Terrestrial Water Balance over North America in Atmospheric Reanalyses and Land-Surface Simulations: Variance in Runoff

Alfredo Ruiz-Barradas
Department of Atmospheric and Oceanic Science

University of Maryland
College Park, MD 20742-2425,USA

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Corresponding author: Alfredo Ruiz-Barradas
3435 Computer & Space Sciences Bldg.
University of Maryland, College Park, MD 20742-2425
Email: alfredo@atmos.umd.edu

Abstract

The terrestrial water balance over North America, and the Great Plains in particular, are analyzed in this work. Emphasis is made in contrasting model outputs from the hydrological model VIC and the multi-model mean from GSWP-2 against global reanalyses NCEP/NCAR, ERA-40, the newest Japanese reanalysis JRA-25, and regional reanalysis NARR. The University of New Hampshire/Global Runoff Data Centre (UNH/GRDC) observationally constrained runoff is used as reference too, and as a way to diagnose evaporation from NARR.

Models and reanalyses have similar features in the spatial distribution and annual cycle of precipitation minus evaporation (P-E) along the Pacific northwest, however, large differences exist over central and southeastern US. All products agree in that there is no long-term change in water storage but there are substantial differences in runoff over the southeastern US compared to the UNH/GRDC data set: runoff is negligible in ERA-40; it is small in NCEP/NCAR and even smaller in NARR, but it is comparable in JRA-25, VIC, and GSWP-2, although the structure in JRA-25 is too broad. The small annual runoff in NARR implies that P - E is underestimated and evaporation is larger than needed for a more closed water balance. Winter and summer means confirm that runoff in NARR is much smaller than runoff given by the observationally constrained products like UNH/GRDH and VIC.

Over the Great Plains NARR has seasonal imbalances due to evaporation and runoff errors. Yet in spite of these inconsistencies, the long-term mean balance is practically closed. The global reanalysis JRA-25 has large errors related to little seasonal variability in P-E and runoff, but large seasonal variability in the change in water storage.

1. Introduction

Comprehension of seasonal-to-interannual variability of our current hydroclimate is paramount for our water-dependent societies. Discerning regional changes to the water cycle under climate change scenarios is complicated by both the lack of consistent and homogeneous hydroclimate data (e.g., evaporation, soil moisture, runoff) and by our own inability to correctly simulate the main mechanisms involved in precipitation variability; obviously, the lack of observations also complicates the assessment of the models. Because having coherent data sets is of primary importance to study the water cycle, one has to rely on model-derived data sets such as those produced by reanalyses, hydrological models, and land-atmosphere coupled models.

The lack of routinely observed data of terrestrial water cycle fields at continental scales usually restricts the analysis and assessment of reanalyses and model simulations to river basins such as the Mississippi (e.g., Maurer et al. 2001; Betts et al. 2003) or sub-grid rich observed data regions like the Illinois State Water Survey field sites (e.g., Schaake et al. 2004; Mitchell et al. 2004; Fan et al. 2006; Onogi et al. 2007). In view of the importance of the terrestrial water cycle fields for climate studies, the Global Energy and Water Cycle (GEWEX) program has led efforts to produce large-scale data sets of soil moisture, runoff, surface fluxes, etc. via offline uncoupled land-surface-atmosphere models.

Understanding the annual and seasonal water cycle as well as its interannual variability at regional-to-continental scales requires the ability to correctly simulate local land-atmosphere interactions as well as interactions with remote water sources. One approach toward the analysis of the terrestrial water cycle is to use offline macroscale hydrological models, forced at the surface with observed variables such as precipitation and temperature. Clearly, these models only provide the terrestrial component of the water cycle with no interaction with the atmosphere. Alternatively inline simulations by coupled land-atmosphere models, forced by observed sea surface temperatures, can be used; in this way, atmosphere and terrestrial water balances are closed by design. Although local land-surface-atmosphere interactions as well as interactions with remote water sources are considered in these models, their relative contributions are model dependent and there are not observational constraints in the simulations. An approach similar to land-atmosphere coupled modeling is given by the reanalysis of historical data; in this case, observational constraints are imposed on numerical weather forecast models via the assimilation of mostly atmospheric observations.

