle and time series of water equivalent of accumulated snow depth (a and f), total soil moisture (b and g), evaporation (c and h), runoff (d and i), and observed streamflow (e and j) converted to mm day^{-1}. Dotted lines in Figures 8f and 8i are estimated from VIC. Dotted line in Figure 8e is the 1962–2000 average.


Mean Annual Cycle
Time series
(a) Snow
(b) Soil moisture
(c) Evaporation
(d) Runoff
(e) Obs Streamflow
(f) Snow
(g) Soil moisture
(h) Evaporation
(i) Runoff
(j) Obs streamflow
mm
mm/day
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
JUL 1998
JAN 1999
JUL
JAN 2000
JUL
JAN 2001
JUL
JAN 2002

the limited overlap between the Eta and VIC time series, no clear conclusions can be inferred for the runoff (Figure 8i) and the observed streamflow (Figure 8j), but the magnitudes and year-to-year changes are similar.

[30] The mean annual cycle of all variables seems to have a consistent evolution. The Eta model's water equivalent of accumulated snow (Figure 8a) has nonzero values starting in November, achieves a maximum of about 25 mm in January and later decays (snowmelt) until April-May. Soil moisture (Figure 8b) achieves a maximum in spring, about 3 months after the maximum in snow. Then it decays monotonically until October, due to the increasing evaporation (see Figure 8c), and reduced precipitation during summer. Recall that during the first half of the year, the model evaporation is larger (by about 1–2 mm day^{-1}) than the estimates as a residual from the water balance as shown in Figure 6c. The reasons for the excessive evaporation during spring and subsequent reformulation of the bare soil evaporation are discussed by *Mitchell et al.* [2002] and Ek et al. (submitted manuscript, 2003). Model runoff (Figure 8d) also achieves a maximum during late winter and spring, while snow is melting, after which it also decays until the following winter. The annual cycle of Eta model runoff is like the longer term (1962–2000) mean annual cycle of the observed streamflow (dotted line in Figure 8e). However, the observed streamflow mean annual cycle for the period 1998–2000 is irregular and almost constant from February to July. (Further work with routing and management models is needed to transfer model runoff to an accurate simulation of streamflow.)

[31] Although model upgrades prevent a reliable analysis of the interannual variability, there are changes that occur consistently among all variables and observations. The winter of 1999/2000 had a minimum in water equivalent of accumulated snow (Figure 8f) which was followed by low values of soil moisture the next spring (Figure 8g), and somewhat smaller evaporation and runoff also during spring (Figures 8h and 8i). Note that observed streamflow (Figure 8j) also was smaller during the year 2000, which is a confirmation that the independently computed values in the model are consistent. Similarly, the peak in snow in January 1999 was followed by larger values of soil moisture and runoff in March 1999, and evaporation in June 1999. A similar sequence can be noticed after the peak in snow in December 2000.

[32] The annual means of the surface variables are presented in Table 3. Differences in precipitation are larger (5%) than for the 7-year period, despite the improvements in model estimates, but at the same time a shorter period is covered. VIC's evaporation falls in between the two Eta evaporation estimates: the Eta model parameterized evaporation (E_m) and the estimate as a residual of the balance equation differ from VIC's by about +17% and −20% respectively. Measured streamflow at Vicksburg was converted to mm day^{-1} to compare to runoff estimates. The difference between VIC's runoff and streamflow is of about 4%, while the Eta model parameterized runoff differs from them by about 15–20%.

3.3. Land Surface Energy Balance

[33] The Eta model is known to have a positive bias in downward shortwave radiation at the surface [see, e.g., *Berbery et al.* 1999], and the results here verify it. The other surface radiation terms compensate such bias, and consequently the surface energy balance is closer to observations and other models [*Berbery et al.*, 1999]. Figure 9 compares the downward shortwave radiation of the Eta model (Figure 9a) with that estimated from GOES satellite products derived by *Pinker et al.* [1999] (Figure 9b). Differences in the southwestern United States are of the order of 10%, but increase toward the northeast, achieving a bias of 30–40% near the Great Lakes and eastward (Figure 9c). This bias is present throughout the year, but is largest during summer (Figure 9d).

Table 3. June 1998 to May 2002 Annual Mean Basin-Averaged Observed Precipitation (P_o), Eta Model Precipitation (P_m), Evaporation From VIC (E_{VIC}), From the Eta Model (E_m), and From the Water Balance Equation (E_{res}), Eta Model Runoff (R_m), and VIC Runoff (R_{VIC})

	Value, mm day^{-1}
P_o	2.00
P_m	2.10
E_{VIC} (6/1998–5/2000)	1.66
E_m	1.95
$E_{res} = P_o - MFC$	1.33
S_o (6/1998–5/2000)	0.48
R_{VIC} (6/1998–5/2000)	0.50
R_m	0.40

