The Observed Mean Annual Cycle of Moisture Budgets over the Central United States (1973–92)

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ABSTRACT

The mean annual cycle of the atmospheric and terrestrial water balance over the central United States is examined through an analysis of observational data over the 20-yr period 1973–92. The mean quantities from this study are expected to serve as a climatology for empirical investigations and a benchmark for numerical model-based water balance computations for the central United States. Monthly means and statistics of atmospheric water balance quantities were computed from twice daily radiosonde data. These data form a monthly ''climatology'' and 240 month time series of the major water budget components, including the vertically integrated vapor flux divergence, the rate of change of precipitable water, and precipitation minus evapotranspiration, $P - E$. The mean annual cycle of evaporation given estimates of precipitation over the same area is also computed. Through comparison with observed river discharge, estimates are formed of the mean annual cycle of surface and subsurface storage and its interannual variability (as a residual). The mean observed and residual quantities of the historical water budget components are in general agreement with earlier studies based on shorter time series.

The 20-yr mean water budget shows a maximum of $P - E$ in March–April with a secondary maximum in November–December. In this analysis, mean evaporation exceeds mean precipitation during the June–September period with largest evaporation values in July and August. Thus, the heartland of the United States acts as mean net moisture source during the summer months. Individual monthly estimates of evaporation, given the gauge-estimated precipitation over the region, show negative evaporation estimates during some cold season months over the 1973–92 period. This suggests that gauge-measured precipitation is underestimated, at least during the cold months, in agreement with several rain gauge intercomparison studies.

The sonde-based budgets also confirm previous studies in showing that the rate of change of precipitable water is a small contributor to the atmospheric water budget through most of the mean annual cycle. However, the relative importance of this term increases during the transition seasons (late spring and early fall) when the magnitude of the vapor flux divergence term in the atmospheric water balance is also quite small.

The mean $P - E$ estimates computed from the vertically integrated atmospheric moisture flux were found to average 0.4 mm day^{-1} low in comparison to the observed total net river discharge. When the mean atmospheric $P - E$ is adjusted to the net discharge, the annual cycle of storage shows an amplitude of 14 cm yr^{-1}, consistent with local measurements of soil moisture in Illinois (Hollinger and Isard) and also in agreement with earlier studies. The 20-yr time series shows multiyear variations in the storage term with magnitudes of near 45 cm, far in excess of the mean annual cycle. This low-frequency variability in storage is generally consistent with the accumulated precipitation anomaly, an independently estimated quantity, for most of the analysis period.

1. Introduction and background

There is a need for better understanding of the mechanisms associated with the hydroclimatic cycle on the large scale, in general, and the central United States, in particular. Understanding of the hydrologic cycle is a crucial step on the road to improved modeling of seasonal and interannual dynamics associated with observed moisture anomalies. The ultimate goal is to provide a quantitative basis for improving seasonal climate predictions through the use of coupled atmosphere–land models over the continents in conjunction with coupled ocean–atmosphere models. However, before any of these lofty goals can be addressed adequately, a better understanding and description of the mean atmospheric and terrestrial water balance is highly desirable. A major

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part of the scientific challenge is to establish an observation-based benchmark for the continental-scale mean seasonal and long-term variability of the atmospheric and terrestrial branches of the hydrologic cycle and their individual components. In this paper we document the mean water balance for the central United States based on an analysis of monthly radiosonde, precipitation, and river discharge data for a 20-yr period. A major emphasis here is on obtaining the best estimates of precipitation minus evapotranspiration ($P - E$) from the radiosonde-based atmospheric budget and, in addition, in obtaining the best estimates of evaporation and surface–subsurface water storage as the residuals from the combined atmospheric–terrestrial water balance.

Benton and Estoque (1954) were first to report the results of a radiosonde-based water budget study for North Africa. They examined the continental-scale atmospheric water budget for the calendar year 1949 based on estimates of the geostrophic wind and moisture from analysis of 30 radiosondes at three levels (850 hPa, 700 hPa, and 500 hPa). Their study established the close links between the seasonal patterns of moisture transport and precipitation over the continent and provided estimates of evapotranspiration (E) over North America as a residual in computations of the vertically integrated flux divergence and climatological precipitation. They were the first to show that continental-scale estimates of evaporation exceed precipitation during the warm part of the year (May–August). In a more detailed study, based on an analysis using two years of radiosonde-observed winds and moisture, Rasmusson (1967, 1968) confirmed that the North American continent is a source of moisture during the core of the summer season. He also presented the first intercomparisons between the independently observed ($P - E$) and stream discharge (D).

While there have since been a number of North American atmospheric water balance studies based on numerical-model-assimilated analyses, for example, Roads et al. (1994), Higgins et al. (1996a), Berbery et al. (1996a), this study is the first radiosonde-based analysis to examine the mean annual cycle of the large-scale atmospheric water balance over the central United States in comparison to surface discharge since the pioneering work of Rasmusson (1967, 1968). Our ultimate goal is to produce the longest reliable data series to document the annual cycles and long-term variations of the atmospheric and terrestrial water budgets over the central United States. We describe the data in section 2, the mean annual cycle of the atmospheric moisture budget in section 3, the time series of selected atmospheric water budget components in section 4, and discuss these analyses in section 5.

2. Data

a. Radiosonde observations

The radiosonde data were extracted from the Radiosonde Data of North America (Forecast Systems Laboratory 1993), which covers the period 1946–92. However, here we restrict the analysis to the 1973–92 period to avoid the most severe known problems with the humidity sensors (Elliott and Gaffen 1991; Gaffen 1992) and because the network was relatively uniform over that period.