It is clear that there are some tradeoffs when working with reanalyses and model simulations. For instance, water budgets cannot be closed in reanalyses because of the so called “analysis increments” that change the total water of the atmospheric column. On the other hand, although climate models close the water budget, they tend to do it in various ways due to errors in their physical processes. Along these lines, the authors’ previous works on seasonal-to-interannual hydroclimate variability over North America highlighted the following issues relevant to the atmospheric water balance over the Great Plains (Ruiz-Barradas and Nigam 2005, 2006; Nigam and Ruiz-Barradas 2006): 1) The North American Regional Reanalysis (NARR) is the best reanalysis product in depicting seasonal-to-interannual variability; 2) climatological evaporation is larger than needed for a tighter water budget over the Great Plains region in NARR; 3) reanalyses indicate that interannual variability of summer precipitation is in large part due to convergent moisture fluxes from remote water sources rather than local land-surface-atmosphere interactions with local water sources; 4) some climate models, in contrast to reanalyses, prioritize local water sources (i.e., land-surface-atmosphere interactions) versus remote ones (i.e., moisture flux convergence from adjoining oceans) when simulating interannual variability of summer precipitation.

The present work analyzes the terrestrial component of the water cycle from the latest reanalyses and offline model simulations in order to complete the authors’ assessment of the water cycle over North America and the Great Plains. A central issue to further pursue in the current study is the quality of the (dubiously large) evaporation in NARR.

This analysis makes use of the following products: 1) the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global reanalysis; the European Center for Middle Range Weather Forecasts 40-year global reanalysis (ERA-40); the Japan Meteorological Agency 25-year global reanalysis (JRA-25), and NCEP's North American regional reanalysis (NARR); 2) the observed/observationally constrained climatological river discharge/runoff data set from the University of New Hampshire and the Global Runoff Data Center (UNH/GRDC); 3) the off-line simulations from the Variable Infiltration Capacity (VIC) hydrological model, and from the Second Global Soil Wetness Project (GSWP-2). Given our previous findings on the atmospheric water balance (including the wet and dry bias in NCEP/NCAR and ERA-40 reanalyses over the US), comparisons of the models will be centered around, but not limited to, the regional reanalysis NARR. Furthermore, the observationally constrained runoff from the UNH/GRDC data set provides the unique opportunity to assess this field in the different products, and so, the dubious evaporation (i.e., evaporation plus transpiration) from NARR.

The paper is organized as follows. Data sets are described in section 2. The annual cycle and annual mean of the components of the terrestrial water balance over North America are analyzed in section 3, while the terrestrial water cycle over the Great Plains is studied in section 4. Winter and summer seasonal means of surface fields are compared in section 5. Finally, concluding remarks are presented in section 6.

2. Data Sets and Methods

As mentioned earlier, the present analysis of the terrestrial water budget is carried out using several data sets. Some important features relevant to this study are described next.

a. NCEP/NCAR

The National Centers for Environmental Prediction/National Center for Atmospheric Research produced a 50-year-long global reanalysis (NCEP/NCAR; Kalnay et al. 1996) designed mainly for atmospheric studies. It spans the period from 1948 up to the present, and it is valuable for its global coverage and long duration. The representation of the land-surface is simplified, with many parameters set as global constants. Soil moisture is nudged to an assumed climatology of Mintz and Serafini (1981; Mintz and Walker 1993) with a 60-day time scale. The surface model is driven by simulated precipitation from the reanalysis atmospheric model. The hydrological model (e.g., Pan 1990) is mainly employed as a lower boundary condition in the model, and reflects an imposed hydrological cycle. Biases in precipitation, and their impact on soil moisture nudging (e.g., Maurer et al. 2001), make this reanalysis not a very good tool for hydroclimate studies. However, in spite of its limitations, NCEP/NCAR reanalysis is still an important benchmark for other global reanalyses. The data set is on a Gaussian grid of 192x94 points, with a two-layer soil column: a top layer of 0.10 m thickness, and a lower layer 1.90 m in depth.

b. ERA-40

The European Centre for Medium-Range Weather Forecasts (ECMWF) has produced a 45-year-long global reanalysis (ERA-40; Uppala et al. 2005) from September 1957 to August 2002 in collaboration with many institutions. This product benefitted from many of the changes introduced into operational forecasting since the mid-1990s, when the systems used for the 15-year ECMWF reanalysis (ERA-15) and the NCEP/NCAR reanalysis were implemented. The analysis system includes the land-surface scheme described by Van den Hurk et al. (2000), and a 3-D variational assimilation system. The surface scheme is characterized by a tiled treatment of subgrid fractions of evaporation surfaces, the use of a global vegetation database plus an associated set of model parameters, changes to the parameterization of snow processes, the coupling of the skin layer to the soil, and the vertical soil moisture transport. Soil moisture is nudged by a linear combination of the screen-level relative humidity and temperature increments every six hours; soil moisture drift is prevented by nudging to observed 2-m relative humidity and temperature (Douville et al. 2000, Mahfouf et al. 2000). However, in spite of the improvements made in the reanalysis, biases are present in the water budgets (e.g., Betts et al. 2003; Hageman et al. 2005).The data used in this study is on a 2.5°x2.5° longitude-latitude grid, while the soil layer of 2.89 m depth is discretized in four layers of thickness 0.07m, 0.21 m, 0.72 m, and 1.89 m from top to bottom.