[34] The terms of the summer (defined as May through August) mean surface energy balance are presented in Figure 10. Model constraints mandate that the net radiation flux at the surface be mostly compensated by sensible, latent and ground heat fluxes (plus other minor terms). Net radiation (Figure 10a) shows largest gain (~200 W m^{-2}) over the eastern part of the country, with a weak gradient and minimum values (~120/150 W m^{-2}) toward the western U.S. Loss of energy at the surface is mostly partitioned between sensible heat and latent heat fluxes, with a minor contribution of the ground heat flux. The loss of energy by sensible heat (Figure 10b) is largest in the western semiarid regions and other areas with reduced clouds. Minimum values between −40 and −20 W m^{-2} are noted south of the Great Lakes, over the Upper Mississippi and Ohio basins. In general, within the Mississippi basin, values do not exceed −80 to −100 W m^{-2}. The latent heat flux (Figure 10c) has largest values toward the east, where there is more moisture availability, and smallest toward the west. As a result of the opposing gradients, the Bowen ratio (Figure 10e), is less than one over most of the Mississippi, reflecting the dominance of the latent heat, and increases toward the semiarid regions of the southwestern United States and northern Mexico. Over desert regions it exceeds 10, highlighting the different climate regimes. The ground heat flux (Figure 10d) is typically one order of magnitude less than the other terms, and therefore is a small part of the surface energy balance.

[35] Figure 11a presents the mean annual cycle of the surface energy terms area-averaged for the Mississippi basin. Latent heat exceeds the magnitude of the sensible heat at all times, and during summer is about double. Therefore June-July values of net radiation, which are about 170 W m^2, are balanced two thirds by the latent heat (~100 W m^{-2}), somewhat less than one third by the sensible heat (~60 W m^{-2}) and less than 10 W m^{-2} by the ground heat flux. The Bowen ratio (Figure 11b) increases

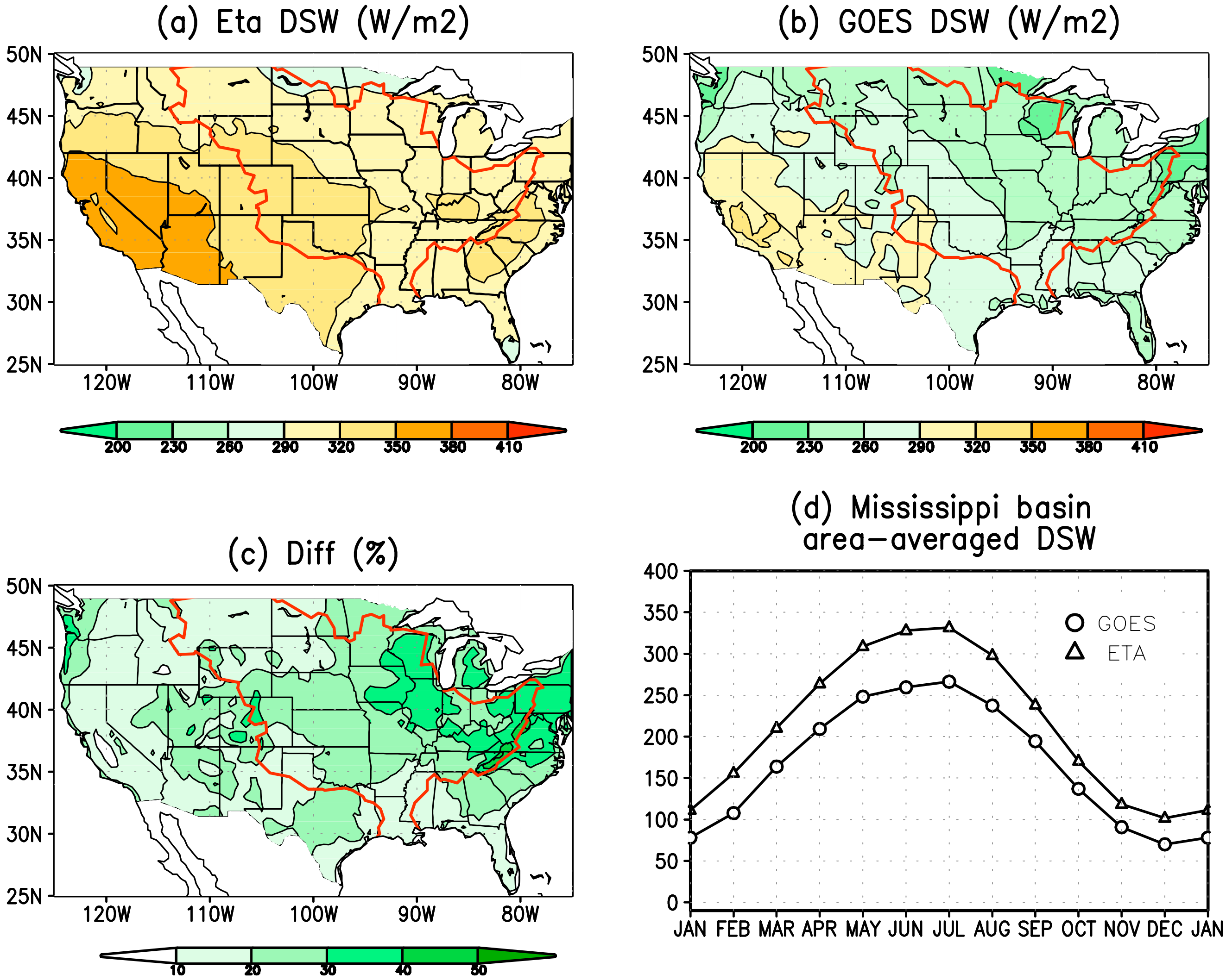


Figure 9. The 1998–2001 summer (MJJA) mean fields of downward shortwave radiation estimated from (a) the Eta model 12–36 h forecasts and (b) from GOES satellite products, (c) their ratio, and (d) their mean annual cycle.

