Regional terrestrial water storage change and evapotranspiration from terrestrial and atmospheric water balance computations

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[1]   In this study we estimate the regional terrestrial water storage change (TWSC) and evapotranspiration (ET) in Illinois ($\sim 2 \times 10^5$ km^2) from reanalysis data for a 22-year period (1984–2005) using terrestrial and atmospheric water balance computations. The estimates are compared with in situ observations of TWSC as well as ET, derived as the residual of observed precipitation, streamflow, and TWSC. The 22-year mean annual cycles of estimated TWSC and ET agree well with observations. Monthly estimates of TWSC and ET match favorably with observations, with correlation coefficients of 0.66 and 0.69, respectively. However, annual average TWSC and ET estimates significantly deviate from the observations; the correlation coefficient drops to 0.31 and 0.19, respectively. A 52-mm/a imbalance (17% of the average streamflow in Illinois) was found between the mean water vapor convergence and streamflow, which also results in a similar magnitude of error in the estimated TWSC and ET based on reanalysis convergence. This imbalance is due in large part to the systematic bias in reanalysis data. It is concluded that the reanalysis data have the potential to estimate the climatology and monthly TWSC and ET variations but are not suitable for the diagnosis of their interannual variability. This is due to the accumulation, rather than cancellation, of the systematic errors in the reanalysis data. Whether the average streamflow would balance the average convergence depends on which particular period of time is under analysis. A longer time period of analysis does not necessarily ensure the balance between streamflow and convergence, as commonly assumed in regional water balance analyses.

1. Introduction

[2]   The global water cycle directly affects the general circulation of both the atmosphere and the ocean and hence plays a central role in shaping Earth's weather and climate. An accurate representation of the exchanges of water between the atmosphere, the ocean, and the land surface in global climate models is one of the biggest challenges for weather forecasting and climate prediction. However, our quantitative knowledge of the global water cycle is quite poor; large-scale measurements of the stocks and fluxes for various global reservoirs on timescales appropriate to their dynamics are deficient.

[3]   Terrestrial water storage (snow, ice, surface water, soil moisture, groundwater, etc.), as a fundamental component of the global water cycle, is of great importance for water resources, climate, agriculture and ecosystems. Moreover, terrestrial water storage change (TWSC) is a basic quantity for closing the water balance. Improved quantification of TWSC would reduce water budget uncertainty, while a better understanding of the potential links between TWSC and atmospheric phenomena would result in enhanced parameterization in climate models. While the Gravity Recovery and Climate Experiment (GRACE) mission provides a satellite-based view of TWSC [*Syed et al.*, 2008], very limited in situ network data are currently available for monitoring large-scale variations of TWS and its individual components. Despite of its importance, reliable data sets of large-scale TWS are extremely scarce.

[4]   Evapotranspiration (ET) is another important but least understood component of the terrestrial water cycle that is normally unmeasured. Evapotranspiration links the land and atmospheric branches of the hydrological cycle by dictating exchanges of heat and moisture between them, thus exerting a strong influence on the patterns of atmospheric water vapor transport. Since ET is difficult to observe at a regional scale, validation of hydrological and land surface model estimates is difficult. One approach has been through comparison to ET derived from a large-scale atmospheric water balance using reanalysis data [e.g., *Abdulla et al.*, 1996; *Berbery et al.*, 1996; *Lenters et al.*, 2000; *Maurer et al.*, 2002]. In atmospheric water budget analyses, ET is derived as the residual of precipitation and water vapor convergence [*Rasmusson*, 1967, 1968; *Roads et al.*, 1994; *Oki et al.*, 1995; *Yeh et al.*, 1998; *Ropelewski and Yarosh*, 1998; *Berbery and Rasmusson*, 1999]. A common approach

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to check the accuracy of atmospheric water balance computations is through the comparison between the long-term average atmospheric convergence and streamflow. *Yeh et al.* [1998] demonstrated that regional evaporation can be satisfactorily estimated from atmospheric water balance computations over Illinois for a 12-year period from 1983 to 1994.

[5] The goal of this paper is to investigate the validity of terrestrial and atmospheric water balance computations for the estimation of regional-scale TWSC and ET, by comparing derived estimates with those obtained from a comprehensive and unique 22-year (1984–2005) observed data set in Illinois, including soil moisture, water table depth, snow depth and streamflow [*Hollinger and Isard*, 1994; *Yeh et al.*, 1998]. In this study, 22-year monthly TWSC is computed from the combined land-atmospheric water balance [*Oki et al.*, 1995; *Gutowski et al.*, 1997; *Masuda et al.*, 2001; *Seneviratne et al.*, 2004; *Hirschi et al.*, 2006] This TWSC estimate is then compared to that derived from the in situ measurements. Evaporation derived from the atmospheric water balance computation is compared to that estimated independently from the terrestrial water balance computation based on observed data. Since the scale of interest here is comparable to the typical size of an atmospheric model grid cell, we believe that if the two independent approaches yield similar estimates of TWSC and ET, then the future combined applications of terrestrial and atmospheric water balance computations can aid in the validation of current land surface hydrological simulations in climate models.

2. Study Area

[6] Illinois was chosen as the study region for several reasons. First, it is one of only a few regions in the world where a comprehensive hydrologic in situ network described below has systematically monitored most of the water storage components over the last several decades [*Hollinger and Isard*, 1994; *Yeh et al.*, 1998]. Although a larger area would provide more accurate atmospheric moisture convergence estimates, limiting the region to Illinois will allow for comparison of our estimated ET and TWSC to observations. Second, Illinois has rather flat and homogeneous terrain so that topography-related problems of atmospheric variables over mountainous areas due to vertical interpolation in the reanalysis data will be minimized [*Alexander and Schubert*, 1990; *Trenberth*, 1991, 1997; *Berbery and Rasmusson*, 1999]. Finally the relatively high density of upper-air observations in the Upper Mississippi basin should result in a better characterization of atmospheric water vapor transport in the study region [*Gutowski et al.*, 1997], and also Illinois is not near coastal areas where the errors in the atmospheric variables of the present reanalysis systems are relatively large [*Roads et al.*, 1994].

3. Methods and Materials

3.1. Terrestrial Water Balance Computation

[7] The terrestrial water balance equation can be written as

$$\frac{d\overline{S}}{dt} = \overline{P} - \overline{E} - \overline{R}, \tag{1}$$

where $\overline{S}$ (the overbar denotes the large-scale monthly mean value) is the total terrestrial water storage (mm); $\overline{P}$ (mm/month) is the precipitation; $\overline{E}$ (mm/month) is the evapotranspiration; and $\overline{R}$ (mm/month) is the total runoff. Alternatively, $d\overline{S}/dt$ can be expressed in terms of its surface, soil moisture, and groundwater components as

$$\frac{d\overline{S}}{dt} = \frac{d\overline{W_S}}{dt} + \overline{n}\overline{D}\frac{d\overline{s}}{dt} + \overline{S_y}\frac{d\overline{H}}{dt}, \tag{2}$$

where $\overline{W_S}$ (mm) is the total surface water storage including (accumulated) depth of snowpack (liquid equivalent), water in the lakes and reservoirs; $\overline{n}\overline{D}$ (mm) is the available storage depth of the soil: the product of soil porosity and root zone depth; $\overline{s}$ (%) is the soil relative saturation (i.e., soil moisture content divided by soil porosity); $\overline{S_y}$ (%) is the specific yield (i.e., the fraction of water volume that can be drained by gravity in an unconfined aquifer); $\overline{H}$ (mm) is the groundwater level. Previous studies [*Yeh et al.*, 1998; *Rodell and Famiglietti*, 2001; *Seneviratne et al.*, 2004] all concluded that changes in groundwater and soil moisture are typically the largest components of monthly terrestrial water storage variations in Illinois. *Rodell and Famiglietti* [2001, Figure 2] have further shown that the change in snow and reservoir water storage was only occasionally significant with the maximum of ∼10 mm/month. Given the limited role of snow and surface water storage in Illinois, only soil moisture and groundwater storage changes will be considered in this study. The porosity data was provided by ISWS for each of the 19 soil moisture monitoring stations. The specific yield $\overline{S_y}$ was determined as 0.08 for the silt loam soil in Illinois following *Yeh et al.* [1998].