Individual radiosonde observations were processed into monthly files. Detailed description of the technique for processing of individual radiosonde observations can be found in Yarosh and Ropelewski (1996). The stations of interest to our study generally contained data at 50-hPa vertical resolution and thus the we were able to compute monthly estimates of atmospheric transports based not only on mandatory levels but also at 50-hPa resolution from the surface to 200 hPa. The calculations of vertically integrated specific humidity, winds, and moisture flux components were made if an individual sounding contained data for at least the surface and 850 hPa and if there were more than five levels with data that passed quality control checks for the sounding. Vertically integrated quantities were computed using every point of the profiles—that is, both mandatory and significant levels. Separate files of monthly means were created for 0000 and 1200 UTC. Monthly estimates of the atmospheric moisture divergence for the central United States were made from 15 radiosonde stations (Fig. 1), and the rate of change of precipitable water in the area was computed using the data for every station inside the boundary. We found no large systematic differences in the number of soundings or the number of levels per sounding as a function of sounding time. The monthly atmospheric water budget terms were computed separately for 0000 and 1200 UTC and for the daily average if at least 50% of both the 0000 and 1200 UTC soundings were available.

b. Precipitation

Precipitation was obtained from the hourly dataset compiled by Higgins et al. (1996b). They gridded hourly precipitation data from approximately 2500 cooperative observation sites, as well as from National Weather Service stations, into a 2° lat × 2.5° long grid for the coterminous United States. The hourly precipitation totals were converted to daily and monthly mean precipitation rates in mm day^{-1} (or cm month^{-1}) for each month in the 1973–92 period for the gridded area approximating that outlined in Fig. 1. The dataset did not contain information about the types of gauges nor whether they were shielded or not.

c. Discharge

Monthly and/or daily river discharge data were obtained from the United States Geological Survey (USGS), which they augmented with data from the U.S. Army Corp of Engineers. Only the streamflow (inflow and outflow) crossing the boundaries of the analysis area

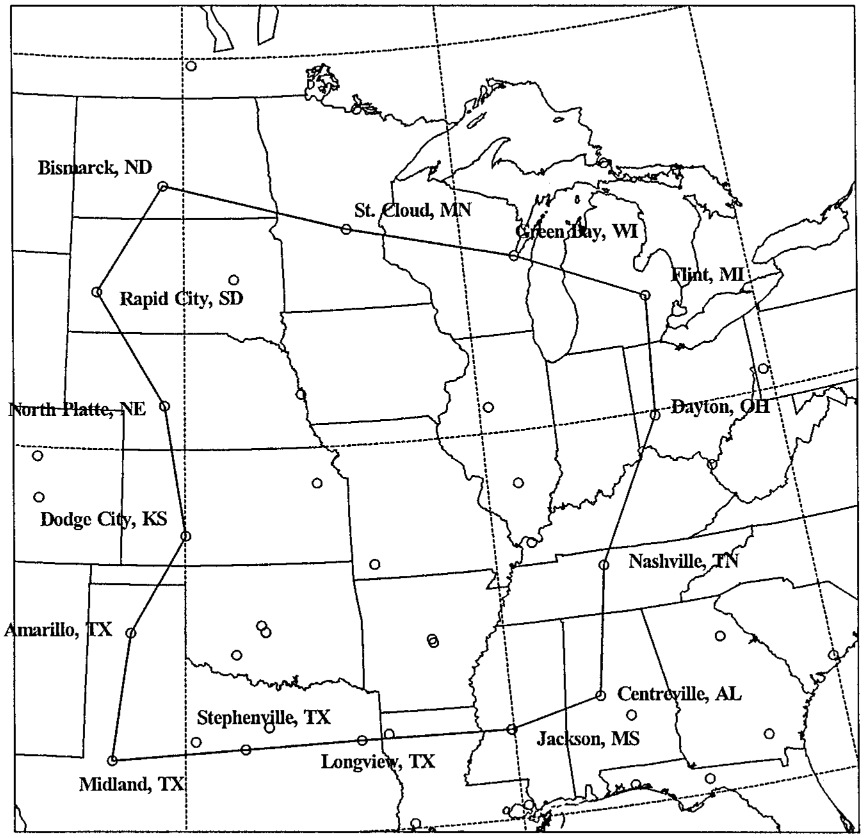

FIG. 1. Locations of the 15 radiosonde stations used to compute the components of the atmospheric water budget for the 1973–92 period are connected by the solid line defining our ''big box.''

outlined in Fig. 1 were considered in the total monthly discharge computations. A list of all of the rivers in the USGS dataset that contribute to the total discharge computations is given in Table 1. Even though there are over 40 inflow/outflow river gauge sites listed in Table 1, the vast bulk of the net discharge, over 90% of annual mean, can be accounted for in the main river systems (the Ohio, Tennessee, and Mississippi) in our study area.

3. Moisture budget computations

The atmospheric branch of the water budget can be estimated solely from radiosonde data. If we assume that there is negligible average flux of atmospheric water in either liquid or solid form through the boundaries of the area of interest, and if we also assume that there is negligible change in the atmospheric storage of liquid and solid water over this area, then the atmospheric water balance can be written as

$$\frac{\partial \langle W \rangle}{\partial t} + \frac{1}{A} \oint_C F_n \, dC = -\langle P - E \rangle, \qquad (1)$$

where $\langle W \rangle$ is the average vapor content over the area, A is the estimated area of the area, C is the curve bounding the area, F_n is the vertically integrated vapor transport normal to the contour of the area, E is the rate of evapotranspiration from the surface, P is the rate of precipitation over the area, and $\langle \cdot \cdot \rangle$ denotes a spatial mean. The values obtained from these integral computations are formally equivalent to the vertically integrated flux divergence. The computations are performed on pairs of radiosondes to remove the ambiguity in defining the normal at a single radiosonde location.

Further discussion of Eq. (1) and an evaluation of its terms can be found in, for example, Rasmusson (1977), Peixoto and Oort (1983), and Trenberth and Guillemot (1995). It is generally accepted that increasing temporal and spatial averaging in the evaluation of (1) leads to better compliance with the assumptions made in its derivation. Thus here we focus our attention on the 20-yr means over a large area in the heart of the country.