during January–March due to the increase of sensible heat, and then remains nearly constant during spring and summer. However, with the progress of the warm season and the drying of the vegetation, there is a reduction of the latent heat (evapotranspiration) that results in a peak of the Bowen ratio in September. The ratio's negative values during winter imply that the sensible heat is toward the surface (as seen in Figure 11a). The time series of the same variables (Figure 11c) do not depart significantly from the mean annual cycle, and are consistent with the time series presented in Figures 2 and 8. The summer of 1999 had the largest precipitation (Figure 2) and accordingly the latent heat was largest and sensible heat small. Conversely, precipitation during the summer of 2000 was smaller, and consequently sensible heat is larger and latent heat smaller.

4. Land Surface Linkages to Energy and Precipitation

[36] Precipitation over a given basin can be modulated by the interaction with land surface processes. In turn, soil moisture depends on precipitation and acts as a strong control on the partitioning between sensible heat flux and latent heat flux (Bowen ratio). The importance of these interactions, or feedbacks, has become increasingly evident in the last decades, when numerical simulations were employed to investigate the sensitivity of precipitation to land surface characteristics (including soil moisture, vegetation, albedo, surface roughness). Moreover, the link between surface states and the atmospheric hydrologic cycle involves the atmospheric boundary layer: as discussed in the Introduction, it has been shown that the boundary layer variables, like equivalent potential temperature and specific humidity, depend at least in part on the underlying soil moisture. In this section we will explore the dependence of surface and boundary layer variables on soil moisture.

[37] The discussion in this section will focus on the differences between subbasins and two of them, the lower Missouri and Ohio, will be described in detail as examples of different land surface-atmosphere interactions. The Ohio basin is notably wet–in terms of total soil moisture–with