3.2. Atmospheric Water Balance Computation

[8] The atmospheric water balance equation can be written as [*Yeh et al.*, 1998]:

$$\frac{d\overline{W_a}}{dt} = \overline{E} - \overline{P} + \overline{C}, \tag{3}$$

where $\overline{W_a}$ is the mean precipitable water, $\overline{C}(= -\nabla \cdot \overline{Q})$ is the mean convergence of the lateral atmospheric vapor flux, and $\overline{Q}$ is the vertically integrated mean total moisture flux. $\overline{C}$ can be calculated by taking the line integral of the moisture flux around the area under study. $\overline{W_a}$ and $\overline{Q}$ can be calculated by integrating the profiles of specific humidity q, zonal and meridional wind components, u and v, from the pressure at the ground surface p_s to that above which moisture content becomes negligible p_u (i.e., $p_u = 300$ mb in this study). More details about the computations of atmospheric vapor convergence can be found in the work of *Yeh et al.* [1998]. Our reanalysis-based estimates of ET are obtained by solving (3) for ET using observed precipitation and the water vapor storage change and convergence computed from the reanalysis data. This estimate will be compared to that deduced as a residual from (1).

[9] The TWSC term in (1) can be derived by combining (1) and (3):

$$\frac{d\overline{S}}{dt} = \overline{C} - \overline{R} - \frac{d\overline{W_a}}{dt}, \tag{4}$$

which provides an independent comparison to the in situ measurements of TWSC. Over the long term, the two derivative terms in (4) generally can be assumed negligible, thus $\overline{R} = \overline{C}$, which expresses that, for any climate equilibrium, the long-term atmospheric moisture convergence toward any hydrologic unit has to be balanced by the long-term net discharge of water out of the same unit. Therefore, for any studies using the combined water balance equation (4), $\overline{R} = \overline{C}$ can be viewed as a criterion for evaluating the agreement between the atmospheric and hydrological data sets and for assessing the water balance closure over the long term.

3.3. Source of Data

[10] The in situ hydrological data used in this study include 22 years (1984–2005) of soil moisture, water table depth, and streamflow observations. The locations of various measurement stations are shown in Figure 1. Weekly to biweekly neutron probe soil moisture have been collected by the Illinois State Water Survey (ISWS) from 1981 until the present. Fifteen of the 19 total sites covering the period of 1984–2005 were used in this study. The groundwater data consists of monthly water table depth measurements at 19 wells scattered throughout the Illinois for monitoring the shallow unconfined aquifers. Sixteen out of 19 wells with complete records from 1984–2005 were used here. Streamflow data collected by the U.S. Geological Survey (USGS) consists of daily discharge measurements of the selected three largest basins in Illinois: Illinois River at Valley city, Rock River near Joslin, and Kaskaskia River near Venedy. Their total drainage areas cover approximately two thirds of the area of Illinois. Their 22-year (1984–2005) monthly discharges were weighted by drainage areas to give the average monthly time series of streamflow in Illinois.

[11] The atmospheric moisture data, including specific humidity and wind speed, is taken from the NCEP/NCAR global reanalysis [Kalnay et al., 1996]. The NCEP/NCAR data used here has a 6 hourly temporal resolution and $2.5° \times 2.5°$ horizontal resolution at eight pressure levels (1000, 925, 850, 700, 600, 500, 400, 300 mb). The total area examined in this study (Figure 1) encompasses nine grid points of the NCEP/NCAR $2.5° \times 2.5°$ reanalysis data (3×3 points from 87.5°–92.5°W and 37.5°–42.5°N). Almost all of Illinois, except for the southern tip of the state, is covered by the study region, along with some portions of surrounding states. Additional details about the data used in this study can be found in the work of Yeh et al. [1998] and Eltahir and Yeh [1999].

[12] Figure 2 shows the 22-year (1984–2005) monthly time series of the state average atmospheric moisture convergence, precipitation, soil moisture from 0 to 2 m, water table depth, and streamflow. The signatures of hydrologic extremes such as the late spring drought in 1988 and the summer flood in 1993 are clearly observed in the soil moisture, water table depth and streamflow time series. More recently, Illinois experienced another severe drought in early spring of 2005, which can also be clearly seen in water table depth and streamflow shown in this figure. Yeh et al. [1998] has found close agreement between the 12-year (1983–1994) regional evaporation estimates from both the terrestrial and water balance computations, suggesting that the role of human withdrawal or interference in streamflow

is not significant in the regional water balance for the state of Illinois.

4. Results

4.1. Mean Annual Cycles of Water Balance Components

[13] Figure 3a illustrates the mean annual cycles of terrestrial water balance components: precipitation, evaporation (ET), streamflow, TWSC, and monthly change in the soil moisture and groundwater storage. The 22-year (1984–2005) mean annual evaporation (638 mm/a) and runoff (301 mm/a) are approximately 70% and 30% of annual precipitation (935 mm/a). For the ET estimates, a seasonal cycle is clearly demonstrated with a peak of 131 mm/month in July and a trough of almost zero during the winter (December–February). The ET is highest in the summer because plants grow rapidly and transfer large amounts of soil water to the atmosphere, whereas ET is lowest in the winter due to cold temperatures and the dormancy period of plants. The summer peak value of ET is consistent with roughly 4 mm/d July ET estimated by both Berbery and Rasmusson [1999, Figure 10] and Roads et al. [2003, Figure 15] for the Mississippi River basin. In summer (June–August), ET exceeds that of precipitation, while during the winter ET falls well below precipitation. Upon examination of each individual year some ET estimates during the late fall and winter months appear to be below zero because of their limited accuracy. One major reason for this discrepancy is the undercatch problem of winter precipitation, as will be discussed later. The contributions of storage changes in both soil moisture and groundwater to the annual water balance are small (for the total of −4 mm/a). However, from month to month these storage changes can be significant because of their apparent seasonal cycles, and even their annual changes are not negligible for some of the 22 years (as shown later in Figure 7).

[14] The mean annual cycles of the 22-year atmospheric water balance components (precipitation, evaporation, water vapor convergence, and change in water vapor storage) are shown in Figure 3b. On average, the annual ET is 582 mm, and the net convergence of water vapor is 353 mm. As expected, the atmospheric storage change $d\overline{W_a}/dt$ is negligible (<4 mm/month throughout the entire 22-year) and integrates to zero annually. Similar to Figure 3a, a seasonal cycle of the ET estimates with a peak of 117 mm/month in July is seen in this figure, while the ET is lowest in winter with a trough almost equal to zero. Evaporation exceeds precipitation during the summer months. The annual amount and the peak magnitude of ET is about 10% smaller than that estimated from the terrestrial water balance computation, which is caused by the overestimation of atmospheric convergence (as will be discussed in section 4). During the summer months, atmospheric moisture diverges away from this region, and the subsurface storage of water acts as a significant source of water to the atmosphere. However, these patterns are reversed during the remaining months of the year: precipitation exceeds ET, significant amounts of atmospheric moisture converge toward the region, and this helps to replenish subsurface water storage before the onset of dry conditions in the following summer.
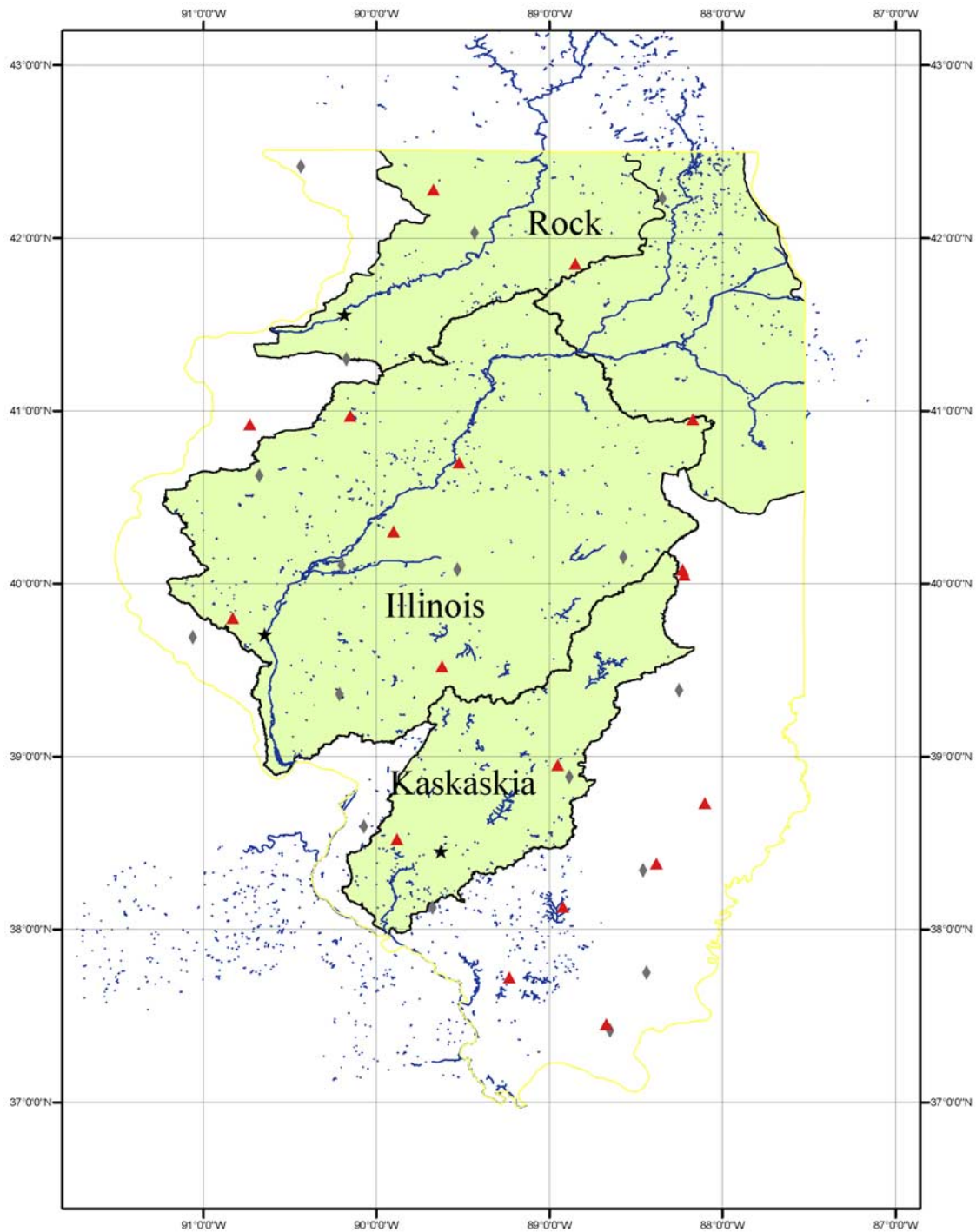
Figure 1. The in situ network of soil moisture (red triangles), water table depth (gray diamonds), and streamflow (black stars) measurements in Illinois and the basin boundary of three largest river basins in Illinois: Illinois River at Valley City (69,237 km^2); Rock River near Joslin (24,721 km^2); and Kaskaskia River near Venedy Station (11,373 km^2). These three stations were selected as downstream as possible, and their total drainage areas cover about two thirds of the area of Illinois.