Uncertainties in the atmospheric budget computations are minimized by the relatively large area and relatively long temporal averaging. Previous estimates of the errors in the convergence computations due to observational error (Rasmusson 1977; Malinin and Rumyantsev 1981) show that for areas larger than 1 million square kilometers the accuracy of vapor flux convergence es-

TABLE 1. List of rivers and station numbers used to compute the total net discharge over the region of the central United States outlined in Fig. 1. Streamflow data are from the U.S. Geological Survey.

Inflow	Outflow
03277200 Ohio River at Maryland Dam near Warsaw, KY	02467000 Tombigbee River at Demopolis L&D near Coatopa, AL
03290500 Kentucky River at lock 2, at Lockport, KY	02486000 Pearl River at Jackson, MS
03298500 Salt River at Shepherdsville, KY	04084500 Fox River, Rapide Croche Dam near Wrightstown, WI
03320000 Green River at lock 2 at Calhoun, KY	04101500 St. Joseph River at Niles, MI
03426310 Cumberland River at Old Hickory Dam, TN	04105500 Kalamazoo River near Battle Creek, MI
03589500 Tennessee River at Florence, AL	04119000 Grand River at Grand Rapids, MI
03599500 Duck River at Columbia, TN	04193500 Maumee River at Waterville, OH
05288500 Mississippi River near Anoka, MN	07289000 Mississippi River at Vicksburg, MS
05369500 Chippewa River at Durand, WI	07290000 Big Black River near Bovina, MS
05381000 Black River at Neillsville, WI	07367630 Ouachita River at Columbia L N D near Riverton, LA
05395000 Wisconsin River at Merrill, WI	07368000 Boeuf River near Girard, LA
06342500 Missouri River at Bismarck, ND	07369500 Tensas River at Tendal, LA
06349000 Heart River near Mandan, ND	08020000 Sabine River at Gladewater, TX
06354000 Cannonball River at Breien, ND	08062700 Trinity River at Trinidad, TX
06357800 Grand River at Little Eagle, SD	08093100 Brazos River near Aquilla, TX
06359500 Moreau River near Faith, SD	08121000 Colorado River at Colorado City, TX
06423500 Cheyenne River near Wasta, SD	
06454500 Niobrara River above Box Butte Reservoir, NE	
06470500 James River at Lamoure, ND	
06768000 Platte River near Overton, NE	
06837000 Republican River at McCook, NE	
06861000 Smoky Hill River near Arnold, KS	
07140000 Arkansas River near Kinsley, KS	
07157950 Cimarron River near Buffalo, OK	
07227500 Canadian River near Amarillo, TX	
07237500 North Canadian River at Woodward, OK	
07344210 Sulphur River near Texarkana, TX	

timates is comparable with the accuracy of river discharge measurements (4%–6%). To further test the observational uncertainties in the atmospheric flux convergence, we performed ‘‘Monte Carlo’’ estimates of the errors in line integral calculations for the central United States. For each of the 15 radiosonde locations, time series of winds and humidity were generated assuming that standard observational errors were distributed as white noise with zero means and the ranges of standard deviations of from 0.5 m s^{-1} to 2.0 m s^{-1} and from 0.5 g kg^{-1} to 1.0 g kg^{-1}. This stochastic ‘‘noise’’ experiment was run for 240 months to simulate the 20-yr dataset. The experiment was also repeated varying the number of levels and number of days with data within every month. In these experiments the mean ‘‘noise-related’’ convergence value did not exceed 4% of the computed monthly means, in general agreement with the earlier studies.

Any complete study of the hydrologic cycle also involves examination of the terrestrial branch of the budget. In general, for monthly means over any large basin, we can write

$$\langle \Delta S \rangle = \langle P - E \rangle - D, \qquad (2)$$

where the $\langle \cdot \cdot \rangle$ indicate the spatial average over the ‘‘big box’’; the left-hand side represents the month to month change, Δ, in total surface and subsurface storage (S) within the area; D is the net discharge into and out of the area; and $\langle P - E \rangle$ is estimated through flux divergence by (1) above.

In most previous studies the month-to-month surface–subsurface storage change is estimated as centered difference from (2). Typically these previous studies then accumulate the relative storage *changes* to arrive at time series of surface/subsurface storage. However, here we found it more straightforward to apply the direct integration of $\langle P - E \rangle$ and D as in (3). This leads to an evaluation of the storage that is more in keeping with the derivation of the water budget equations. Since we have no direct measurements of the storage term for this study, the value chosen for the initial storage is completely arbitrary. As in the centered difference computations, we assume zero storage as an initial value, that is, for the month previous to the start of the integration. The time series are expressed as the accumulated difference of $\langle P - E \rangle$ and D:

$$\langle S_i \rangle = \int_{t=1}^{t=i} (\langle P - E \rangle - D)\, dt. \qquad (3)$$

The resulting values of relative storage obtained by two methods are about the same, our technique does not smooth storage time series.