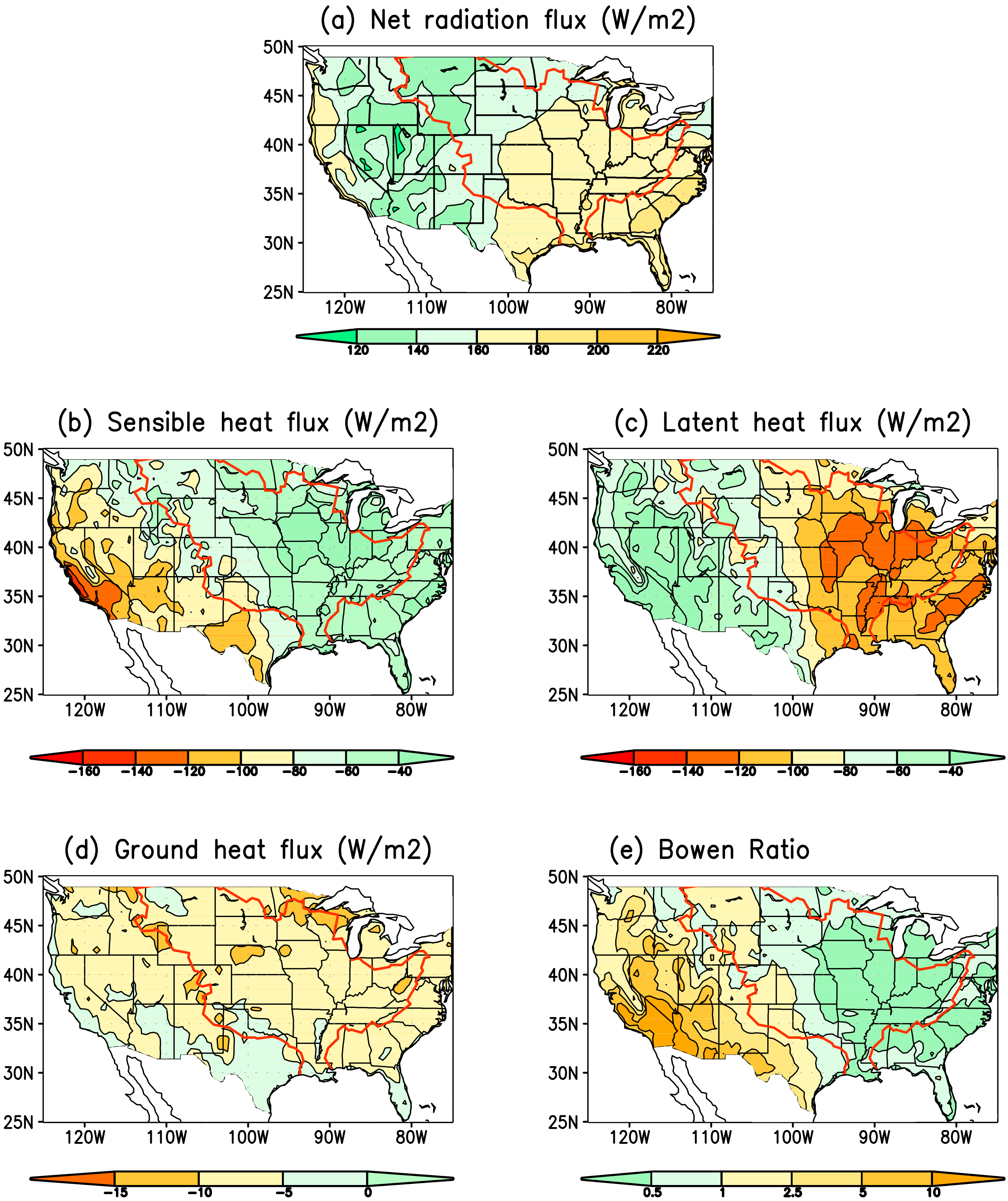


Figure 10. The 1998–2001 summer (MJJA) mean fields of (a) net radiation flux, (b) sensible heat flux, (c) latent heat flux, (d) ground heat flux, and (e) Bowen ratio. The time series of the energy terms is presented in Figure 10c.

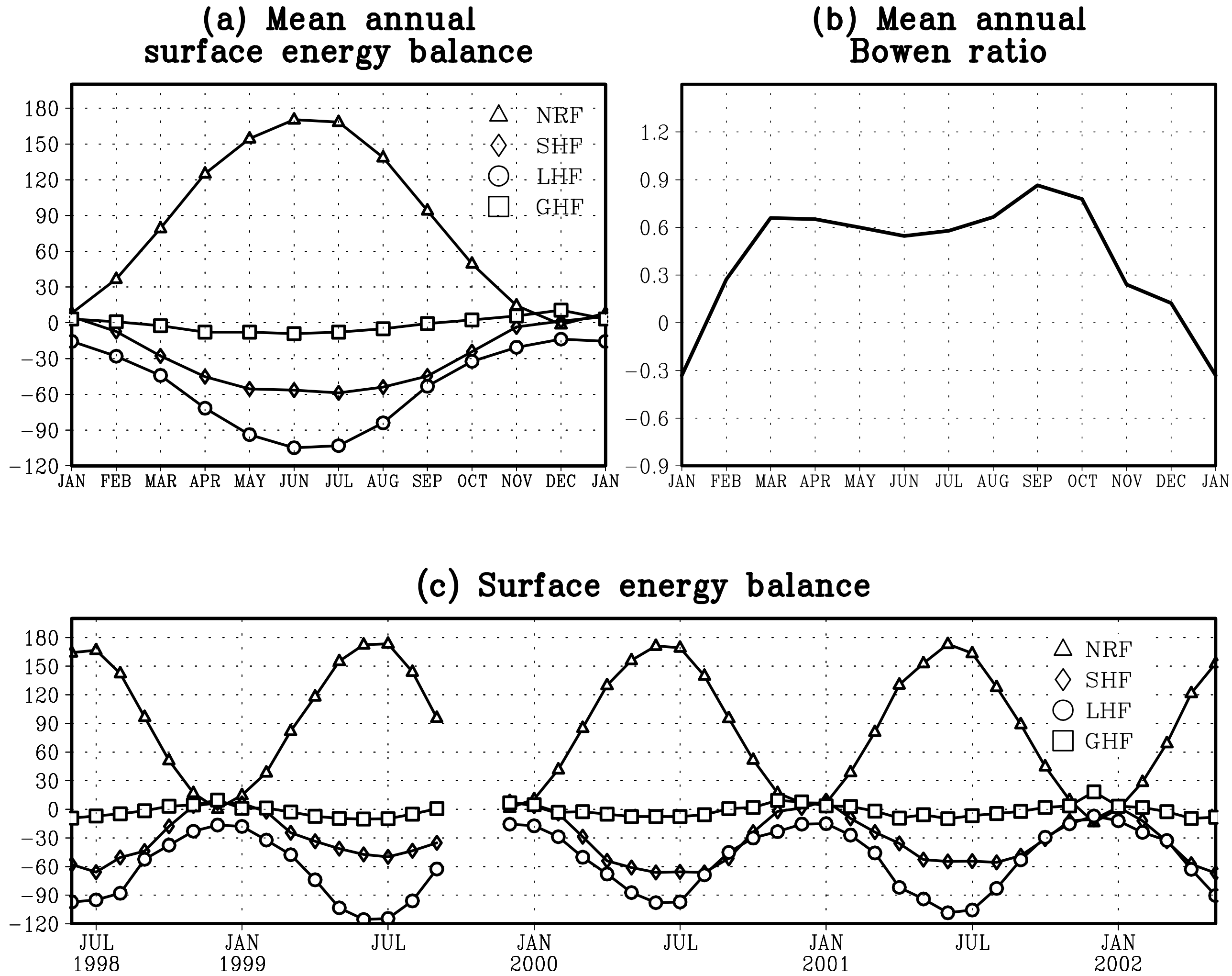


Figure 11. June 1998 to May 2002 mean annual cycle of the Mississippi basin area-averaged (a) surface energy balance terms (b) and the Bowen ratio. (c) The time series of the energy terms. NRF stands for net radiation flux, SHF stands for sensible heat flux, LHF stands for latent heat flux, and GHF stands for the ground heat flux.

values ranging between 600 and 700 mm. The lower Missouri, on the other hand, is much drier with total soil moisture ranging between 450 and 550 mm.