[15] Annually, however, the atmospheric moisture convergence toward this region is 353 mm/a, while the annual measured streamflow is 301 mm/a. The difference between streamflow and convergence, 52 mm/a, is less than 20% of streamflow. For a consistent water balance of the atmosphere and of the land surface, the long-term average of these two fluxes must be balanced. Since the used USGS streamflow data can be assumed to be accurate with a few percent for its long-term average [*Gutowski et al.*, 1997; *Hirschi et al.*, 2006] and the contribution of the change in atmospheric water vapor is nearly zero, it can be inferred that this imbalance to a large extent stems from the systematic bias in the atmospheric convergence computed from the reanalysis data.
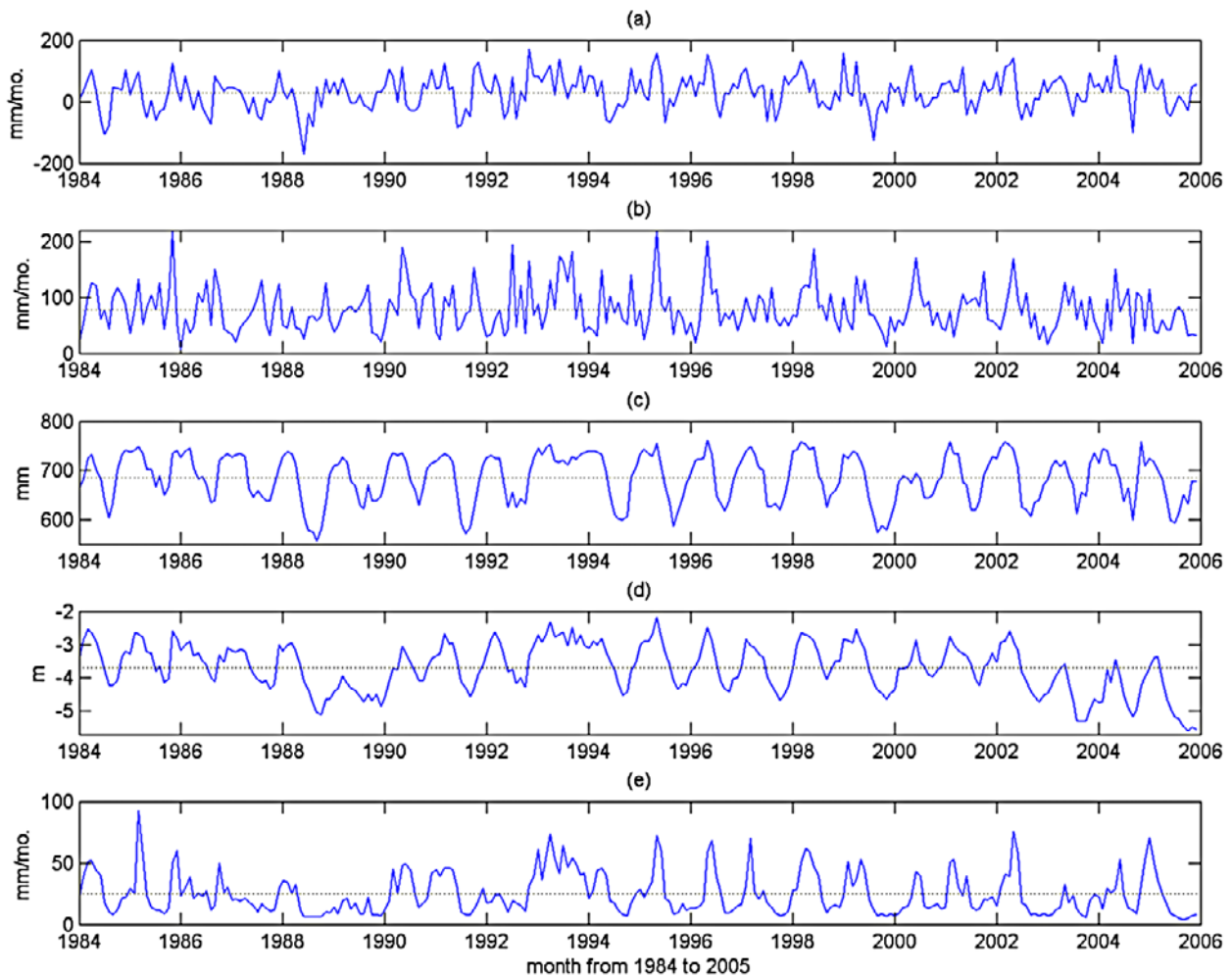
Figure 2. The 22-year (1984–2005) monthly time series of (a) atmospheric moisture convergence, (b) precipitation, (c) soil water depth, (d) water table depth, and (e) streamflow.

[16] Similar to most of the Mississippi River basin [*Ropelewski and Yarosh*, 1998; *Seneviratne et al.*, 2004], in Illinois there is atmospheric moisture convergence in the cold season and moisture divergence in summer. The seasonal variability of the evaporation estimates based on the terrestrial water balance is largely balanced by the seasonal pattern of subsurface storage, whereas the seasonal variability of evaporation estimates from the atmospheric water balance is almost entirely balanced by the seasonal pattern of lateral fluxes of moisture. This contrast reflects a fundamental difference in the hydrology of the terrestrial and atmospheric branches of the regional water cycle in Illinois as well as in most of the Mississippi River basin [*Yeh et al.*, 1998; *Seneviratne et al.*, 2004].

[17] A summary of the 1984–2005 mean annual cycles and annual averages for the observed and estimated TWSC and ET is given in Table 1. The comparison between observations and water balance estimations is presented in the following sections.

