Precipitation Recycling over the Central United States Diagnosed from the GEOS-1 Data Assimilation System

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(Manuscript received 4 April 2000, in final form 5 September 2000)

ABSTRACT

Precipitation recycling has been computed for 15 yr of reanalysis data from the National Aeronautics and Space Administration Goddard Earth Observing System (GEOS-1) Data Assimilation System using monthly mean hydrological data and a bulk diagnostic recycling model. This study focuses on the central United States and the extreme summers of 1988 (drought) and 1993 (flood). It is found that the 1988 summer recycling ratio is larger than that of 1993, and that the 1988 recycling ratio is much larger than average. The 1993 recycling ratio was less than average during the summer, but it was larger than average during the springtime, when the soil was being primed for flooding. In addition, the magnitude of summertime recycled precipitation was smaller than average in both 1988 and 1993. During the summer of 1993, the extremely large moisture transport dominates evaporation as the source of water for the extreme summer precipitation. The diagnosed recycling data show that the recycled precipitation is large when moisture transport is weak and convergence and evaporation are large. The analysis identifies the summer of 1989 as having the largest magnitude of recycled precipitation, resulting from a combination of low moisture transport and high moisture convergence.

1. Introduction

The extreme events of the 1988 drought and 1993 flood in the central United States have prompted significant research in understanding the influence of land surface processes on the development and occurrence of precipitation. Here, we are interested in the process of precipitation recycling, defined as ‘‘the contribution of evaporation within a region to precipitation in that same region’’ (Eltahir and Bras 1994). Precipitation recycling characterizes a nonlinear relationship between regional evaporation, moisture transport, and precipitation and quantifies the recycled (or local) precipitation. Using 15 yr of reanalyzed data, we compare the diagnosed precipitation recycling for the summers of 1988 and 1993 with the annual mean.

A significant amount of research has been conducted regarding the interactions between the land surface and atmospheric precipitation. For example, Atlas et al. (1993) demonstrated the important impact of soil moisture by showing that the 1988 central United States precipitation anomalies could be reproduced in a global simulation with prescribed soil moisture anomalies. Oglesby and Erickson (1989) demonstrated the persistence of a dry soil moisture anomaly in perpetual season general circulation model (GCM) simulations implying a reinforcing feedback between soil moisture and precipitation during drought. Further seasonal simulations by Oglesby (1991) showed that dry soil lead to a weaker meridional transport of water vapor in the central United States, thereby reducing the precipitation. However, simulations of the 1993 flood show that dry initial soil moisture can reduce the magnitude of precipitation, but do not necessarily initiate widespread persistent drought (Bosilovich and Sun 1999a). Beljaars et al. (1996) found that improvements in 1993 flooding precipitation forecasts could be achieved with increased soil water. Koster and Suarez (1995) show that precipitation variability over land follows local evaporation variability, especially during the summer. In these studies, the surface boundary conditions (such as soil wetness) are imposed and modified. While numerical simulations show sensitivity of the flooding precipitation to the evaporation rate, the surface heating is inexorably altered in comparison with the respective control simulation, which affects the regional-scale environment and precipitation processes (Beljaars et al. 1996; Paegle et al. 1996; Seth and Giorgi 1998; Bosilovich and Sun 1999a,b). With both thermodynamic and hydrometeorologic feedback processes affecting the atmospheric circulation of these simulations, it is difficult to isolate and to quantify the precipitation recycling process. In particular, a question remains as to whether the precipitation changes because

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the water content has changed (due to surface evaporation) or because the thermodynamic stability of the vertical profile has changed.

During 1993, springtime precipitation thoroughly saturated the soil over a wide area of the Mississippi River basin (Bell and Janowiak 1995). When record precipitation occurred in the same region, the feedback between local water and the flooding precipitation seemed to be a likely mechanism (Betts et al. 1994; Bell and Janowiak 1995). By analyzing regional estimates of precipitation and evaporation for 1988 and 1993, Trenberth and Guillemot (1996) determined that the local water contributed to the flooding precipitation through surface evaporation and that this process was significant.

The concept of precipitation recycling has been debated for many decades and is a critical link between the hydrological and meteorological processes [see Brubaker et al. (1993) and Eltahir and Bras (1996) for a review]. Recently, Dirmeyer and Brubaker (1999) used back-trajectory analysis with precipitation observations and the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis to determine the recycling ratio for the summers of 1988 and 1993 over the Mississippi River Basin. They determined that the fraction of local precipitation (recycling ratio) during the 1993 summer was less than that of 1988 (33% and 41%, respectively) because of the increased transport of water from the Gulf of Mexico in 1993. However, the relationships of these values to a normal value are not discussed.

More simple methods of quantifying the precipitation recycling have been developed. Savenije (1995) derived a continuous function for a recycling coefficient for the Sahel region based on a Lagrangian approach to the hydrological budget. Brubaker et al. (1993) developed a linear calculation (based on Budyko 1974) using area-averaged monthly mean evaporation, precipitation, and moisture transport. Gridded data were used to diagnose the mean annual cycle of precipitation recycling for several regions of the globe. The advantage of this method (termed the bulk diagnostic model) is the computational efficiency, which permits the analysis of long-term data. Trenberth (1999) used this method to evaluate global maps of seasonal precipitation recycling. Similarly, Eltahir and Bras (1994) developed a method of diagnosing precipitation recycling that uses the spatial variability of the gridded hydrological data in the calculation. This method was tested for the Amazon Basin and Mississippi River Basin mean annual cycles of recycling.