[38] Figure 12 presents the scatterplots of monthly summer (MJJA) surface variables versus soil moisture area-averaged over the Mississippi, lower Missouri and Ohio basins. Table 4 complements Figure 12 with the corresponding correlations between soil moisture and surface variables for all subbasins. With only sixteen months in the sample (four per year) the significance of the correlations may be dubious, but they are included for guidance and comparison purposes. In the case of the Mississippi, the relation between soil moisture and net radiation (Figure 12a, red dots) is rather weak and positive (correlation ~0.34). Similarly to the Mississippi basin, the lower Missouri basin net radiation does not correlate well with soil moisture (Figure 12a, blue dots). The Ohio basin (Figure 12a, black dots) contrasts notably with the lower Missouri as the net radiation and soil moisture have a higher correlation (~0.74). Most points lie around soil moisture values of 700 mm, showing the higher wetness of the basin. From Figure 12 the small increase of net radiation with soil moisture from west to east can also be noticed. Table 4 also shows that despite not being significant, all correlations between soil moisture and net radiation flux are positive.

[39] The response of the radiation budget to changing soil water is an important climatic feedback. As evaporation increases with soil moisture in summer, skin temperature decreases, and generally humidity and cloud cover increase. This affects both the longwave (LW) and the shortwave (SW) radiation budget: the changes of net LW with soil moisture are about 13% larger (in magnitude) than the changes in net SW. In other words, the small increase in net radiation with column soil water, seen in Figure 12a, means that the decrease of net outgoing longwave radiation with lower skin temperature and to a lesser extent higher cloud cover (the "LW feedback" associated with increasing soil moisture) slightly exceeds the decrease of net incoming short wave radiation with increasing cloud cover (the corresponding "SW feedback"). The results shown here are of course specific to the Eta model, which may