4.2. Monthly Comparisons of TWSC and ET

[18] Figure 4 shows that the seasonal patterns of the observed and estimated (by equation (4)) 1984–2005 monthly TWSC are in general agreement with a correlation coef-

ficient of 0.66. Because monthly TWSC is estimated from the residual between the two large terms in the combined water balance equation (atmospheric convergence and streamflow), small errors in these two terms are likely to be amplified into larger discrepancies in the estimated TWSC. Thus, the general agreement shown in Figure 4 indicates that the combined water balance computation can provide reasonable estimates of monthly TWSC variations at the scale of the Illinois ($\sim$2 $\times$ 10^5 km^2).

[19] The comparison of 1984–2005 monthly evaporation estimates from two independent water balance computations is plotted in Figure 5. As seen, the two time series agree reasonably well with a correlation coefficient of 0.69, although some month-to-month differences are evident. The difference between the two evaporation estimates is 56 mm/a (less than 10% of both fluxes themselves). Since the annual changes in both the atmospheric and subsurface water storages are rather small (Figure 3), the difference between the two evaporation estimates is nearly equal to the imbalance between convergence and streamflow. In light of the fact that independent data sets were used in two estimates, the result is encouraging: the atmospheric water balance computation has the potential for the estimation of the mean annual cycle
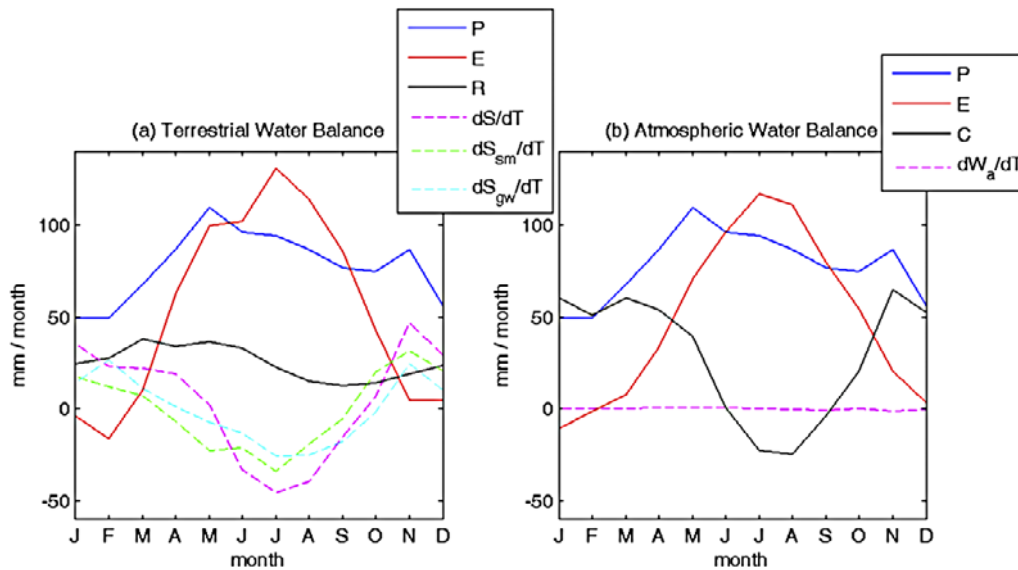
Figure 3. The 22-year (1984–2005) mean annual cycles of (a) terrestrial water balance components (P, precipitation; E, evaporation; R, runoff; dS/dT, terrestrial water storage change (TWSC); dS_{sm}/dT, monthly change in soil moisture storage; dS_{gw}/dT, monthly change in groundwater storage) and (b) atmospheric water balance components (P, precipitation; E, evaporation; C, atmospheric moisture convergence; dW_a/dt, monthly change in atmospheric water vapor storage).

(Figure 3) and the monthly variations (Figure 5) of regional evaporation in Illinois.

[20] The precipitation measurements from rain gauges have a systematic negative bias in that they underestimate the actual precipitation occurring over an area due to the local wind effects around the gauge. This can be especially pronounced when snow occurs because the snowflakes are much more prone to wind deflection than raindrops. According to *Groisman and Legates* [1994], the average gauge undercatch bias is 9% of the annual precipitation for the continental United States, with a seasonal maximum of 15% in winter and a minimum of 5% in summer. The negative bias of precipitation measurement may result in the underestimation of evaporation, especially during the winter. This explains some of the negative evaporation in winter months found from both approaches (Figure 5). However, since precipitation is used in both terrestrial and atmospheric water balance equations, the bias should affect both evaporation estimates to an equal extent and hence is independent from the difference between two evaporation estimates.

[21] The 22-year (1984–2005) mean annual cycles of the two independent estimates of TWSC and ET are plotted in Figure 6. As shown, although the amplitude and peak of the annual cycles compare favorably, noticeable differences occur from spring to midsummer for both TWSC and ET estimates. The estimated TWSC and ET both have slightly smaller peak values in July than the observations. As noted above, evaporation estimates from the two independent approaches have a difference of 52 mm/a. The same amount of difference is reflected in the TWSC estimates from the combined water balance computation due to that the same erroneous convergence data being used.

4.3. Yearly Comparisons of TWSC and ET

[22] The accuracy of the estimated TWSC and ET at the yearly timescale is evaluated in Figure 7 against the

observations. Although the observed TWSC has a 22-year mean close to zero (−4 mm/a), for each individual year TWSC does not necessarily integrate to zero. The annual TWSC is characterized by large interannual variability with a 22-year standard deviation of 102 mm. The minimum TWSC over 22-year is −170 mm/a occurred in both 1999 and 2002, while the maximum is 179 mm/a in 1990, hence the interannual range of annual TWSC is close to 400 mm. In contrast, annual observed evaporation exhibits considerably smaller variability (mean 638 mm/a, standard deviation 65 mm/a). The maximum and minimum annual observed evaporation during the 22-year period, 766 mm/a and 536 mm/a, occurred in 2002 and 1984, respectively; hence the interannual range of evaporation can be estimated as about 200 mm.

[23] Figure 7 shows that both the estimated annual TWSC and ET significantly deviate from the corresponding observations. From monthly to yearly timescale, their correlation coefficient drops from 0.66 to 0.31 for TWSC and from 0.69 to 0.19 for ET. Notice that from 1984 to 1988, the estimated TWSC (ET) was underestimated (overestimated), while it was overestimated (underestimated) for most of the years during 1992–2005. This discrepancy is due to the bias in the atmospheric convergence which changed sign from negative to positive around 1990, as will be shown in section 4.4. Also plotted in the Figure 7a is the TWSC estimated from the corrected terrestrial water storage using the procedures which will be detailed in section 4.4.

4.4. Long-Term Drift in the Estimated Terrestrial Water Storage

[24] The terrestrial water storage (TWS) can be estimated as the temporal integration with respect to (4):

$$\overline{S}(t) = \overline{S_0} + \int_{t_0}^{t} \left(\overline{C} - \overline{R} - \frac{d\overline{W_a}}{dt} \right) dt, \qquad (5)$$

Table 1. The 1984–2005 Mean Annual Cycles and Annual Averages of the Evapotranspiration Estimates From Terrestrial Water Balance and Atmospheric Water Balance Computations, E_{obs} and E_{AWB}, the Observed Terrestrial Water Storage Change (TWSC), $(dS/dT)_{obs}$, and the Estimated TWSC From the Combined Water Balance Equation (4), $(dS/dT)_{WB}$

	$(dS/dt)_{obs}$, mm	$(dS/dt)_{WB}$, mm	E_{obs}, mm	E_{AWB}, mm
By month				
Jan	28.5	35.7	−3.7	−11.0
Feb	37.9	23.3	−16.1	−1.5
Mar	20.0	22.1	9.9	7.8
Apr	−9.6	19.2	62.3	33.5
May	−26.3	2.2	99.6	71.1
Jun	−39.0	−33.0	102.0	96.0
Jul	−59.7	−45.4	131.2	116.9
Aug	−42.7	−39.5	114.4	111.2
Sep	−21.3	−15.2	85.8	79.6
Oct	18.0	6.8	43.2	54.3
Nov	62.9	46.8	4.6	20.7
Dec	27.4	29.0	4.7	3.1
Total, mm/a	−4.0	52.0	637.9	581.8
By year				
1984	140.9	−93.3	532.1	766.3
1985	30.0	−172.6	687.2	889.9
1986	−28.0	−128.5	580.3	680.8
1987	−32.0	−96.1	661.7	725.8
1988	−133.1	−354.1	675.4	896.4
1989	−56.8	63.3	695.8	575.7
1990	179.0	106.5	686.8	759.3
1991	−23.0	22.0	586.3	541.3
1992	66.4	177.6	594.9	483.7
1993	11.9	232.3	636.1	415.6
1994	−66.8	−84.0	665.4	682.6
1995	−75.7	200.4	714.7	438.5
1996	30.6	275.1	641.9	397.3
1997	−44.0	131.8	664.9	489.2
1998	58.6	82.0	661.1	637.7
1999	−169.6	−102.7	735.4	668.4
2000	159.6	116.4	571.4	614.5
2001	87.1	74.9	547.1	559.3
2002	−168.3	138.3	765.9	459.2
2003	78.9	255.4	598.7	422.1
2004	22.5	272.8	558.6	308.3
2005	−155.8	27.3	571.2	388.1
Average, mm/a	−4.0	52.0	637.9	581.8