In the current study, we analyze the precipitation recycling from the National Aeronautics and Space Administration Goddard Earth Observing System (GEOS-1) Data Assimilation System (DAS; Schubert et al. 1993). The bulk diagnostic recycling model developed by Eltahir and Bras (1994) is applied to 15 yr of GEOS-1 DAS data for a region over the central United States. Previous studies with diagnostic recycling models have focused on the annual mean and seasonal variations of recycling. Here, we investigate the interannual variability of the recycling and the relationship of recycled precipitation and recycling ratio with conventional hydrologic data (total precipitation, evaporation, and moisture transport and convergence). We focus on the differences of the 1993 flood, the 1988 drought, and the annual average, as well as the evolution of the 1993 flood and 1988 drought in the central United States. Section 2 describes the input data, analysis, and model used in the study. Section 3 analyzes the hydrological conditions, including recycling for the central United States, and section 4 discusses some limitations of the bulk diagnostic models.

2. Models and data

a. GEOS-1 DAS

Global reanalyses provide a long-term gridded dataset with key variables constrained by observations. The global modeling system uses the same physics and dynamics throughout the assimilation of observations (Bengtsson and Shukla 1988). The key dynamical states of the atmosphere follow observations (if observations are present), but physical processes that are not constrained can differ substantially from reality. Here, we use the GEOS-1 DAS global reanalysis atmospheric hydrological dataset (Schubert et al. 1993), which includes monthly mean precipitation P, evaporation E, vertically integrated (on sigma levels at the model time step) total moisture transport qV, and moisture flux convergence. We take advantage of the fact that the GEOS DAS output includes the incremental analysis update (IAU) term (Bloom et al. 1996). The IAU produced a nonnegligible moisture tendency (Molod et al. 1996) that can be used to correct errors in the physical processes (Schubert and Chang 1996). The vertically integrated atmospheric hydrological budget in the DAS is written as

$$\frac{\partial q}{\partial t} = E - P - \boldsymbol{\nabla} \cdot q\mathbf{V} + \left(\frac{\partial q}{\partial t}\right)_{\mathrm{IAUQ}}. \qquad (1)$$

The analysis increment update of specific humidity [IAUQ; last term in Eq. (1)] reflects the mismatch between model and observation and must be considered when evaluating the analyzed hydrologic cycle data. The method of Schubert and Chang (1996) computes a correction to the physical terms by relating fluctuations in the analysis increments to a linear transformation of the budget terms. In that study, the analysis increment of specific humidity was related primarily to errors in precipitation and evaporation. In view of their results, we use this statistical correction to partition the analysis update into evaporation and precipitation but not the moisture flux convergence term. We expect this to be a good approximation, because the GEOS-1 reanalysis has been shown to provide reasonable depictions of the Great Plains low-level jet and moisture transport (e.g., Higgins et al. 1997; Min and Schubert 1997; Schubert et al. 1998). The statistical corrections are applied to the monthly gridpoint data, as described in the appendix. For any given month, the statistically corrected hydrological budget becomes

$$\frac{\partial q}{\partial t} = E^* - P^* - \nabla \cdot q\mathbf{V} + \varepsilon, \tag{2}$$

where P^* and E^* now include a portion of the analysis update (with ε the remaining error in any give month). These estimates of evaporation and precipitation will be used to examine the precipitation recycling. The differences between P^*, P, and observed precipitation, as well as a comparison of the analysis increment and the error term, are discussed in the appendix.

Subsurface hydrological processes are a critical component to the global water cycle. Savenije (1996) has found links between precipitation recycling, runoff, and land use. However, the GEOS-1 DAS used prescribed soil water and constant surface characterization parameters in its land surface boundary condition. This was done to reduce the degrees of freedom over land and provide more accurate forcing to the atmosphere. However, the diagnosis of the annual cycle of runoff from the system has fundamental limitations related to the prescribed soil water and the lack of snowmelt processes (Bosilovich et al. 1999). Therefore, we focus on the atmospheric branch of the water cycle.

b. Bulk diagnostic recycling model

Although we have tested both the Brubaker et al. (1993) and Eltahir and Bras (1994) recycling models, we focus primarily on the results of the latter. Savenije (1995) showed that the linearity of the Brubaker et al. (1993) model underestimates precipitation recycling. Dirmeyer and Brubaker (1999) quantified this result with comparisons to their back-trajectory calculations. In section 4, we compare these bulk models and the limitations of diagnostic estimates of recycling, where the results indicate that the Brubaker et al. (1993) model produces less recycling than the Eltahir and Bras (1994) model. In this section, we will provide the main points of the Eltahir and Bras (1994) recycling model's derivation.

Eltahir and Bras (1994) derive the precipitation recycling model from the vertically integrated water vapor (precipitable water) budget. The rate of change of precipitable water on monthly timescales is small in comparison with all the other terms and is neglected. Here, we also neglect the random error term in Eq. (2), ε, from the bulk diagnostic calculations. By assuming water from local evaporation is well mixed with advected water, the local and advected sources of precipitation and moisture leaving a grid point occur in the same ratio,

$$\rho = \frac{O_l}{O_l + O_a} = \frac{P_l^*}{P_l^* + P_a^*}. \tag{3}$$

This approach allows the separation of the hydrological budget into local and advected equations:

$$I_l - O_l = P_l^* - E^* \quad \text{and} \tag{4}$$

$$I_a - O_a = P_a^*, \tag{5}$$

where I, O, l, and a stand for inflowing water, outflowing water, local source, and advected source, respectively. Equations (3)–(5) are combined to solve for the ratio of local to total precipitation (ρ, the recycling ratio),

$$\rho = \frac{I_l + E^*}{I_l + I_a + E^*}. \tag{6}$$

The Eltahir and Bras model considers the spatial distribution of the hydrologic variables within the region of interest by iteratively solving for the recycling at each grid point. Eltahir and Bras (1994) discuss the specifics of solving Eq. (6) for gridded datasets.