c. JRA-25

The Japan Meteorological Agency (JMA) has produced a 25-year-long global reanalysis (JRA-25; Onogi et al. 2007) covering the period 1979-2004. This is the JMA's latest numerical assimilation system (via 4-Dimensional Data Assimilation cycles) which consists of an atmospheric model forecast, 3-D variational data assimilation, and land analysis; it uses specially collected observational data (e.g., snow, and wind profiles around tropical cyclones). JRA-25 is a consistent high quality 6-hourly reanalysis data set designed for climate research, operational monitoring and forecast. The global model has a spectral T106 resolution and 40 vertical layers in the atmosphere up to 0.4hPa. Land-surface processes are computed every six hours by a modified Simple Biosphere model (SiB; Tokuhiro 2002; Sellers 1986). Although observed snow depths are taken into the land-surface analysis once a day using a 2-D optimum interpolation method, no land observed data are assimilated. The Japanese reanalysis is the newest of the reanalyses and its usefulness in portraying regional hydroclimate is just starting to be evaluated. A preliminary assessment of soil moisture at the mid-latitudes in general, and over Illinois in particular by Onogi et al. (2007), suggests it is reasonably portrayed. Surface data from JRA-25 are given at T106 resolution, and the soil column has three vertical layers of variable depths (shallow, root and deep).

d. NARR

The regional reanalysis is a long-term, consistent, data assimilation-based, climate data suite for North America (Mesinger et al. 2006). It is produced at high spatial and temporal resolutions (32-km, 45-layer, 3-hourly) and spans a period of 25 years from October 1978 to December 2003. NARR is based on the April 2003 frozen version of NCEP's mesoscale Eta forecast model and its data assimilation system (EDAS). NARR benefits from two advancements with respect to global reanalyses: the assimilation of observed precipitation, and decade-long improvements over Noah, NARR's land-surface model (Mitchell et al. 2004; Fan et al. 2006). Moreover soil moisture is not nudged as it is in NCEP/NCAR global reanalysis. However, NARR assimilates precipitation from several sources: oceanic data comes from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), while land precipitation comes from different sources for the Continental United States (CONUS), Mexico, and Canada. The assimilation is in fact successful with downstream effects, including a two-way interaction between precipitation and the improved land-surface model. The analysis of surface data from NARR is done on a 1˚x1˚ longitude-latitude grid, with a 2 m deep column made of four layers of thicknesses: 0.1 m, 0.3 m, .6 m and 1.0 m, from top to bottom.

e. VIC

The variable infiltration model (VIC; Liang et al. 1996) is a macroscale hydrological (offline) model that balances both surface energy and water over a grid at every time step. In this case, the VIC model has been applied over the conterminous US at 1/8°x1/8° resolution with three vertical layers of variable depths for the 01/1950-01/2000 period (Maurer et al 2002). The model is forced with observed surface air temperature and precipitation from NOAA Cooperative Observer (Co-op) stations. Derived fields driving the model include air pressure, vapor pressure and incoming longwave and shortwave radiation, as well as surface wind and temperature from NCEP/NCAR reanalysis; additional sources of precipitation and temperature data outside the US, over Mexico and Canada, come from institutions in those countries and the Global Precipitation Climatology Project (GPCP). The model has several special features such as the representation of the soil moisture dependence of the partitioning of precipitation into runoff and infiltration, the mechanisms of a slow baseflow runoff response, and explicit treatment of vegetation on the surface energy balance. The implication of being specifically applied over the US is that VIC has been tuned up to optimize its hydrological performance over the domain, for instance, runoff is routed and validated against observed streamflow. VIC data is analyzed on a 1˚x1˚ horizontal grid in this study[1].