where $\overline{S_0}$ is the initial value arbitrarily set as 0. The estimated $\overline{S(t)}$ is compared to the observed TWS in Figure 8. As seen, the range of the observed TWS variations is about ±200 mm, while the estimated TWS shows a dramatic downward trend from 1984 to 1988 and followed by a rebound from 1992 until 2005. The trend of accumulated errors in TWS changed sign from negative to positive around 1990, which apparently reflected certain analysis system changes rather than the natural variability [*Seneviratne et al.*, 2004]. The alternation from a downward to an upward trend in the TWS variations was also observed by *Seneviratne et al.* [2004, Figure 9] in their 1987–1996 analysis in Illinois using ERA-40 data, but not for the whole Mississippi River basin.

[25] The magnitude of the imbalances (i.e., drift) prevents the integration of estimated monthly TWSC over a multi-year period of time. Several studies have attempted to correct the imbalance by adjusting the atmospheric convergence to force the long-term balance (i.e., $d\overline{S}/dt = 0$). *Rasmusson* [1968] reported a positive bias in storage of

210 mm over the 5-year period in the continental United States, and corrected it by adding a uniform 3.5 mm/month of water to the convergence. This simple correction procedure was subsequently used by *Roads et al.* [1994] and *Masuda et al.* [2001]. *Oki et al.* [1995] applied a constant reduction factor of 0.18 to the atmospheric convergence to balance streamflow. Using a different approach, *Ropelewski and Yarosh* [1998] defined the mean annual cycle of basin storage as the departure from its 12-month running mean in order to remove the drift in the estimated TWS. *Seneviratne et al.* [2004] corrected the annual drift separately for each year by assuming an unchanged annual mean of TWS over the study period; similarly, *Hirschi et al.* [2006] subtracted the 3-year running mean from the estimated TWSC to remove the drift.

[26] Following *Ropelewski and Yarosh* [1998], we correct the estimated TWS by subtracting its 12-month running mean (centered in the month of interest). The corrected TWS is plotted in Figure 8, which clearly shows although the drift is effectively removed, this procedure is unable to reproduce the observed TWS variations. Remarkable discrepancies can still be noted in 1988, 1993, 1999 and 2003–2004 which suggest the nonuniform distribution of the systematic bias over the time in the reanalysis data. We also use the corrected TWS to compute the annual TWSC; the result is plotted in Figure 7a. As seen, the corrected TWSC tends to damp the interannual variability in contrast to the overly large range of the uncorrected TWSC. Neither of them was able to capture the interannual variations of TWSC.

5. Discussion

[27] The imbalance between the mean atmospheric convergence and streamflow, 52 mm/a (~0.14 mm/d) as identified in this study, is only 17% of the average streamflow. Despite its small size, this bias in Illinois is comparatively smaller than that reported by other studies conducted in the Mississippi River basin or in the central United States: 0.2 mm/d by *Roads et al.* [1994], 0.4 mm/d by *Ropelewski and Yarosh* [1998] and 0.3 mm/d by *Berbery and Rasmusson* [1999]. This appears to be contradictory to the traditional view that the atmospheric water balance is more suitable to be applied to larger domains. *Rasmusson* [1968] has indicated that the atmospheric water balance computation is applicable for regions with area larger than 2×10^6 Km^2. However, the study of *Yeh et al.* [1998] concluded that the threshold size for the atmospheric water balance computations using reanalysis data is approximately the order of 10^5 km^2, which was later confirmed also by *Berbery and Rasmusson* [1999] and *Seneviratne et al.* [2004]. *Seneviratne et al.* [2004] found that for the whole Mississippi basin, the total imbalance is relatively small due to the compensation of positive and negative biases for various subbasins. Such compensation effect is exactly the reason why the atmospheric water balance for larger domain tends to be more accurate, and why a longer time period of analysis is to be favored. It has been identified that the magnitude of the imbalance decreases as the size of basins increases and possibly linked with regional climate characteristics [*Oki et al.*, 1995, Figure 13]. *Hirschi et al.* [2006] stated that the magnitude of the
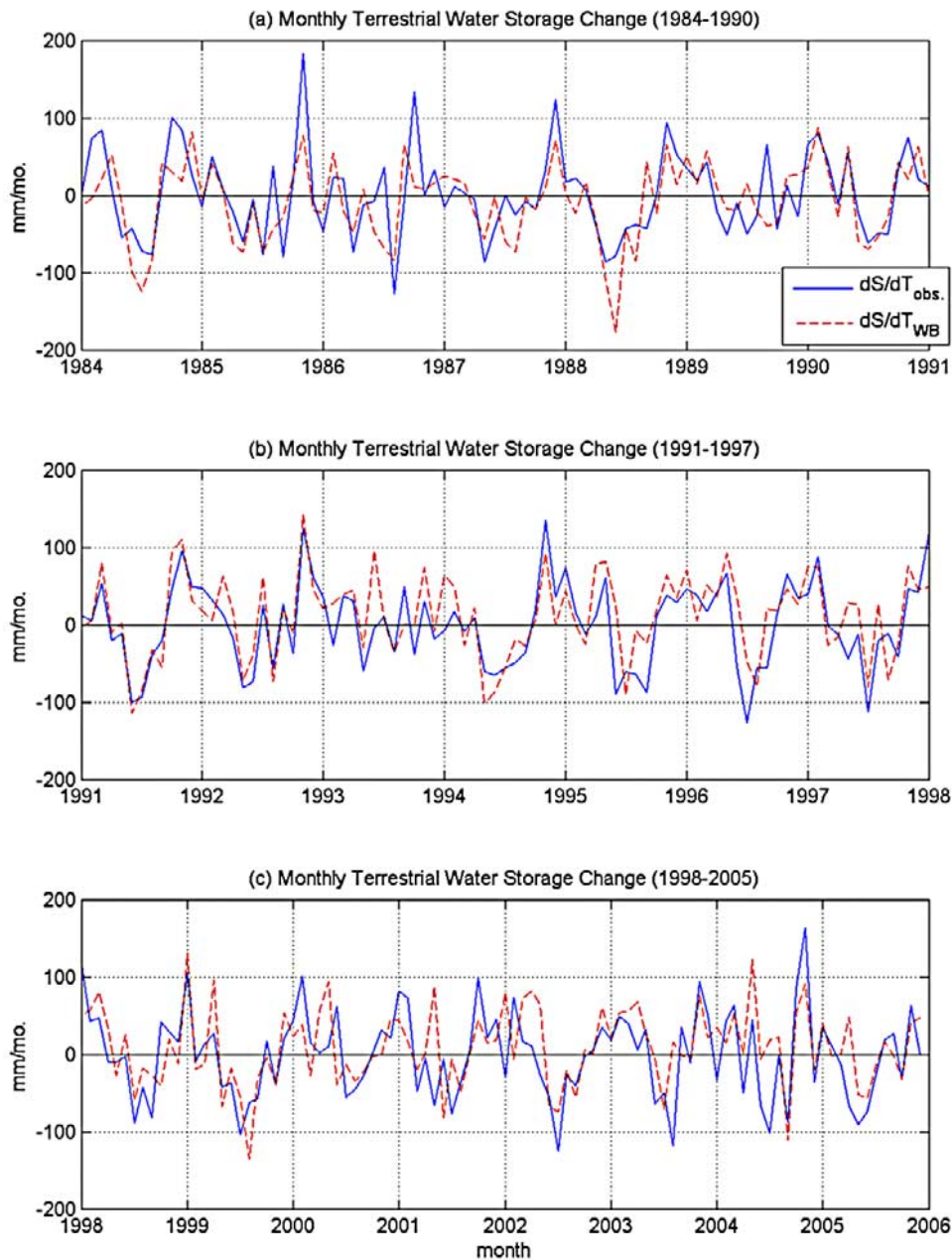
Figure 4. Comparison of the 1984–2005 monthly time series of observed against estimated TWSC. The estimated TWSC is from the combined water balance equation (4).

imbalance depends on the basin size, the geographic region and the underlying topography.