In this study, we have applied the Eltahir and Bras (1994) bulk recycling model to 15 yr of GEOS-1 DAS data. We will focus on the precipitation recycling during specific periods (1988 and 1993) for the central United States and how it relates to the 15-yr average.

3. U.S. regional hydrological behavior

In this section, we discuss the results of the precipitation recycling calculations by first intercomparing the development of the 1988 drought and 1993 flood in the central United States (Fig. 1) with respect to the mean annual cycle of the hydrological behavior, focusing on the recycling ratio and the amount of recycled precipitation. We will also examine the conditions that lead to large recycled precipitation and when it occurs in the central United States. In the next section, we assess the quality of the recycling estimates, the impact of transients, the differences with the Brubaker et al. (1993) recycling model, and discuss some limitations of the simple calculation of recycling.

Total precipitation and moisture transport are presented in Fig. 2 for the mean annual cycle, 1988 and 1993. Henceforth, we will refer to the 15-yr mean annual cycle as normal. The vertical bars indicate one standard deviation from normal. Precipitation is much above normal for most of 1993, especially the summer. The 1993 moisture transport is very intense during June and July, but less than normal during the springtime. For the spring and summer of 1988, precipitation is less than normal, and moisture transport reaches an extremely low value in June.

The recycling ratio in the summer of 1993 is much less than in 1988 (Fig. 3), in agreement with Dirmeyer and Brubaker (1999). A comparison with the 15-yr mean, however, indicates that the summer 1993 recycling ratio is much less than normal (by almost 2 standard deviations), and summer 1988 recycling is well above normal. These anomalies are associated with the moisture transport anomalies, in the sense that large

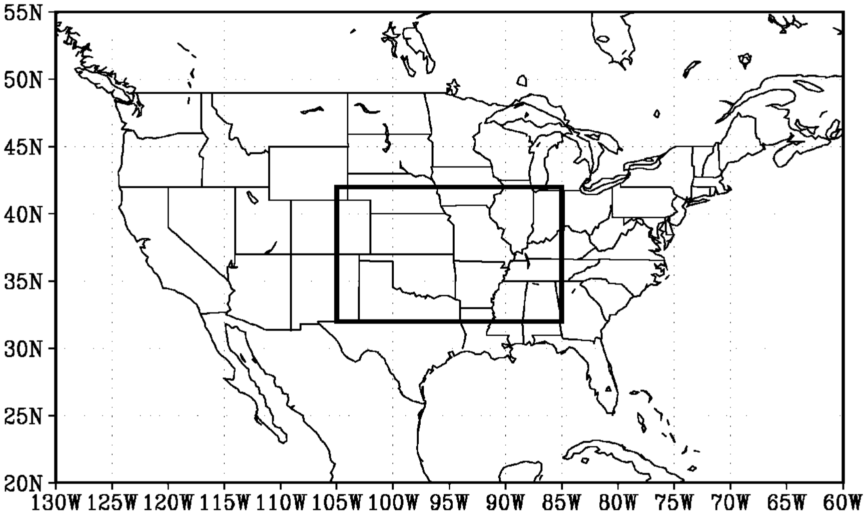

FIG. 1. Map depicting the area in which the precipitation recycling is analyzed.

moisture transport in 1993 leads to less recycling, and small transport in 1988 leads to large recycling.

We next focus on the magnitude of recycled (or local) precipitation and the differences from the mean annual cycle. Figure 3 shows that 1993 June and July local precipitation is much below normal at a time when the moisture transport is strongest. Although precipitation recycling is small during the summer, the model indicates that during the springtime local precipitation is somewhat above normal. The implication is that local feedback helped to saturate the soil water during springtime, when the region was being primed for significant flooding, but the heaviest precipitation during the summer was driven by low-level moisture transport from outside the region.

The 1988 local precipitation is close to the mean an-

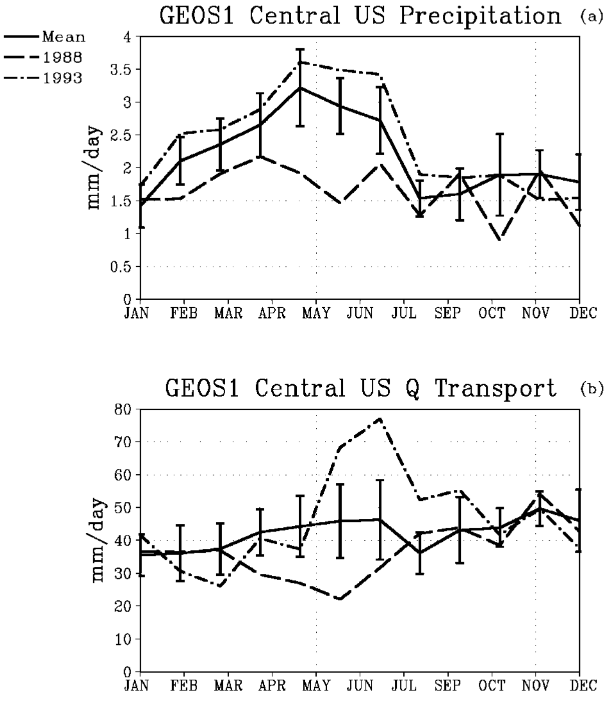

FIG. 2. Annual cycles of (a) precipitation P^* and (b) moisture transport qV for the GEOS-1 15-yr mean annual cycle (solid), 1988 (dash), and 1993 (dot–dash). Data are areally averaged over the central United States, and error bars indicate 1 standard deviation of the 15-month average.