4. Analysis

a. Mean annual cycle

The mean annual cycle of each of the terms in the atmospheric water budget is evaluated for the central United States using the full 20 years of radiosonde data

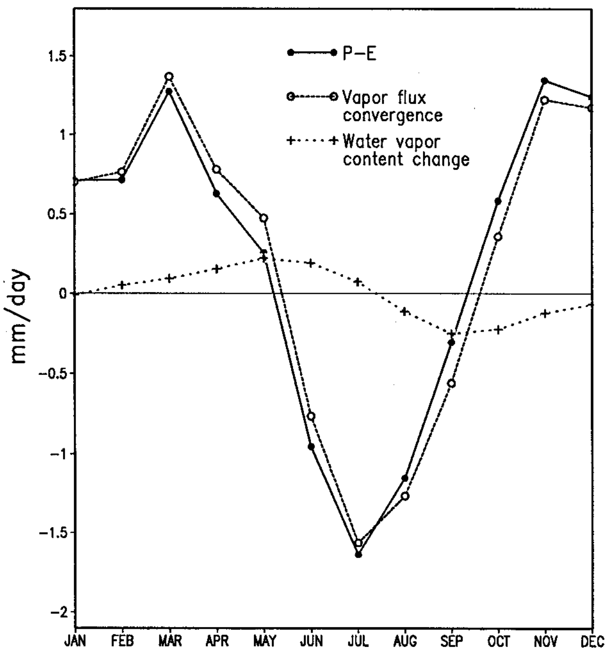

FIG. 2. The mean annual cycle of the atmospheric vertically integrated flux divergence, atmospheric water vapor change, and $\langle P - E \rangle$ all in mm day^{-1}, over the central United States based on radiosonde data for the 1973–92 period.

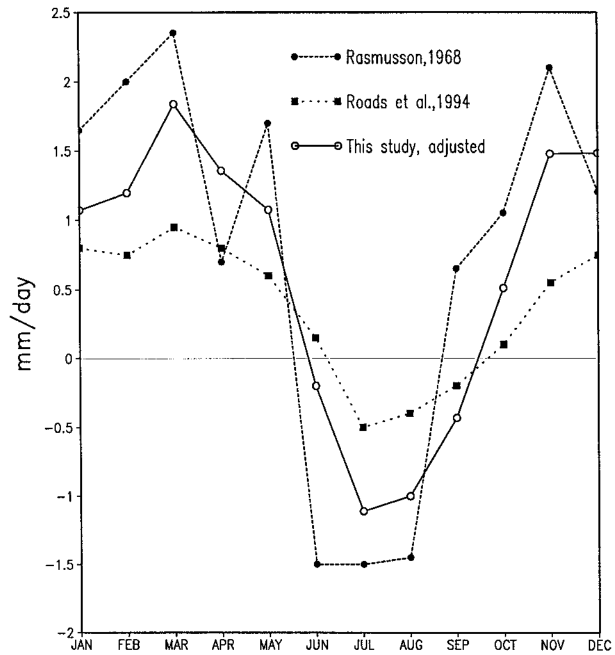

FIG. 3. Comparison of the mean annual cycle of $\langle P - E \rangle$ (mm day^{-1}) based on (a) an average for May 1961–April 1963 for the central plains from a radiosonde-based study (Rasmusson 1968); (b) the 7-yr mean estimates for 1984–90 based on the National Meteorological Center (now known as the National Centers for Environmental Prediction) operational global model analyses for the Mississippi River Basin (Roads et al. 1994); and (c) the 20-yr mean adjusted radiosonde-based estimates for 1973–92, for the central United States from this study.

(Fig. 2). Vertically integrated moisture flux convergence dominates the budget except during the seasonal-transition months of May and September–October when the change in atmospheric water vapor is roughly the same order of magnitude as the $\langle P - E \rangle$. The analysis shows that in the mean, evaporation exceeds precipitation during the June–September period. Thus the central United States is a mean moisture source during the summer and early fall. The balance indicates that precipitation exceeds evaporation from October–May so that the same area is a moisture sink from fall through the spring.

The $\langle P - E \rangle$ from the atmospheric water budget can be independently evaluated by comparison to the surface water budget given by (2). If we assume that the total change in storage over the 20-yr period examined here is negligible then, according to (2) averaged over the whole period the 20-yr mean discharge should be balanced by the 20-yr mean atmospheric $\langle P - E \rangle$ over the area. We have no observational evidence to either support or refute the assumption that total storage change over the 20-yr period is near zero. We defer to (section 4b) discussion of the implications in relaxing the zero-storage-change assumption. Here we note that the comparison of the atmospheric flux divergence to the discharge indicates that the mean atmospheric $\langle P - E \rangle$ is underestimated by 0.4 mm day^{-1}. The model-based computations in Roads et al. (1994) showed a mean bias of about 0.2 mm day^{-1}. In all of the analyses that follow we have adjusted the radiosonde-derived $\langle P - E \rangle$ by 0.4 mm day^{-1} for each month.

We compare the adjusted monthly mean $\langle P - E \rangle$ for the 1973–92 period to the average of the two years, May 1961–April 1963, appearing in Rasmusson (1968), and to the mean model-assimilation-based estimates for 1984 through 1990, calculated from Roads et al. (1994, their Fig. 5). The annual mean flux convergence in this study is 0.6 mm day^{-1}, 0.7 mm day^{-1} in Rasmusson (1967), and 0.5 mm day^{-1} in Roads et al. (1994). This agreement among these three estimates is remarkable given the differences in datasets, the disparity in the analysis periods, the differences in the areas for which the water budgets were computed, and the computational differences between the model-derived water budget quantities and the radiosonde-based analyses. The mean annual cycle of $\langle P - E \rangle$ in the three studies also agree quite well (Fig. 3). The main differences, in addition to the much smaller annual cycle amplitude in the model-based analysis, is that the June value of $\langle P - E \rangle$ is positive in the Roads et al. (1994) analysis and both Rasmusson (1968) and Roads et al. (1994) show positive or near-zero $\langle P - E \rangle$ in September compared to negative values in both those months in the 20-yr means presented here. However, the mean September $\langle P - E \rangle$ value comes into closer agreement—that is, becomes slightly positive—when the budget values are recomputed for the same 7-yr period as in the Roads