[28] According to the present analyses, however, the reason for the small imbalance is primarily that the accumulated systematic bias changed sign from negative to positive around 1990 (Figure 8) and hence part of the overall bias was canceled out on the 22-year average. To test the sensitivity of the imbalance to the length of time period analyzed, the imbalances corresponding to an increasing number of years averaged (with all cases considered starting from 1984 but ending in different years) as plotted in Figure 9. A 52 mm/a imbalance between convergence and streamflow would be identified if 22-year (1984–2005) data were used for analysis. The largest error (~170 mm/a) would correspond to the

period of 1984–1988, while no imbalance would be found if the period of 1984–1996 was analyzed.

[29] Therefore, the magnitude of the imbalance between the mean atmospheric convergence and streamflow depends on which specific time period is chosen for analysis rather than the length of the analysis time period. This at least partially explains the wide range of imbalances reported in the previous studies cited above. Although it is commonly accepted that the accumulated errors should cancel out if a longer time period is considered, it does not necessarily imply a longer time period would certainly reduce the bias by averaging. The long-term balance also does not imply the overall accuracy of the estimated monthly or annual TWSC and ET. Instead, it merely indicates the unbiased
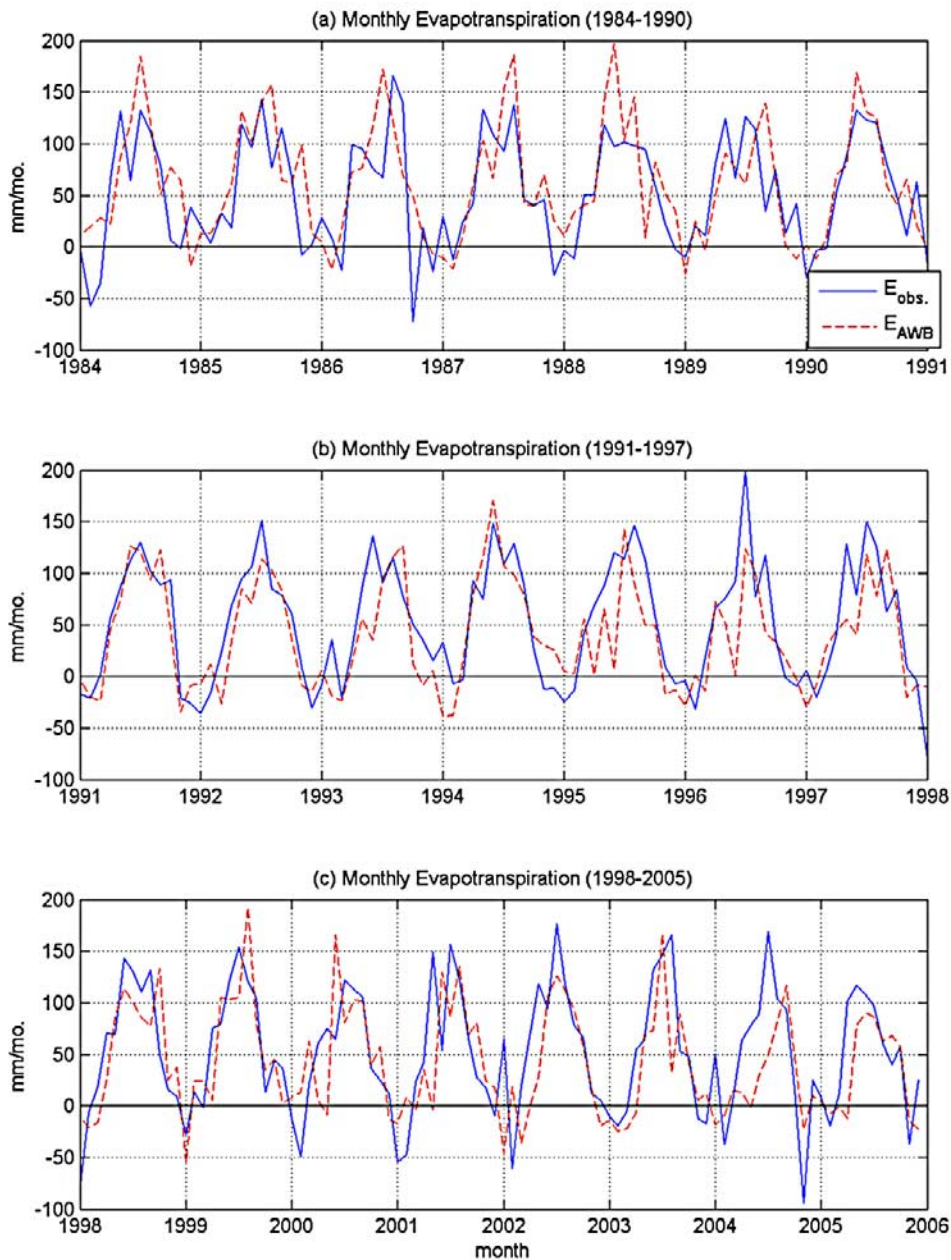
Figure 5. Comparison of the 1984–2005 monthly time series of evapotranspiration estimates from the terrestrial water balance and the atmospheric water balance, respectively.

estimate that preserves the long-term mean, and more likely leads to less biased estimation of the average seasonal cycle.

[30] All the correction methods used in the previous studies lack any physical basis other than the removal of the low-frequency trend in order to force the long-term TWSC zero. The constant correction method can only balance the long-term average, but not balance the monthly, seasonal, and annual variations. On the other hand, the bias removal by subtracting the running means can only suppress the seasonal cycle without any corrections to the biased anomalies. To our knowledge, there is yet no reported observational evidence to support these correction methods.

[31] Since the observed data on TWSC, streamflow, and atmospheric water vapor change are available, we introduce

them into (4) to deduce the bias-corrected convergence. This result is plotted in Figure 10 in comparison with the raw atmospheric convergence at different timescales. Although the temporal evolution of the raw convergence appears to track the bias-corrected convergence fairly well (Figure 10a), it frequently underestimates the magnitude of the convergence maxima and minima. Significant month-to-month discrepancies can often be noted over the 22 years with the largest errors of about 100 mm/month. The main difference between the mean annual cycles of the raw and the corrected convergence (Figure 10b) occurs in spring to summer transition months (April–August), which corresponds to the months with a large scatter in the precipitation simulation in the Mississippi River basin among several
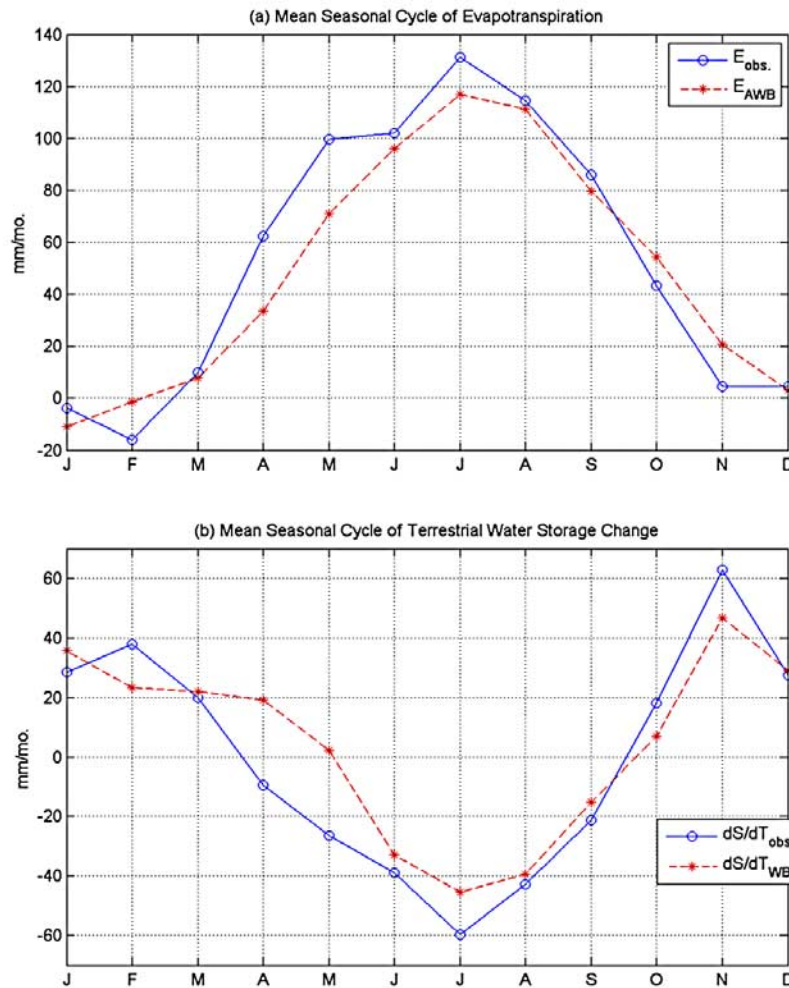
Figure 6. The 1984–2005 mean annual cycle of (a) evaporation estimates from terrestrial water balance and atmospheric water balance computations and (b) observed and estimated TWSC from the combined water balance equation (4).