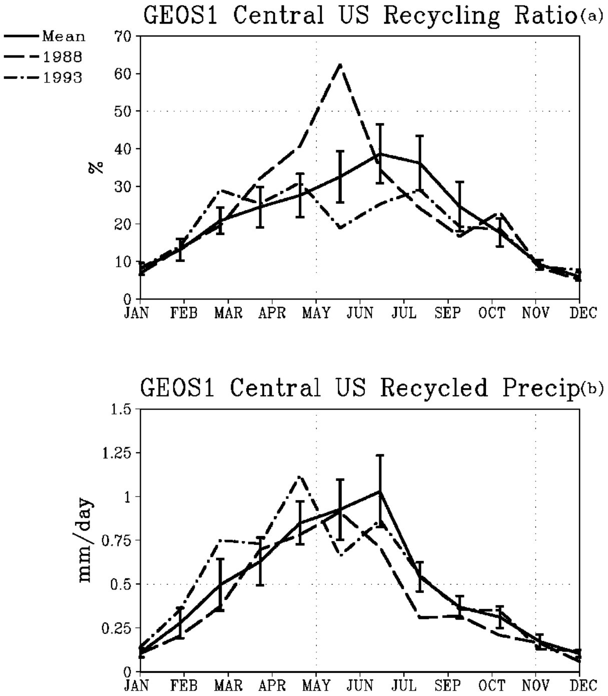

FIG. 3. As in Fig. 2, but for (a) recycling ratio ρ and (b) recycled precipitation P_l^*.

nual cycle throughout the spring and early summer. During June 1988, when the moisture transport is lowest and recycling ratio is very high, the recycled precipitation is near the mean value. It was not until after the drought and low-precipitation anomalies were entrenched in the region that the recycled precipitation becomes much less than normal. This implies that the low precipitation that occurred during the initiation and main phase of the drought was associated with the reduction of water from outside the region rather than the local source of water.

Despite nearly opposite atmospheric circulations and precipitation anomalies, neither the 1993 flood nor the 1988 drought has above-normal local precipitation. We have analyzed the data to examine the conditions for increased recycled precipitation. Figure 4 shows total and recycled precipitation in comparison with moisture convergence and recycling ratio in comparison with moisture transport. Each point is a monthly mean for May–August, and the shading indicates high (red) and low (blue) evaporation rates. For low evaporation, precipitation increases nearly linearly with increasing moisture convergence (Fig. 4a). Precipitation is larger for higher values of evaporation, but there is more scatter. On the other hand, recycled precipitation appears to have more dependence on evaporation and less on moisture convergence (Fig. 4b). Corresponding to Eq. (3), the recycling ratio increases for decreasing moisture mean transport, and it increases for larger evaporation (Fig. 4c). Recycling ratio has a low correlation with moisture convergence (Fig. 4d).

Given the conditions for high precipitation recycling discussed above, when does high precipitation recycling occur? Figure 5 shows the regional hydrological time series of summers (June, July, and August). The highest recycled precipitation occurred in the summer of 1989 and the summer of 1995. Moisture transport was lower than average in 1989 (but not the lowest) and close to that of 1988. The summer 1989 moisture flux divergence was small and comparable to the 1993 divergence. Associated with the small moisture divergence, the 1989 precipitation is comparable to 1993. Therefore, with low transport influencing a higher recycling ratio, and low divergence leading to higher precipitation, the resulting 1989 recycled precipitation is higher than normal. This result is particularly interesting, because the summer of 1989 is generally considered to be a normal period in the U.S. climate record (Chelliah 1990). However, the results presented here indicate that the summer of 1989 may make a good case study to investigate the local