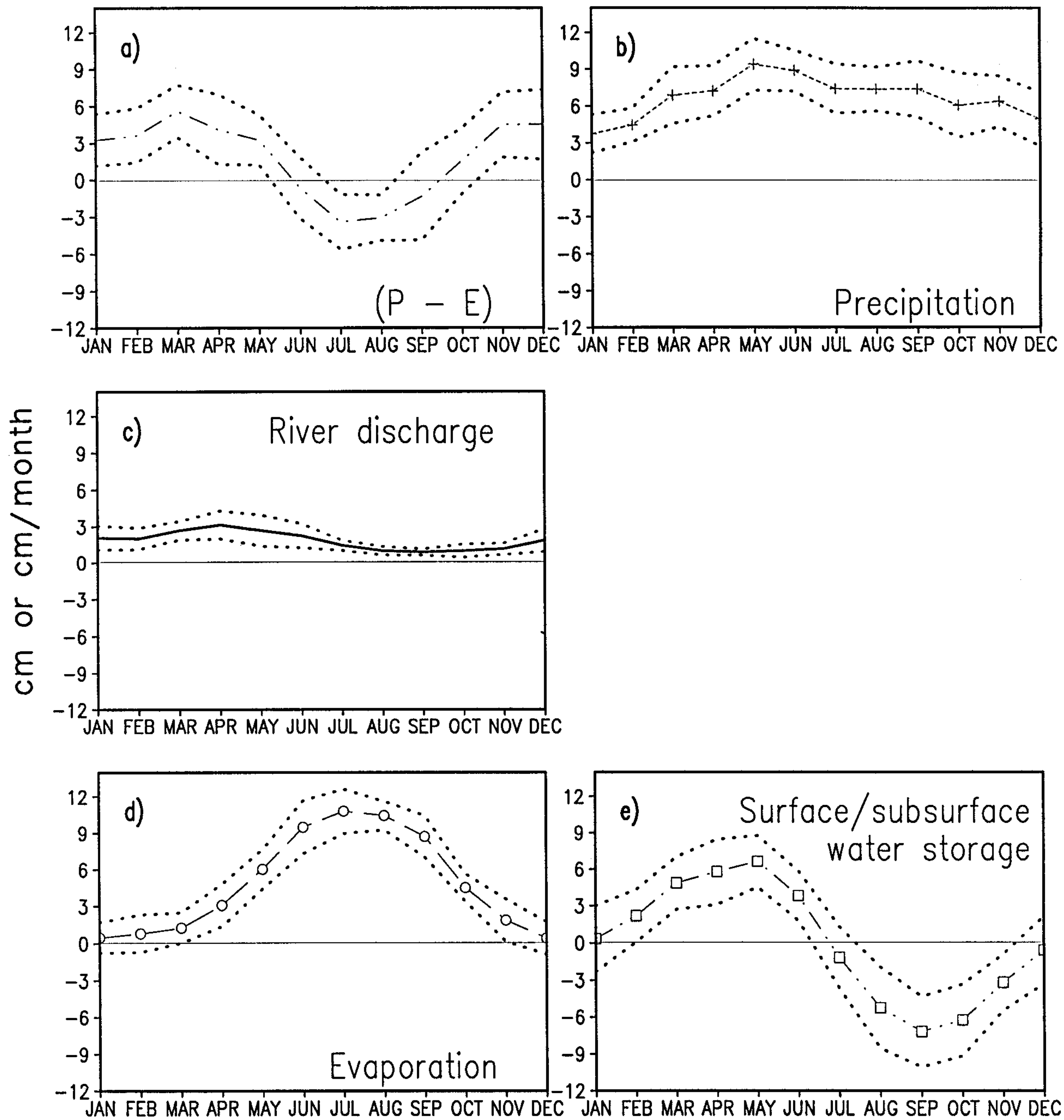

FIG. 4. Mean annual cycle and standard deviations of the major atmospheric and terrestrial water budget components for the central United States: (a) $\langle P - E \rangle$, (b) precipitation, (c) river discharge, (d) evaporation (all in cm month^{-1}), (e) surface–subsurface storage (in cm). The dotted lines indicated plus and minus one standard deviation based on the 1973–92 period.

analysis (1984–90). Further, an examination of the standard deviation of $\langle P - E \rangle$ for each month (Fig. 4a; Table 2) indicates that positive values are not unusual in June and September and that evaporation can generally be expected to exceed precipitation only in July and August.

The 20-yr mean monthly precipitation is computed for the central United States using the data described above (Fig. 4b), and with (1) can be used to estimate monthly mean evaporation and its standard deviation (Fig. 4d; Table 2). Monthly mean precipitation shows a maximum (9.4 cm) in May and a decrease to minimum values (3.7 cm) in January. The magnitude of the annual range in the derived mean evaporation is much larger than the range in precipitation. Minimum mean evaporation values are less than 1 cm in the winter months,

TABLE 2. Annual cycle of the elements of the water balance of the central United States and their variability (in cm or cm month^{-1}).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
							$(P - E)$					
Mean	3.1	3.7	5.6	4.1	3.4	−0.6	−3.4	−3.2	−1.2	1.8	4.3	4.5
Standard deviation	2.1	2.2	2.1	2.9	2.0	2.5	2.3	1.8	3.5	2.6	2.9	2.9
												Precipitation
Mean	3.7	4.4	6.9	7.2	9.4	8.9	7.4	7.4	7.4	6.1	6.4	4.9
Standard deviation	1.6	1.4	2.3	2.0	2.1	1.7	2.0	1.8	2.3	2.6	2.1	2.2
												Discharge
Mean	2.1	2.0	2.7	3.2	2.7	2.2	1.4	1.0	0.9	1.0	1.1	1.9
Standard deviation	1.0	0.9	0.8	1.2	1.3	1.0	0.4	0.4	0.3	0.5	0.5	1.0
												Evaporation
Mean	0.7	0.7	1.3	3.0	5.9	9.5	10.8	10.5	8.6	4.3	2.1	0.4
Standard deviation	1.5	1.5	1.3	1.8	1.6	2.3	1.8	1.3	1.7	1.3	2.1	1.4
												Storage
Mean	0.3	2.2	4.9	5.8	6.6	3.8	−1.2	−5.3	−7.2	−6.3	−3.2	−0.6
Standard deviation	2.7	2.1	2.1	2.7	2.1	2.0	2.5	3.3	2.9	2.9	2.3	2.7

December–February, to maxima of over 10 cm in July and August, exhibiting an order of magnitude change during the course of the annual cycle. The relatively small amplitude in the mean annual cycle of discharge (Fig. 4c) and the generally smaller magnitudes of discharge in comparison to either the precipitation or the derived evaporation illustrate the difficulties in achieving balance in the water budget with these observational data. The relative magnitudes of the water budget components and mean relationships through the annual cycle are more easily compared in Fig. 5.