atmospheric models underlying the reanalysis system [*Roads et al.*, 2003]. It is likely that the unrealistic precipitation leads to biased atmospheric convergence in the reanalysis system. For the yearly comparison (Figure 10c), the raw convergence has overly large interannual variability, which are more reflective of the analysis system changes rather than the natural variability as discussed earlier. The corrections result in the reduction of the dry bias prior to 1989 and the wet bias after 1991, with the largest reductions in the anomalous years of 1988 and 1993. In extremely dry (wet) year of 1988 (1993), the reanalysis data overly exaggerated the amount of anomalously high water vapor divergence (convergence).

[32] We have calculated the 22-year mean annual cycle and monthly standard deviation of the difference between the raw and the corrected atmospheric convergence as an indicator of the range and distribution of the errors in the raw convergence data. Assuming the observed streamflow in Illinois is nearly accurate, the errors also represent the errors in the estimated TWSC and ET. The mean monthly error in the atmospheric convergence is 4.7 mm/mo; however, the standard deviation of the errors for each month is

rather large, in average 44 mm/month. The largest mean water budget residual calculated from the 1988–2000 NCEP/NCAR reanalysis data in Mississippi river basin is about 30 mm/mo [*Roads et al.*, 2003, Figure 15f], which is consistent and within the range found here. This spread of the error is not negligible since it amounts to more than 50% of mean precipitation (78 mm/month) in Illinois. In some months of certain years the error in the atmospheric convergence can be as large as 100 mm/month.

6. Concluding Remarks

[33] In this study we examine the terrestrial and atmospheric water balance over the Illinois. Monthly terrestrial water storage change (TWSC) and evapotranspiration (ET) were estimated for a 22-year (1984–2005) period using two independent approaches: the terrestrial and atmospheric water balance computations. Both estimates were then compared with the corresponding observations based on a 22-year comprehensive hydrological data set in Illinois. The 22-year mean annual cycles of the estimated TWSC and ET generally agree with observations. Monthly estimates of TWSC and ET match favorably with observations with
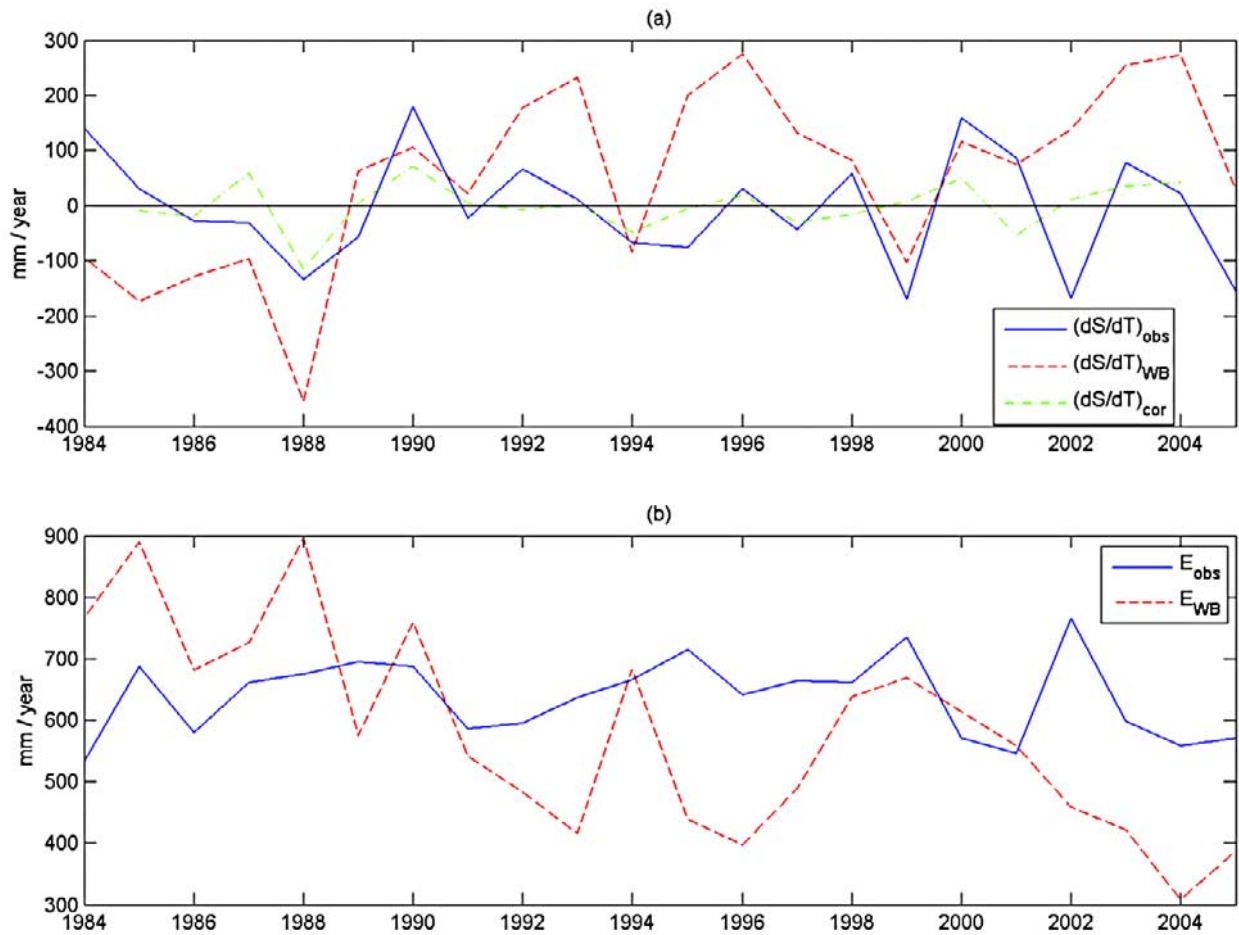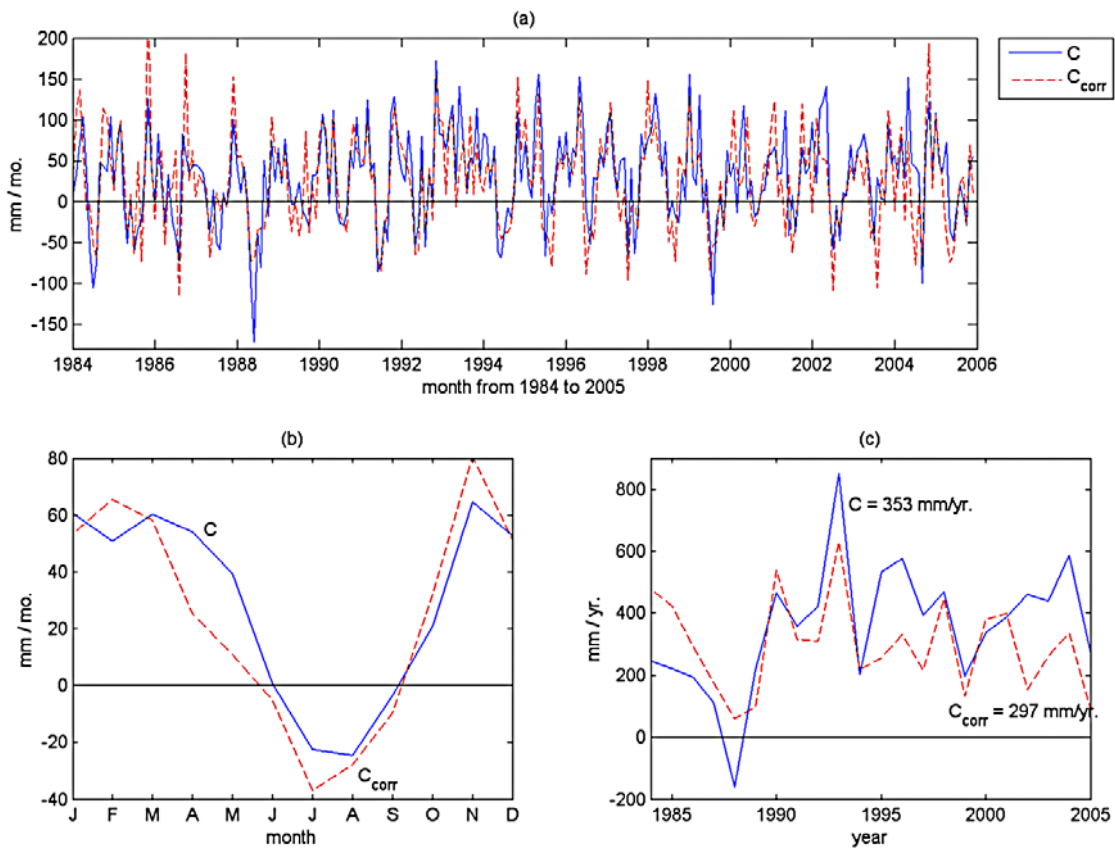
Figure 7. Comparison between the 1984–2005 (a) observed annual TWSC and the corresponding estimate from the combined water balance equation (4) and (b) observed and estimated evaporation from the atmospheric water balance computation.
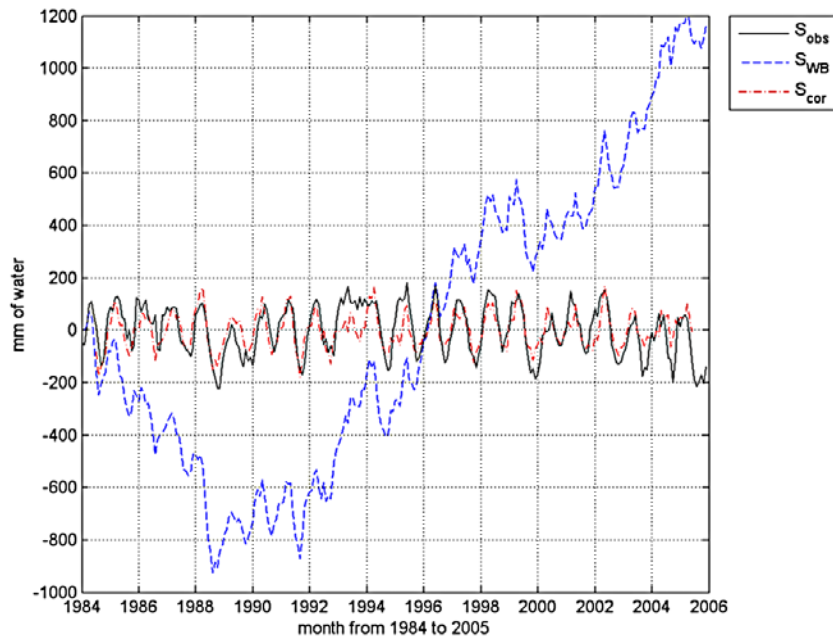
Figure 8. Comparison between the 1984–2005 in situ measured (S_{obs}) and estimated (S_{WB})terrestrial water storage anomaly from equation (5). Also plotted is the corrected storage anomaly (S_{cor}), derived by subtracting the 12-month running mean from S_{WB}.
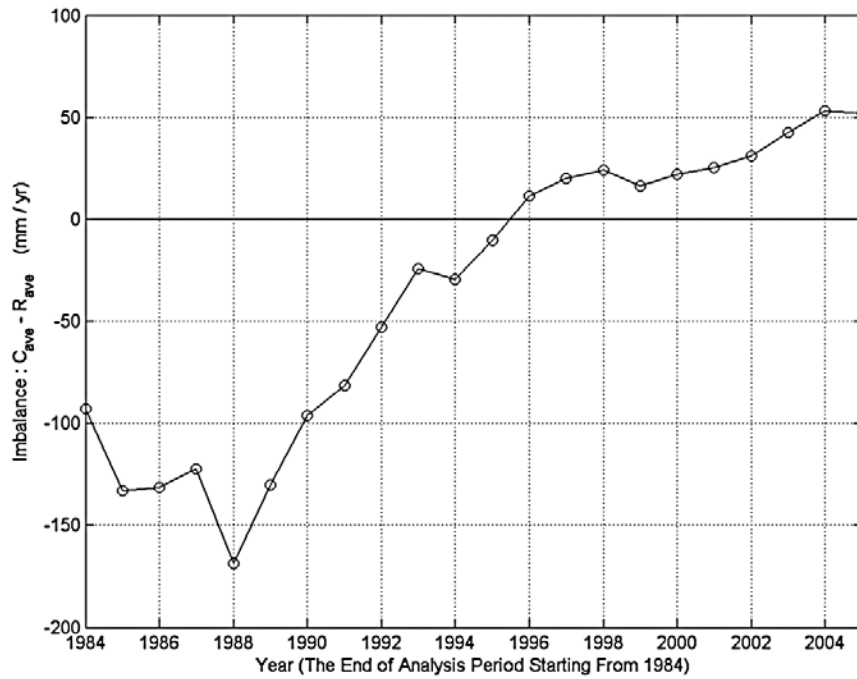
Figure 9. The imbalances between the mean water vapor convergence and measured streamflow corresponding to the different periods of analysis, all starting from 1984 but ending in different years. See the text for explanation.