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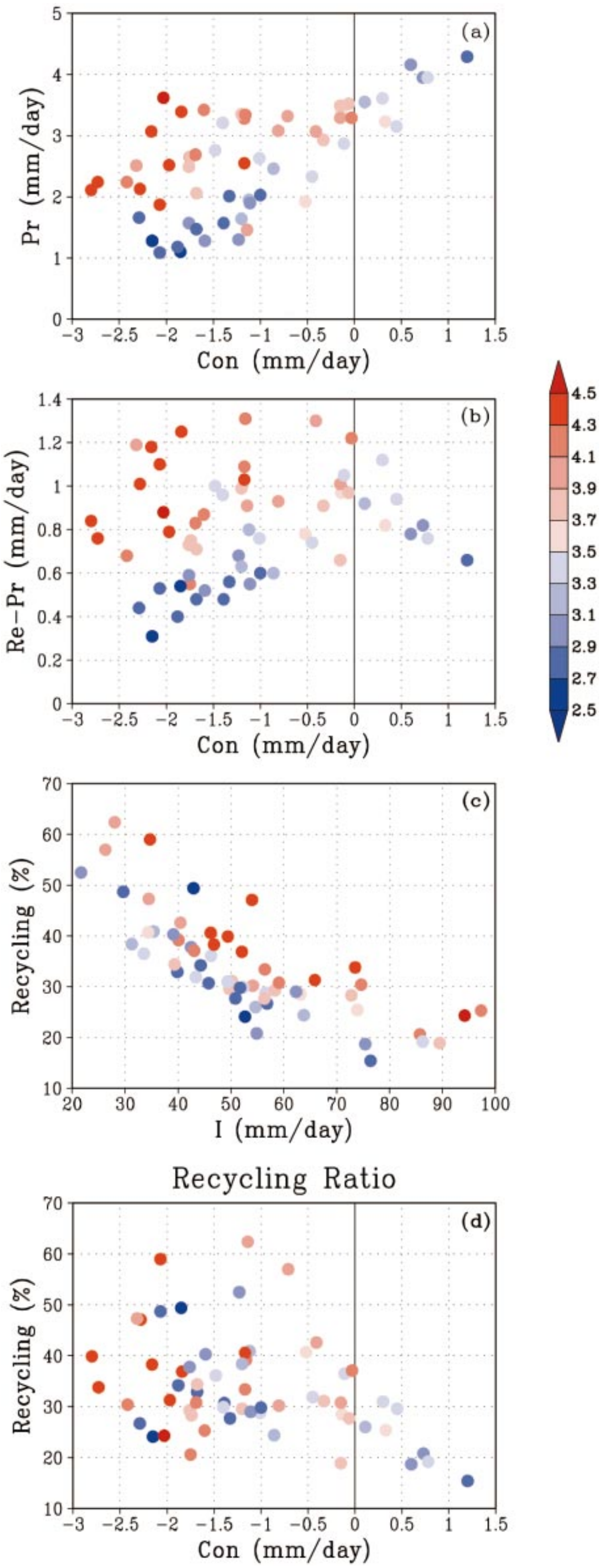

FIG. 4. Comparison of area-averaged monthly mean hydrological conditions (May, Jun, Jul, and Aug only): (a) total precipitation P^* vs moisture convergence, (b) recycled (local) precipitation P_l^* vs moisture convergence, (c) recycling ratio ρ of precipitation vs mean moisture transport I, and (d) ρ vs moisture convergence. Shading (mm day^{-1}) depicts the evaporation.

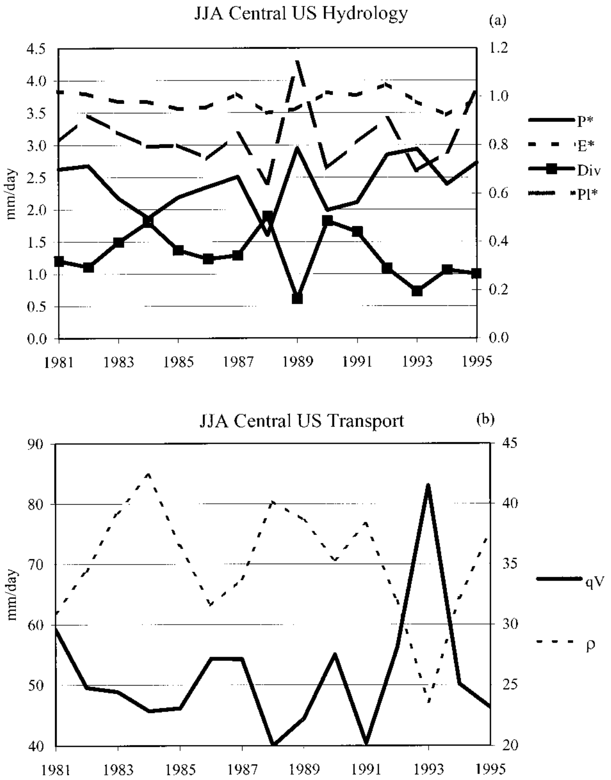

FIG. 5. Time series of summer (Jun, Jul, and Aug) hydrological data for (a) total precipitation, evaporation, moisture divergence, and recycled (local) precipitation and (b) mean moisture transport and recycling ratio. All data in (a) are scaled by the left axis, except for local precipitation (mm day^{-1}), which is on the right axis, and in (b) recycling ratio is scaled on the right axis.

feedback of evaporation as a source of water for U.S. precipitation. The annual cycle of 1989 shows that July has particularly large precipitation recycling and recycling ratio (Fig. 6).

The summer of 1995 is similar to 1989 (Fig. 5). The divergence in 1995 is larger than in 1989 and precipitation is smaller, but the moisture transport is as weak as in 1989. The 1995 annual cycle shows that the large recycled precipitation is spread across June and July, and July 1989 has the largest monthly recycling. In July 1995, the recycling ratio is nearly equal to the normal value, but the recycled precipitation is somewhat above normal. This result indicates that the recycling ratio is only one metric in assessing the local interactions and that the recycled precipitation can yield additional information.

4. Issues in diagnostic recycling

The advantage of a bulk diagnostic approach is that it provides a computationally efficient quantitative assessment of precipitation recycling. There are, however, limitations to this recycling model. For example, the monthly mean data contain no information about the diurnal cycle or synoptic-scale variability. Subseasonal variations (e.g., diurnal and synoptic timescales) are very important to the atmospheric hydrological conditions of the central United States (Schubert et al. 1998). The mean hydrological data have limited information on the physical processes that create the condensation. The back-trajectory method (Dirmeyer and Brubaker 1999) uses 6-hourly data and includes higher-frequency phenomena. Passive tracers for water vapor carried within atmospheric numerical models (moving forward at the model time step) allow a potentially more accurate computation of the precipitation recycling, though the simulations will be time consuming and the results will depend on the quality of the numerical simulation. Previous applications of passive tracers for water vapor have been limited to coarse-resolution GCM studies (Joussaume et al. 1986; Koster et al. 1986; and Numagati 1999).