A 20-yr time series of storage was generated and used to produce a mean annual cycle of relative storage (Figs. 4e and 5). Since time series of relative storage demonstrated significant multiyear variations (see section 4b), we defined its mean annual cycle as the departure from the 12-month running mean. In the mean maximum storage, values are reached in spring, April–May, with minima in fall, September–October. The amplitude of the mean storage annual cycle, about 14 cm, is in general agreement with estimates of the mean amplitude of measured soil moisture in Illinois over a 10-yr period (Hollinger and Isard 1994), as well as in agreement with the earlier water budget–based estimates (Rasmusson 1968). The surface and subsurface water storage within the central United States has the largest mean annual cycle amplitude among all water budget components.

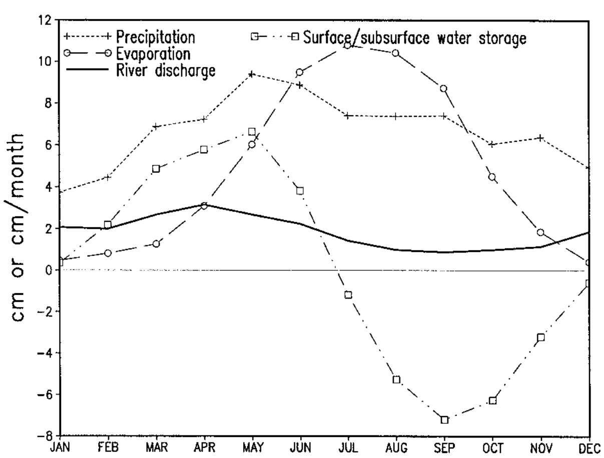

FIG. 5. Comparisons of the mean annual cycles of the measured precipitation to measured river discharge and estimated evaporation (all in cm month^{-1}) and surface–subsurface storage (in cm).

b. *Time series of moisture budget residual components*

The values for the 20-yr mean annual cycle of the atmospheric water budget components are in general agreement with earlier studies and are physically reasonable. A detailed discussion of the interannual variability in the measured components of the atmospheric water budget are deferred to a future paper. The time series of the residual budget quantities are discussed here as another means of estimating uncertainties in the water budget computations. Examination of the time series of monthly evaporation estimated as a residual from the observed flux divergence and precipitation (Fig. 6) shows negative evaporation estimates for about 10% of the months. A closer inspection indicates that all of the negative evaporation estimates occur during the cold half of the year (November–April) with 75% of occurrences during the winter months (December–February). One likely source of this error is underestimation of precipitation. Several studies indicate that gauge-measured precipitation is systematically underestimated, for example, Sevruk (1982). A study by Groisman and Legates (1994) suggests that gauge-estimated mean precipitation over the United States is underestimated by 5%–40%. They found that underestimation is especially significant in the cold season when at least part of precipitation is coming in solid or mixed form. Other studies show precipitation under-

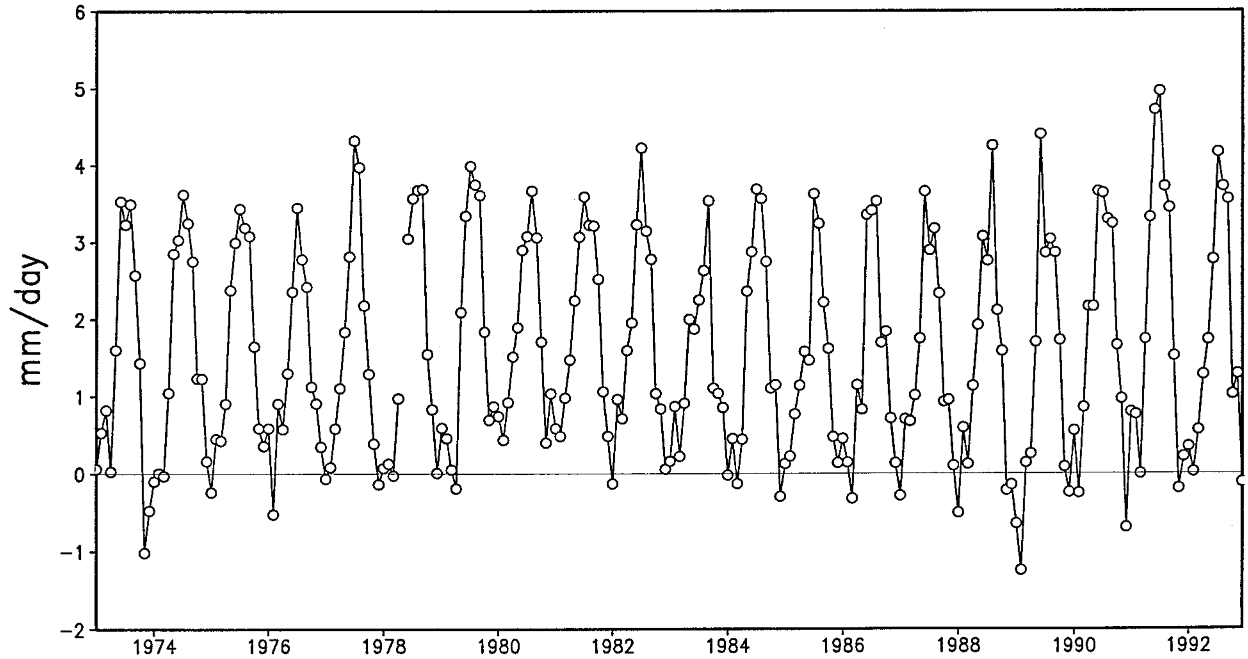

FIG. 6. Time series of monthly evaporation for the central United States (in mm day^{-1}) estimated from the atmospheric water budget and gauge precipitation. Discontinuities in the time series reflect missing data for those months.