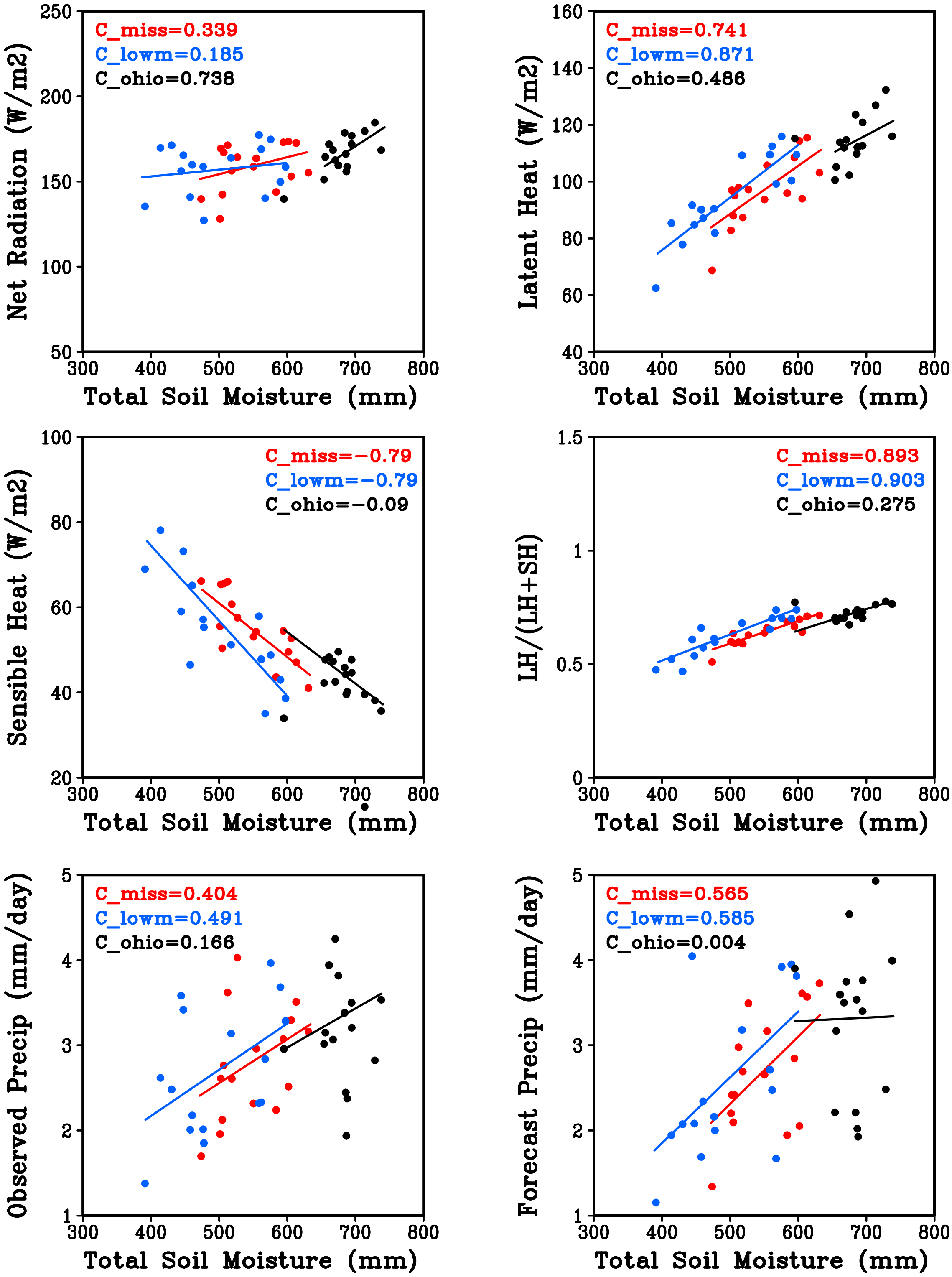


Figure 12. The 1998–2001 summer (MJJA) scatterplots of area-averaged surface variables versus soil moisture for the Mississippi, lower Missouri, and Ohio basins: (a) net radiation flux, (b) latent heat flux, (c) sensible heat flux, (d) evaporative fraction, (e) observed precipitation, and (f) Eta 12–36 forecast precipitation.

underestimate the attenuation of SW radiation in the presence of cloud cover.

[40] Mississippi soil moisture relates better with latent and sensible heat fluxes (Figures 12b and 12c): with increased soil moisture, there is increased latent heat (evapotranspiration), decreased sensible heat and consequently an increasing evaporative fraction [E_f = *LHF*/(*LHF* + *SHF*), where *LHF* is the latent heat flux and *SHF*

Table 4. Correlation Between Total Soil Moisture and Surface Variables[a]

	NetRad	LHF	SHF	Ef	BR	LCL	Pmod	Pobs
Mississippi	0.34	**0.74**	**−0.79**	**0.89**	**−0.86**	**−0.69**	**0.57**	0.40
Arkansas-Red	0.34	**0.84**	**−074**	**0.87**	**−0.82**	**−0.61**	0.45	0.37
Lower Missouri	0.18	**0.87**	**−0.89**	**0.83**	**−0.87**	**−0.83**	**0.59**	0.49
Missouri	0.23	**0.70**	**−0.83**	**0.90**	**−0.80**	**−0.70**	**0.50**	0.44
Upper Mississippi	0.35	**0.65**	**−0.87**	**0.90**	**−0.90**	0.31	**0.50**	0.35
Ohio	**0.74**	0.49	0.10	0.27	−0.27	0.31	0.00	0.17

[a]Correlations marked in bold are significant at the 95% level.

the sensible heat flux] as seen in Figure 12d. Increasing E_f is equivalent to a decreasing Bowen Ratio (see Table 4). The respective correlations are 0.74, −0.79 and 0.89. While it might be argued that the relation between soil moisture and energy variables is a product of the model's internal parameterizations, it is also shown (Figures 12e and 12f) that soil moisture has a significant correlation with the model forecast precipitation, as well as with the observed precipitation (although not at a level that can claim significance).

[41] The soil moisture-latent heat correlation for the lower Missouri is also high (0.87) and both sensible heat and the evaporative fraction (and Bowen ratio) are highly correlated with soil moisture (correlations of −0.89 and 0.83 respectively); they also show that for equal values of soil moisture, the lower Missouri has higher latent heat and lower sensible heat. The soil moisture-precipitation scatterplots (Figures 12e and 12f) show large dispersion, nevertheless, the forecast precipitation has a significant correlation of 0.58, while the observed precipitation has a correlation of 0.49, which is almost at the significance level.

[42] Latent heat for the Ohio basin has a lower correlation with soil moisture (correlation of −0.49) and, compared to the Mississippi basin, for a same value of soil moisture the latent heat is lower. More notably, low or no correlation is found with sensible heat or the evaporative fraction, and neither with forecast or observed precipitation. In large ecoregions such as Ohio Basin, where soil moisture and green vegetation are plentiful (compared to net radiation demand for evaporation), the soil moisture anomalies are not well correlated to monthly or seasonal precipitation anomalies, because the dry soil moisture anomalies are not usually large enough to notably stress the vegetation, and hence not large enough to notably reduce the surface evaporation, and therefore the lifting condensation level (LCL), and convective precipitation, are minimally influenced.

[43] The Ohio basin is an "energy limited" basin, not enough net radiation to evaporate the abundant soil moisture, whereas the lower Missouri Basin is a "water-limited" basin, not enough soil moisture to meet the evaporative demand of the high net radiation. Hence surface evaporation, and thus sensible heat flux and LCL, in the Missouri subbasin are very sensitive to soil moisture anomalies.