[1] The use of the 1/8° resolution data set does not modify the results presented here.

f. GSWP-2

The Second Global Soil Wetness Project (GSWP-2) is an initiative to compare and evaluate 10-year offline simulations by a broad range of land-surface models under controlled conditions (Dirmeyer et al. 2006a). A major product of GSWP-2 is a global gridded multi-model analysis of land-surface state variables and fluxes from January 1986 to December 1995. It is worth mentioning that VIC and NARR's Noah are not part of the multi-model mean. Simulations from 13 land-surface models from five nations have gone into producing the analysis; however, five of those models do not close the water budget within the soil column, especially over central US (Dirmeyer et al. 2006a). The land-surface models are not optimized over a specific region such as the case of VIC over the US. Forcing data driving the models are derived from a combination of gridded atmospheric reanalyses and observations (Dirmeyer at al. 2006b). While NCEP/Department of Energy reanalysis provides several forcing fields like precipitation, temperature, winds and surface pressure and humidity, other sources like GPCP's precipitation are also used. The resulting multi-model mean fields are obtained as the arithmetic mean of the 13 land-surface models. This multi-model mean is on a 1˚X1˚ longitude-latitude grid, with a 1.5 m deep column made of six layers of thicknesses: 0.1 m, 0.2 m, 0.2 m, 0.2 m, 0.3 m, 0.5 m, from top to bottom.

g. UNH/GRDC

In a joint effort between the University of New Hampshire and the Global Runoff Data Centre (UNH/GRDC), Fekete et. al. (2002) produced a global, high resolution, runoff climatology by accessing GRDC river discharge data, selecting significant global gauging stations, and using the UNH water balance model. In this product, gauge stations with records of 12 years or longer are considered. For regions with no observed river discharge data, the observed inter-station runoff is distributed uniformly over the inter-station area. Thus, modeled runoff is adjusted to match the observed river discharge values but preserving the spatial and temporal distribution of modeled runoff. The data set has observed river discharge, and modeled and combined observed/simulated (i.e., composite) runoff products at 0.5°x0.5° resolutions. The composite runoff yields a reasonable estimate of spatially distributed terrestrial runoff at continental scales and preserves the accuracy of the discharge measurements (Fekete et al. 2002).

h. Methods

In this analysis, soil moisture is scaled to a 2m depth. For the majority of the data sets, soil moisture is given in volumetric units (vsm [m^3/m^3]). For ERA-40, the 2 meters soil moisture in millimeters (sm) is calculated as: $sm = 1000 \times \left[\sum_{i=1}^{L} vsm_i \times d_i + vsm_{L+1} \times (2 - D) \right]$, where d_i represents the thickness of layer i in meters, and L is the number of layers such as $\sum_{i=1}^{L} d_i = D < 2$ meters. In the case of NCEP and NARR, the 2m soil moisture in millimeters is simply: $sm = 1000 \times \sum_{i=1}^{N} vsm_i \times d_i$, where d_i represents the thickness of layer i in meters, and N is the total number of layers such as $\sum_{i=1}^{N} d_i = 2$ meters. For GSWP-2, soil moisture is given already in millimeters; however, it has a total depth of 1.5 meters. Soil layers in VIC and JRA-25 have a variable depth, so the above equations are applied at each grid point depending on the total layer depth, which not always reaches 2m.

Water storage is defined differently in the various products. However, all of them have two common terms: soil moisture and snow water equivalent. An additional term is the canopy intercepted water, which is present in both NARR and GSWP-2. A final term, the surface liquid water storage is only present in GSWP-2.

Now, the tendency of the different components of the water storage is only provided by VIC and GSWP-2 products with some differences. While the monthly tendencies in VIC are sum up from each time step tendencies, the monthly tendencies in GSWP-2 are calculated as the change from the beginning of each *archiving* time step (i.e. month) to the end. On the other hand, the temporal changes in the water storage terms in the reanalyses products are calculated in the present study as centered differences of the monthly storage terms.

Surface fields from NARR will be used as reference because from our previous analyses this data set has the smallest imbalance in the atmospheric component of the hydrological cycle compared to the other global reanalyses (Nigam and Ruiz-Barradas, 2006).

Climatology is calculated for the common base period 1979-1999, except for GSWP-2, which is 1986-1995. Boreal winter and summer means are defined as averages over December, January, February, and June, July, August, respectively.