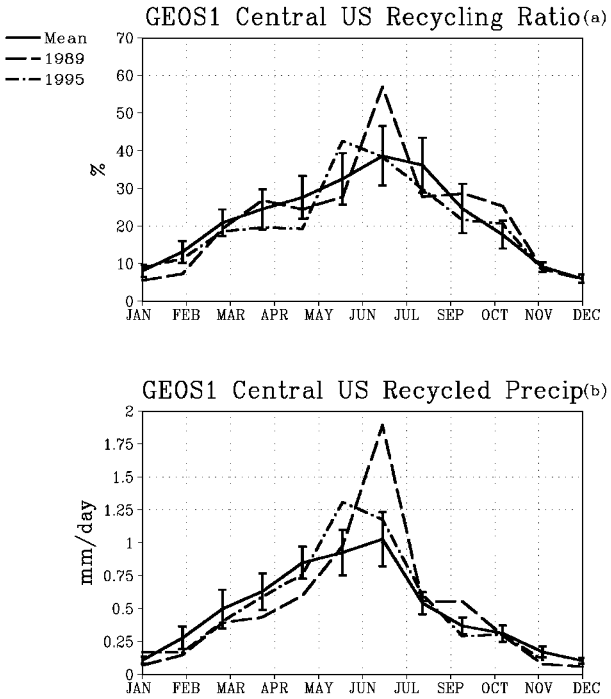

FIG. 6. Annual cycles of (a) ρ and (b) P_l^* for the GEOS-1 15-yr mean annual cycle (solid), 1989 (dash), and 1995 (dot–dash). Data are areally averaged over the central United States, and error bars indicate 1 standard deviation of the time average of the given month.

The simplicity of the bulk method calculations suggests that the quantitative results should be interpreted with some caution. To understand the range of uncertainty in the calculations, we have also computed recycling using the Brubaker et al. (1993) method, and we intercompare U.S. regional hydrological conditions and recycling. This region is similar to that chosen by Brubaker et al. (1993) and facilitates a comparison with that study (Fig. 1). Figure 7 shows the summer mean hydrological conditions for this region, including recycling ratio, recycled precipitation, and the compo-

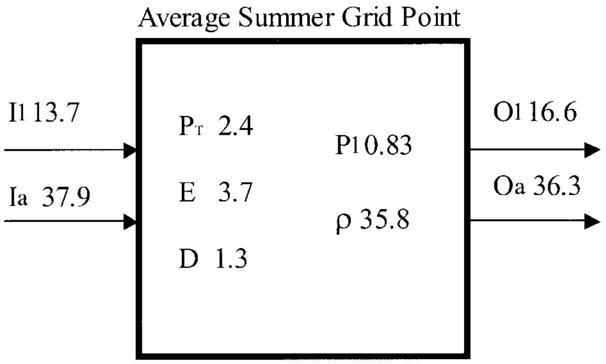

FIG. 7. Mean summer (Jun, Jul, and Aug) hydrological conditions (mm day^{-1}), including total precipitation P_T, evaporation E, divergence D, recycled precipitation P_l, recycling ratio ρ, and the moisture transport (inflow and outflow, advected, and local components).

nents of moisture transport. Brubaker et al. (1993) indicate a summer average 29% recycling ratio (using the Budyko method), from 2.7 mm day^{-1} of precipitation and 4.0 mm day^{-1} of evaporation. We have computed the Budyko-method recycling ratio (following Brubaker et al. 1993) to be 25%, as compared with 36% determined from Eltahir and Bras (1994). Savenije (1995) attributes the systematic differences to the assumption of constant evaporation and precipitation within the area of the computation. Recent results based on back-trajectory calculations from Dirmeyer and Brubaker (1999) confirm that the Budyko method underestimates the recycling. We find this method to be consistently less than Eltahir and Bras (1994) for the entire period in the central United States (figure not shown). Given the differences in these estimates of recycling (for similar areas and input data), the magnitude of recycling ratio and recycled precipitation likely contain uncertainty. We echo the sentiment of Trenberth (1999) that the recycling values should be considered to be an index rather than a physical quantity. With regard to the present results, we believe that the difference or variability of the recycling, relative to the long-term average, is meaningful.

We are also interested in the effect of the transient component of the circulation on the diagnosis of recycling. The total moisture transport is the combination of mean and transient flow (e.g., $\overline{qV} = \overline{q}\,\overline{V} + \overline{q'V'}$). To test the effect of the transient component of the moisture transport on the precipitation recycling calculations, we forced the bulk recycling models with the mean moisture transport ($\overline{q}\,\overline{V}$) instead of the total moisture transport. Figure 8 shows the normalized difference of inflowing total and mean moisture transport for the region and the differences of Eltahir and Bras (1994) recycling ratio and recycled precipitation. As expected in the United States, the mean flow and total moisture transport are very similar during the summer and the transient flow can be larger in other seasons (as in Brubaker et al. 1994). The recycling differences are smaller during spring and summer (5% or less). The normalized recycling differences are larger in autumn and winter (20%), but the magnitude of recycling is smaller than in summer. We conclude here that the transient component of the flow does not have a large effect on the calculation of recycling in this region. This result does not imply, however, that the link between precipitation (and likely recycling) and moisture transport and convergence on timescales shorter than 1 month is unimportant. Note that the effect of the transient moisture flux on moisture convergence and precipitation is not considered in this simple analysis.