Figure 10. The comparison between the 22-year (1984–2005) raw atmospheric convergence (C) and the bias-corrected convergence (C_{cor}) at the (a) monthly timescale, (b) mean annual cycles, and (c) yearly timescale.

correlation coefficients of 0.66 and 0.69 respectively. However, annual average TWSC and ET estimates significantly deviate from the observations; the correlation coefficients drop to 0.31 and 0.19 respectively. A 52 mm/a imbalance was found between the mean water vapor convergence and streamflow, which also results in a similar amount of errors in the estimated TWSC and ET based on reanalysis convergence. The 22-year mean observed TWSC is close to zero (i.e., 4 mm/a), while the estimated TWSC is 52.0 mm/a. The mean ET estimated from the atmospheric water balance is 581.8 mm/a compared to 637.8 mm/a from the terrestrial water balance. This imbalance is due in large part to the systematic bias in the reanalysis data. In order to correct the bias in the atmospheric convergence, the observed TWSC and streamflow data are used to derive to the bias-corrected convergence, and closer correspondence is found between the corrected convergence, streamflow, and TWSC.

[34] Despite the small size of Illinois, the imbalance between the mean atmospheric convergence and mean streamflow is comparatively small (52 mm/a., ~17% of the average streamflow in Illinois) relative to previous studies in the Mississippi River basin. This is because the accumulated systematic bias changed the sign from negative to positive around 1990 (Figure 9). The relatively small imbalance found is a result of larger errors canceling each other over the 22 years, and it partially explains the general agreement in the average seasonal cycles between the observed and estimated TWSC and ET (Figure 6). However, the interannual variability of the estimated TWSC and ET cannot be preserved (Figure 7) due to the reanalysis data error accumulation, rather than cancellation, over the time. Although the average error in the estimated convergence (and hence in the estimated TWSC and ET) is small (4.7 mm/month), its standard deviation is as large as 44 mm/month, which is more than 50% of the mean precipitation in Illinois. Moreover, the magnitude of the imbalance between the mean atmospheric convergence and mean streamflow depends on which particular time period is under analysis rather than the length of the time period analyzed. A longer time period of analysis does not necessarily ensure the balance between streamflow and convergence as commonly assumed in regional water balance analyses. This is due to the accumulation, rather than cancellation, of the systematic errors in the reanalysis data.

[35] In view of the close agreement between the two independent estimates, we concluded that the combined terrestrial and atmospheric water balance computation may have the potential to estimate the climatology and monthly variations of TWSC and ET at the regional scale of Illinois ($\sim 2 \times 10^5$ km^2), but not able to diagnose their interannual variability due to the accumulation, rather than cancellation, of systematic errors over the time. The reanalysis data have to be used, with some cautions, to gain insight into the actual variability of atmospheric moisture transport for the global water cycle studies. Further work is warranted in identifying the causes of the biases in reanalysis data and developing a coherent correction method to remove them.

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