[44] These linkages imply that the boundary layer also participates with changes in stability, the LCL, cloud formation, etc. Figure 13 and Table 4 summarize the different regimes that dominate each of the subbasins of the Mississippi basin. Figure 13a shows a nonlinear inverse relation between soil moisture and the Bowen ratio, while Figure 13b shows that the LCL averaged for the Mississippi basin is inversely correlated with soil moisture, so that the larger the soil moisture the lower the LCL (see also Table 3). This relation is stronger (correlation −0.83) for the lower Missouri, but decreases toward the east where both the Upper Mississippi and the Ohio subbasins show no significant correlation between soil moisture and LCL. Subbasins located in the western and southwestern part of the Mississippi tend to be drier (in terms of soil moisture), with larger Bowen ratio and higher LCL. Toward the north and east, soil moisture increases, and with it the Bowen ratio becomes smaller as a response to the larger influence of the latent heat flux (or evapotranspiration), and the LCL becomes lower. A similar analysis can be drawn from Table 3, where correlations are presented for all subbasins and significantly correlated (at the 95% level) pairs of variables are marked in bold.

[45] In summary, these results support the notion of a positive feedback between soil moisture and precipitation over the western subbasins (the Arkansas-Red and Missouri), where larger soil moisture favors larger latent heat (evaporation), less sensible heat and therefore a higher evaporative fraction and lower Bowen ratio; the increase in soil moisture also results in a lower LCL, a less stable atmosphere, and finally more precipitation [see, e.g., *Betts et al.*, 1996]. On the other hand, the eastern half of the Mississippi basin (e.g., the Ohio subbasin) does not have well defined land surface-atmosphere interactions, suggesting that other effects like mechanical or dynamical forcing (e.g., orography), larger synoptic forcing or the advection of moisture may be more relevant for precipitation processes. If this is the case, the results could be relevant in studies of water recycling.

[46] The positive feedback inferred in this study for the western Mississippi Basin may not necessarily be applicable in the climatology of other ecoregions that have relatively plentiful soil moisture and green vegetation in the multiyear time mean summer. In addition, earlier results by Ek et al. (submitted manuscript, 2003) and *Findell and Eltahir* [2003] indicate that the feedback can be negative in certain regional climatologies, or different on individual days within a given ecoregion. For instance, increased precipitation could act to cool the surface and decrease the daytime maximum PBL depth, thereby decreasing the chance of surface-based convective thermals to reach the LCL (and hence reduce likelihood of precipitating convection), even though the height of the LCL is reduced by increased water vapor from increased surface evaporation.

5. Summary and Conclusions

[47] The regional water cycle and surface energy processes of the Mississippi basin as estimated from forecasts of NCEP's operational Eta model were discussed in this paper. The atmospheric water cycle was computed from a 7-year data set (June 1995–May 2002) while all energy related computations were prepared from the last four years of the data set to avoid parameterization changes during the early years. The 12–36 h forecast precipitation averaged over the 7-year period differed from observations by 2% over the Mississippi basin, although during the first years (1995–