5. Summary and conclusions

Fifteen years of GEOS-1 DAS atmospheric hydrological data has been used in the bulk diagnostic precipitation recycling model of Eltahir and Bras (1994) applied to the central United States. Results indicate that during the 1993 summer, when flooding was most severe and the surface was the wettest, recycled precipitation was below average. Above-normal recycled precipitation occurred during the 1993 spring, when the soil was being primed for flooding. In 1988, recycled precipi-

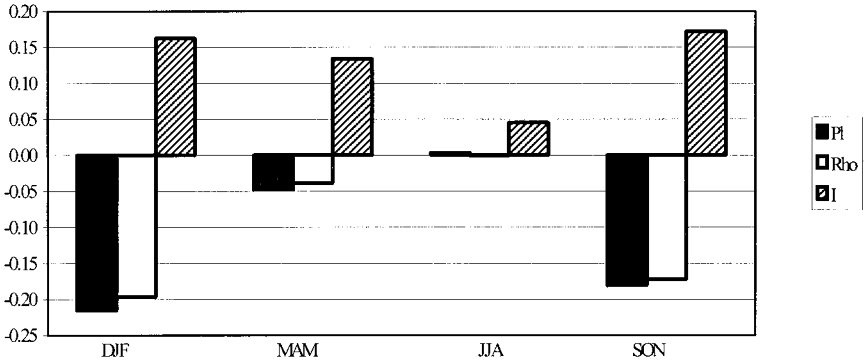

FIG. 8. Seasonal differences of the calculations with the total moisture flux and the calculations with only the mean moisture flux (data are normalized by the value from the total flux experiment). The bars indicate differences of recycled precipitation, recycling ratio, and inflowing moisture transport.

tation did not go below normal until after the significant water deficit was in place. Neither 1993 nor 1988 showed above-normal magnitude of recycled precipitation during summer, despite the occurrence of nearly opposite background atmospheric circulations. In 1993, the summer precipitation recycling was quelled by strong moisture transport. In 1988, summer recycling ratio was extremely large because of the lack of moisture transport. However, the recycled precipitation was either near normal or below normal because of the reduction of both moisture convergence and total precipitation.

Recycled precipitation tends to be larger for higher evaporation and smaller magnitudes of moisture transport and convergence. During the 1989 and 1995 summers, water vapor transport was relatively small and moisture convergence and precipitation were relatively high, leading to the largest amount of recycled precipitation in the 15 yr analyzed here. Although much effort has gone into understanding surface–atmosphere interactions in the extreme years of 1988 and 1993, these results suggest that the summers of 1989 (especially July) and 1995 may make interesting candidates to study the effect of evaporation as a source of local precipitation.

Although the bulk diagnostic models are simple and have limitations, they provide information on the hydrologic cycle that cannot easily be attained otherwise. Specifically, they characterize the link between surface evaporation, precipitation, and moisture transport without altering the dynamic circulation or the thermodynamic structure, as is the case for GCM sensitivity simulations. Such diagnostic calculations could also provide added information in GCM sensitivity studies of the land–atmosphere interactions (e.g., the amount of recycling for wet, dry, and normal soil water initial conditions).

Acknowledgments. We to express our appreciation to Drs. Robert Atlas, Paul Dirmeyer, and Paul Houser for their support and time discussing the results and physical processes. The reviewers provided very useful comments and suggestions in the final version of this paper. Support for this work was provided by NASA Contract NAS5-98181. Much of this work was completed by MGB while at NASA Goddard Space Flight Center with the Universities Space Research Association (USRA) Goddard Visiting Scientist Program.