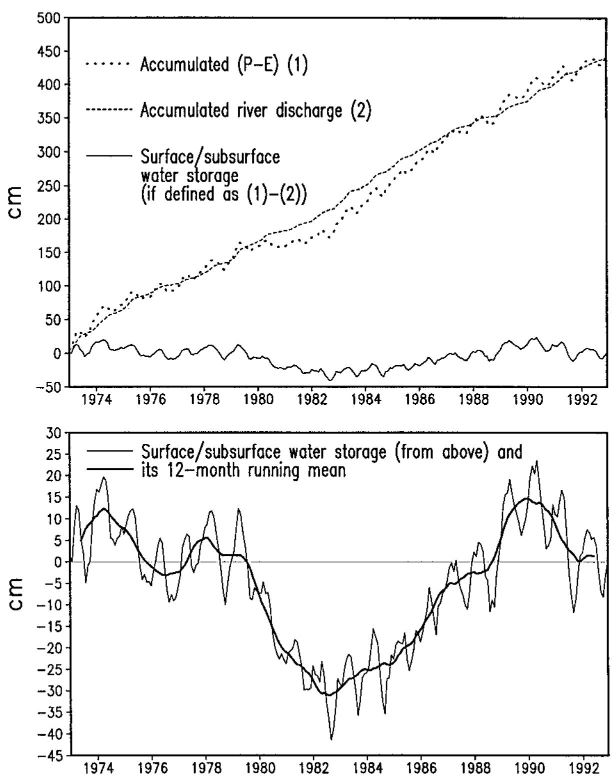

FIG. 7. Time series of accumulated monthly $\langle P - E \rangle$ and accumulated river discharge for the central United States and their difference (top); the relative storage, thin line, and 12-month running mean of relative storage, heavy line, on an expanded scale (bottom). Units are cm.

estimates of 30%–40% compared to shielded standard operational gauges during the winter months [Legates and DeLiberty (1993) and Peck (1997)]. Compared to ''research'' quality instruments even these estimates of gauge underestimates may be substantially too small (E. Peck and P. Groisman 1996, personal communication). The precipitation underestimates for individual stations during winter conditions suggested by the studies referenced above are comparable to the 0.4 mm day^{-1} bias correction in the atmospheric flux convergence. Thus, the uncertainty in precipitation establishes one limit on validation of the water balance–based estimates of evaporation over North America.

We next examine the time series the terrestrial water budget residual, the relative surface, and subsurface storage. There are no data to estimate the actual storage over the central United States so that our analysis is relative to the storage as of December 1972, taken as zero. As noted above, our estimate of relative storage (Fig. 7) is estimated from (3)—that is, the simple difference between the accumulated estimates of $\langle P - E \rangle$ (from the atmospheric water budget) and accumulated river discharge (from observations). The time series of relative storage shows a well-defined mean annual cycle, discussed above, as well as considerable secular variability over the 20-yr period. The 12-month running mean, which suppresses the annual cycle, starts at relatively high levels in 1973 and returns to comparable levels toward the end of the period. However, the character of the time series is dominated by multiyear variability, which includes a dramatic downward trend,

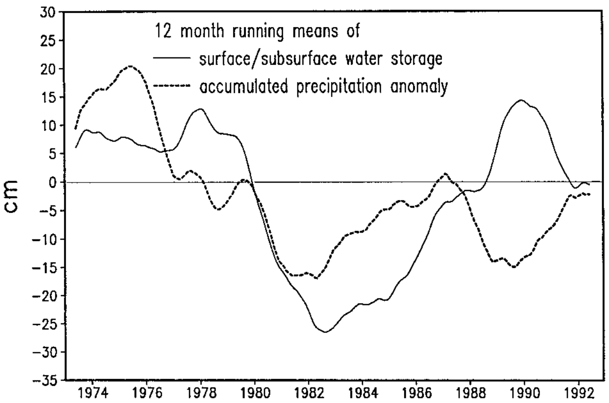

FIG. 8. The time series of 12-month running mean relative storage (thin line) and accumulated precipitation anomaly (dashed). Units are cm.

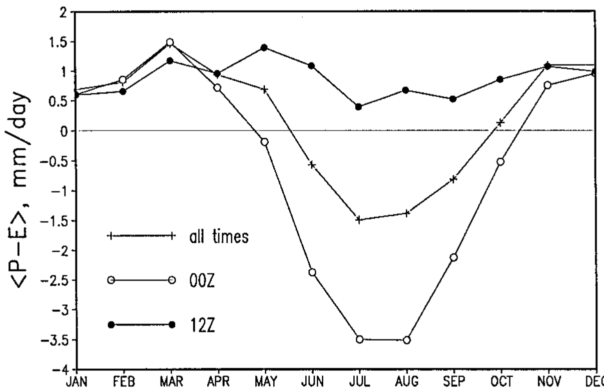

FIG. 9. The mean annual cycle of $\langle P - E \rangle$ (in mm day^{-1}) for the 1973–92 period based on all observations (crosses), 0000 UTC observations only (open circles), and 1200 UTC observations only (closed circles).

reaching a minimum in late 1982, followed by an almost monotonic rise in storage until 1990 followed by a decrease for the remaining 2 yr of the series. This multiyear swing in the 12-month running mean of relative storage has an amplitude of about 45 cm, over three times the magnitude of the mean annual cycle.