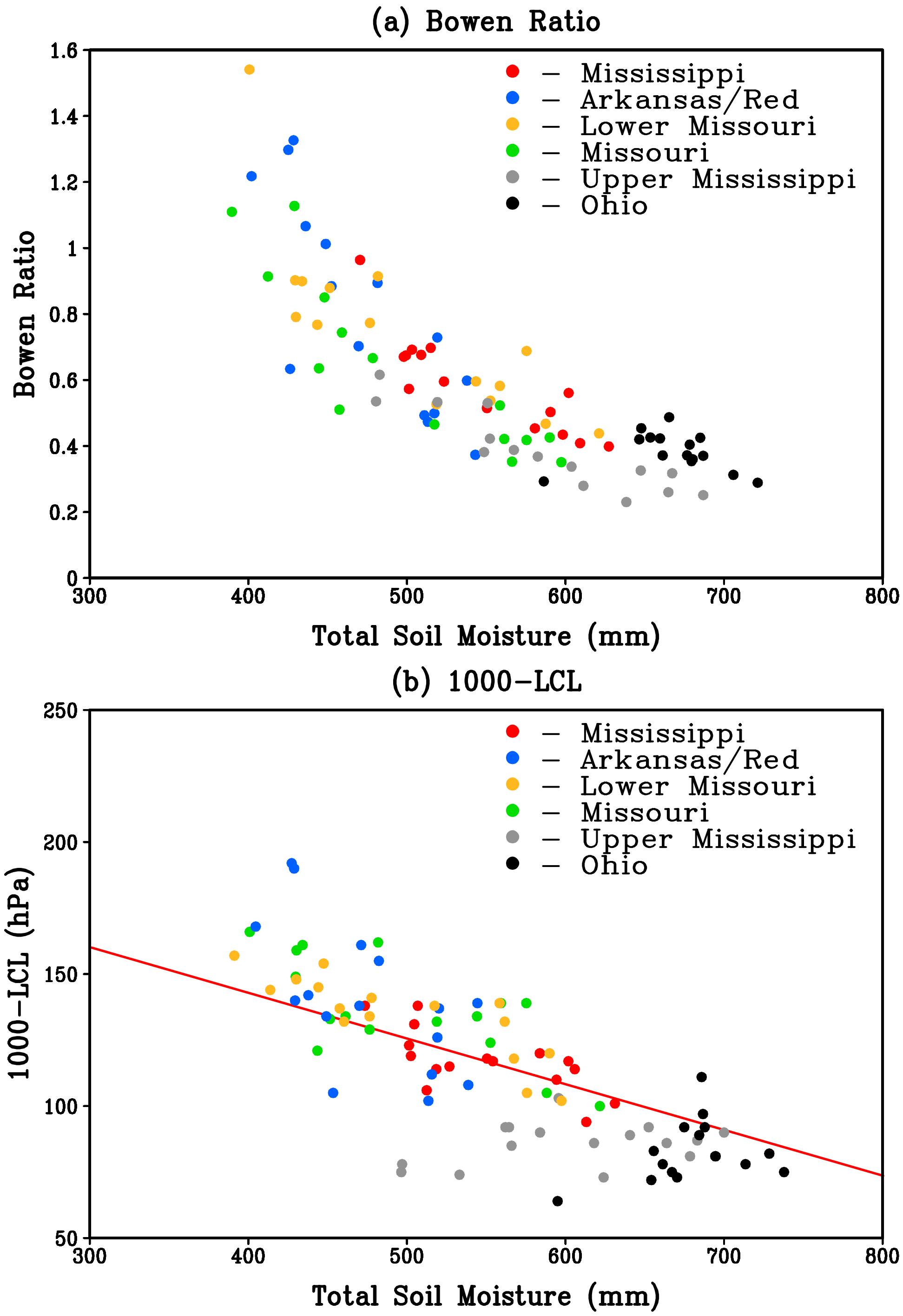


Figure 13. The 1998–2001 summer (MJJA) scatterplots for all subbasins within the Mississippi basin of area-averaged (a) Bowen ratio versus soil moisture and (b) LCL versus soil moisture. The regression line corresponds to the area-average for all the Mississippi basin.

1997) it had a dry bias that was removed during 1998. Differences were also detected in the annual cycle, with the model precipitation being slightly larger than observations during winter and spring, and lower than observations during summer and early autumn.

[48] In the absence of observations, evaporation produced with the macroscale hydrologic VIC model, which uses observations and the energy balance to derive a consistent data set of land surface fluxes, was employed to assess the quality of the Eta model evaporation estimates. Two Eta-based estimates of evaporation were computed, one as a residual of the water balance equation, and the other one from the model parameterization. Their annual cycles are close to the VIC evaporation annual cycle, in terms of magnitude and shape, but the Eta model estimates are shifted one month, resulting in larger values

during spring and smaller during autumn. The evaporation obtained from the water balance equation reduces by about half the bias of the Eta model parameterized evaporation. The excessive bare soil evaporation during spring may have contributed too much moisture in the atmosphere, thereby favoring the larger precipitation and runoff detected in spring, which ultimately is seen as a one month shift in the annual cycle of those variables. The evaporation field computed as a residual of the water balance tends to agree with the above estimates in spatial structure away from mountainous terrain.

[49] A stringent test for atmospheric models is the requirement that in a long-term average the vertically integrated moisture flux convergence be equal to the observed streamflow. The 7-year average of Mississippi basin-averaged Eta model moisture flux convergence is 0.54 mm day^{-1}, while the observed streamflow at Vicksburg for the period 1995–2000 (observations were not available afterward) averages 0.50 mm day^{-1}. This agreement within 10% can be used as a measure of the "closure" of the water budget [*Roads et al.*, 2003], and if the results hold for other long periods, they will provide further evidence that the use of regional models is the best current approach to estimate the water cycle (and lend support to the strategy of developing a regional reanalysis data set based in the Eta model).

[50] Land surface processes during summer were inspected for the different subbasins within the Mississippi basin. In the western half of the Mississippi basin, the soil moisture and other surface variables were related in a manner that is consistent with positive climatic feedback mechanisms. Firstly, increasing soil moisture tends to be associated with increasing net radiation flux at the surface. Our results show that increased soil moisture produces a reduction of the outgoing longwave radiation (likely due to a reduction of skin temperature), which slightly exceeds the decrease of net incoming shortwave radiation, also due to increasing cloud cover. Secondly, the increasing soil moisture is associated with larger latent heat and smaller sensible heat, which implies a smaller Bowen ratio, larger evaporative fraction, and a lower lifting condensation level. Lastly, all these changes are in agreement with increased precipitation due to local effects, and while correlations are not statistically significant at the 95% level, the scatterplots of soil moisture versus precipitation (both forecast and observed) suggest that this is the case.

[51] Toward the eastern half of the basin (e.g., Ohio subbasin), soil moisture is larger and shows no significant relation with most variables (latent heat, sensible heat, Bowen ratio, LCL). A possible reason is that the vegetation may not show signs of transpiration stress with the lesser soil moisture, except in extremely rare, extremely large dry soil moisture anomalies for that moist ecoregion. These geographical characteristics could suggest that physical parameterizations are more relevant over the western part of the basin; if this is the case, the results imply that local and remote sources of moisture, and the amount of water recycling, are very different among the subbasins.

[52] **Acknowledgments.** We thank Ed Maurer and Dennis Lettenmaier for providing the data set of land surface fluxes and states based on the VIC model. The detailed comments of D. Lettenmaier are much appreciated as are those of an anonymous reviewer. This research was supported by NOAA grant NA76GP0291 (GCIP). AKB is supported by NASA under grant NAS5-11578 and NSF under grant ATM-9988618.

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