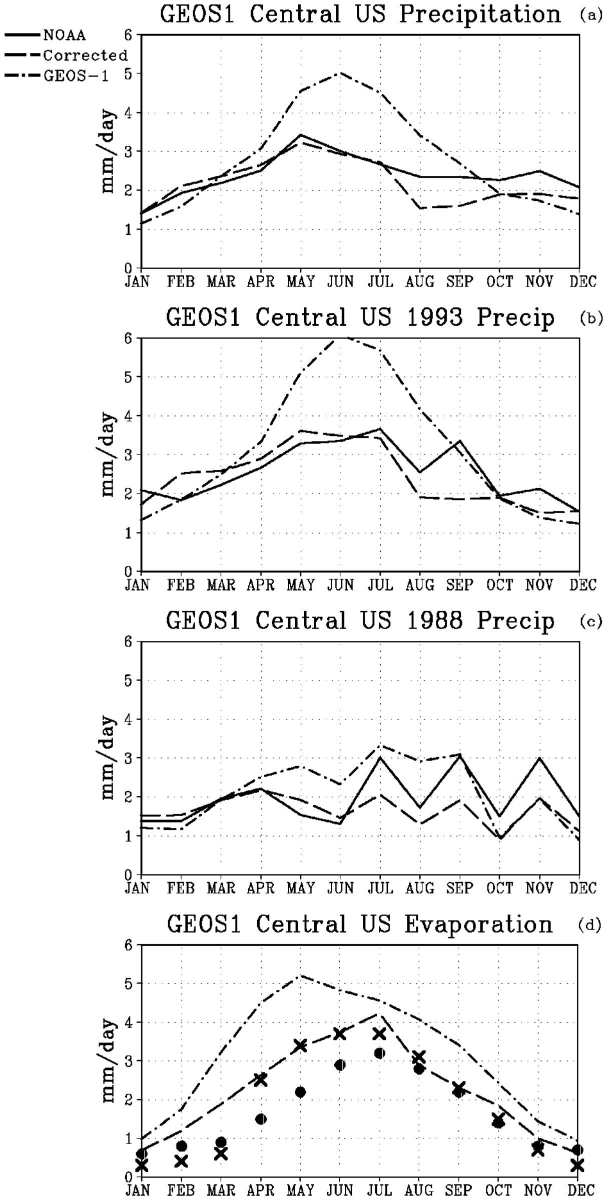

FIG. A1. Time series of reanalysis data (P for the GEOS-1 precipitation, and P^* for the corrected GEOS-1 precipitation) and observations for (a) 15-yr mean precipitation, (b) 1993 precipitation, (c) 1988 precipitation, and (d) 15-yr mean evaporation (E for the GEOS-1 evaporation, and E^* for the corrected GEOS-1 evaporation). The National Oceanic and Atmospheric Administration (NOAA) observations are from Higgins (1996). The evaporation data are from Roads et al. (1994) for Mississippi River Basin (x) pan measurements and (●) hydrologic budget residual.

APPENDIX

Application of Statistical Corrections

A statistical approach to partitioning the analysis increments into contributions from the physical processes developed by Schubert and Chang (1996) is used to correct the reanalysis precipitation and evaporation fields. We use these corrected fields in the Eltahir and Bras (1994) bulk diagnostic precipitation recycling model. Figure A1 compares the GEOS-1 precipitation for the 15-yr mean, 1988, and 1993 annual cycles with the fields and observations, areally averaged for the region in Fig. 1. The precipitation observations are station data interpolated to the GEOS-1 DAS grid (Higgins et al. 1996). In the mean annual cycle, the comparison is greatly improved, especially for spring and summer

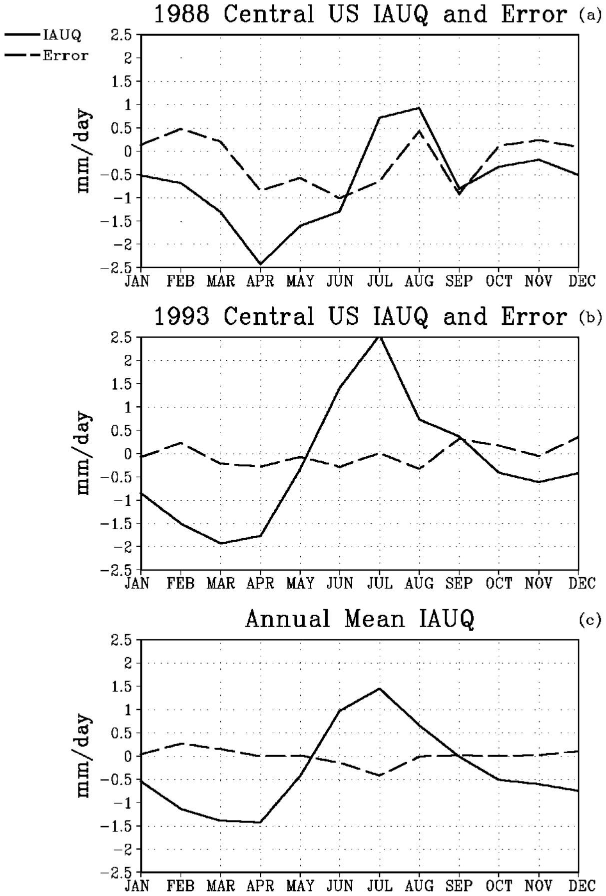

FIG. A2. Central U.S. area-average annual cycles of the analysis increment of water vapor IAUQ and remaining error from the regression analysis [Error ε in Eq. (2)] for (a) 1988, (b) 1993, and (c) the 15-yr mean.

months. Autumn and early-winter precipitation are underestimated. Precipitation during 1993 is especially improved during the summer. In 1988, the regressed precipitation is smaller than the GEOS data, but the improvement is not as dramatic as for 1993, because the GEOS-1 data were already close to observations. Observations of evaporation over long periods are very limited. Figure A1d compares the GEOS evaporation with Mississippi River Basin evaporation from Roads et al. (1994), including pan measurements and residual calculations (see their Fig. 5). The time and area averaging of the data from Roads et al. (1994) do not exactly match those of the GEOS data, so the point of this figure is that the change of GEOS evaporation due to the correction is probably reasonable. Also, note that the annual cycles of both evaporation and precipitation show higher summer values without the regression. Not accounting for the analysis increment in the bulk recycling model produces a larger recycling ratio and recycled precipitation.

The annual cycle of the analysis increment and error is shown in Fig. A2. The error during 1993 is clearly smaller than the analysis increment. The error term in 1988 is smaller than the analysis increment but is still a significant magnitude. For the 15-yr-mean annual cycle some error still exists. After checking the results of the multiple linear regression, we found a few cases for which either the evaporation or the precipitation would change sign. Allowing this sign change to happen returns a negligible mean error, but at the expense of a physical result. Therefore, on the occurrence of a sign change for either evaporation or precipitation at a grid point, the value that does not change sign would be used in a linear regression. The value that did change sign would not be altered. This provided a physical constraint on the regression, but it permitted a small amount of mean error to occur in February and July, but only for a small fraction of grid points in the region of interest.

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