Since the relative storage is estimated as a residual from the surface water budget, it is instructive to compare it to the time series of accumulated precipitation anomaly, which does not enter into the computation. In this comparison (Fig. 8), the time series of accumulated precipitation anomaly has the same general character as the time series of relative storage for most of the period. Accumulated precipitation anomaly is initially positive, sinks to a minimum in 1981, slightly in advance in the relative storage minimum, and then rises until the 1988 drought. The general correspondence between these series is not evident in the most recent 5-yr period. The disparity in the estimates of total storage and accumulated precipitation after 1988 are unexplained and may reflect undocumented changes in the radiosondes instruments, observation techniques, and/or locations. It is also possible that there has been some subtle undocumented changes in the manor of measuring and/or reporting discharge after 1988. Since the storage time series is derived from differences in accumulated atmospheric flux divergence and discharge may reflect accumulations of very small systematic errors or biases in either quantity.

We tested the sensitivity of the storage time series to the 0.4 mm day^{-1} bias adjustment. We find that the 0.4 mm day^{-1} bias adjustment results in the minimum amplitude in the magnitude of the storage change excursions over the 20-yr period and the best overall agreement with the character of the accumulated precipitation times series. The application of the seasonally varying bias adjustment had little effect on the character of the storage time series.

On the other hand there are examples in the hydroclimatic literature for which accumulated precipitation and other measures of storage components do not follow expected behavior. In particular, a recent study by Meadows et al. (1997) shows time series in which Lake Michigan lake level diverges from time series of precipitation for periods of several years. In a more direct example to this study, Todd (1980, his Fig. 6.1) suggests that rainfall is ''not an accurate indicator of groundwater level changes'' and illustrates the disparity between with time series of precipitation and ground water for the San Bernardino Valley, California.

5. Summary and discussion

To summarize, the mean annual cycle of the radiosonde-based budget estimates are in general agreement with the earlier studies, Benton and Estoque (1954) and Rasmusson (1967, 1968), in the magnitude and phase of the mean annual cycle. The amplitudes of the mean annual cycle for evaporation and relative storage are 11 cm and 14 cm, respectively, with relative storage reaching a maximum in spring (April–May) followed by a draw down to a minimum in fall (September–October). The annual cycle of precipitation over the budget study area has roughly half the amplitude, about 6 cm, with a minimum in January, reaching a maximum in May. Given the uncertainties of measurements of solid precipitation, which lead to substantial underestimates of actual precipitation, it is likely that the amplitude of the precipitation annual cycle is even less than indicated here. However, since the mean annual cycle of river discharge reaches a maximum in April, the phase of the mean precipitation annual cycle is probably correct. The river discharge, which we assume to be the best measured of the water budget terms, has a smaller annual cycle and smaller variability than any of the other terms, a measure of the difficulty in obtaining agreement between the atmospheric and terrestrial branches of the water budgets.

This is the first in a series of papers that examine the

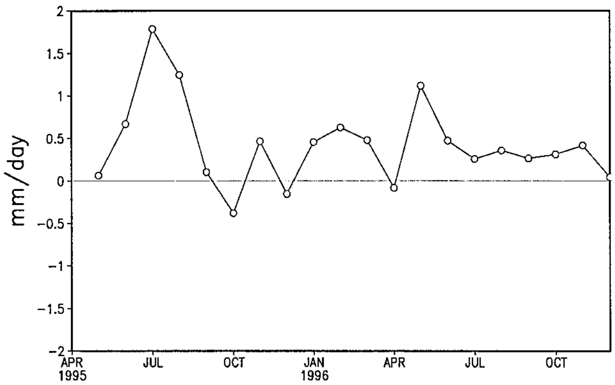

FIG. 10. Differences in $\langle P - E \rangle$ computed from Eta Model subsampled at the radiosonde temporal and spatial resolution and full Eta Model resolution (in mm day^{-1}).

atmospheric and terrestrial water budgets over the heartland of the United States for the period 1973 through the late 1990s. The purpose of this paper was to present a baseline, or reference, ''climatology'' for use in both observational and modeling studies as part of the GEWEX Continental-Scale International Project (GCIP). In the comparisons of atmospheric and terrestrial water budgets it was necessary to adjust the atmospheric estimates of $\langle P - E \rangle$ by 0.4 mm day^{-1} under the assumption that the discharge data represented ''ground truth.'' Preliminary investigations have indicated that part of this mismatch between the budgets may arise from inadequate spatial and temporal sampling by the radiosonde network (Fig. 9). Clearly there is a difference in the mean annual cycle of $\langle P - E \rangle$ between the 0000 and 1200 UTC estimates, in agreement with Rasmusson (1967), who documented significant diurnal variability in the moisture flux fields.

Since radiosonde data are available twice daily, we turned to the NCEP mesoscale Eta Model (Black 1994) for insight on the temporal and spatial sampling problem. Intercomparisons of components of the atmospheric water budget derived from radiosondes and Eta Model were performed on a limited, 6-week period, which contained overlapping data (Yarosh et al. 1996a). They report that Eta Model atmospheric water budget quantities subsampled at the radiosonde resolution compared well with the radiosonde estimates of these same quantities. Temporal and spatial sampling were further investigated by comparisons of Eta Model water budgets subsampled at the radiosonde spatial and temporal resolution compared to water budgets derived from the full Eta Model resolution (Berbery et al. 1996b; Yarosh et al. 1996b). Their results, extended to a 20-month period (Fig. 10), show a mean bias of 0.43 mm day^{-1} between the subsampled and full Eta resolution budget estimates. This strongly suggests that much of the mean bias between the radiosonde-based flux convergence discussed in this paper and the discharge may be due to spatial and temporal sampling. This tentative conclusion will be further investigated as the full five years of GCIP data become available.

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