3. Annual Cycle over North America

The terrestrial branch of the hydrological cycle can be written as S + R = P - E, where S=∂*ws*/∂t is the rate of water storage (i.e., mostly the change in soil moisture and snow water equivalent; the additional terms such as the change in canopy intercept and liquid surface water are at least one order of magnitude smaller), P is precipitation, E is evaporation (actually evaporation plus transpiration), and R is (surface plus sub-surface) runoff. Thus, since over long periods S tends to be small, the net gain/loss of water at the land-surface, (or soil wetness as given by the difference P - E), must be balanced by runoff. The observationally constrained runoff from the UNH/GRDC data set offers the opportunity, through the analysis of the long-term means, of assessing runoff and diagnosing evaporation (via the difference P - E) in NARR[2]. In the following discussion, the annually varying component and the annual mean of those variables are compared for reanalyses and offline hydrological models.

The annual cycle of the components of the terrestrial water budget is analyzed with the help of the first harmonic of the monthly climatological fields and displayed using vectors or dials; the length of the vector denotes the amplitude of the annual cycle, while its direction indicates the month of maximum amplitude. In this way, the larger/smaller the vector, the most/least marked the seasonal changes through the year.

a. Regional Reanalysis

The first harmonic and annual mean of NARR surface fields for the 1979-1999 period are displayed in Fig. 1. Annual mean precipitation, P, shows distinctive regions of high rainfall rates

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[2]It is already known that NARR precipitation, particularly over the US and the Great Plains region, portrays observed precipitation in an excellent manner. Thus, in the long-term average any inconsistency in runoff will be reflected in the difference P - E that in turn can be assigned directly to E alone.

over the west coast and over the eastern half of the US. Maximum annual rainfall is also evident along the Mexican southeastern region. As it is evident from the vectors, those regions of large annual mean precipitation correspond to well-defined seasonal precipitation: winter precipitation over the US west coasts, the Cascade and Sierra Nevada ranges, and southeastern US; early summer rainfall over central US, and late summer rainfall over Mexico; and almost all year-round precipitation over the eastern US coasts. It is also apparent that the western US, between the Rockies and the western coastal region, is drier than the rest of the country; this dryness extends southward to western and northern Mexico. Those features are remarkably in agreement with the Climate Prediction Center 's rain gauge retrospective US-Mexico data set as shown in Nigam and Ruiz-Barradas (2006).

Annual mean evaporation, E, exhibits similar features to those in precipitation: maximum values along the west coasts and to the east of the Rockies over the US, and along the southeast over Mexico (Fig. 1b). However, the annual cycle of evaporation is largest during early summer through the whole US, and late summer over Mexico; note that the magnitudes of the annual cycle vectors are larger(smaller) for E than for P over the eastern half of the US(Mexico). The different timing and magnitude between maximum precipitation and evaporation have important implications for the terrestrial biosphere that depends strongly on the precipitation minus evaporation difference, P -E. Thus, attention is now focused on the P - E map (Fig. 1c). The annual mean difference P - E is positive over almost the whole continent with the largest values along the US western coasts, the Cascade and Sierra Nevada ranges, and the southeast region of the US, and along the southeast coast of the Mexican Gulf of Mexico. The only negative difference is seen over the Colorado Rockies, suggesting an anomalously large evaporation and negative runoff. The P - E difference has a marked annual cycle along both the west coast and the southeastern region of the US where it is highest during winter. The central US has a weak annual cycle of P - E, as indicated by the small arrows over the region, that peaks in winter. It is noteworthy to mention that over the US the difference P - E peaks mostly during winter, as over Mexico it does during summer.

For long-term averages the rate of storage of water, S, must be zero (or very close to it) when compared to the other terms of the terrestrial water balance equation. In fact, this is the case when displaying the annual mean of S from NARR (Fig 1d). The annual cycle of S peaks during winter over the US, and summer over Mexico, and it has a spatial distribution very similar to the difference P - E. Because the rate of storage of water is negligible on the long-term average, the difference P - E must be balanced by the annual mean runoff. This is only partially confirmed in Fig. 1e that shows large values of runoff along the Rocky Mountains of Colorado, Wyoming and Montana but no correspondence in the P - E map. Large values of runoff along the western coasts, the Cascade and Sierra Nevada ranges, and the southeastern region of the US agree well in magnitude and distribution with P - E over the same regions. As expected, runoff has a pronounced annual cycle that peaks in spring over the Rockies, Cascade and Sierra Nevada ranges, and over the southeastern region of the US. The difference P - E is balanced by runoff over the Mexican southeastern states along the Gulf of Mexico states where runoff peaks in late summer and early fall; over the rest of the domain, it is very weak.

Evaporation from NARR over the Great Plains is excessive when analyzed from the perspective of the atmospheric branch of the water cycle, at least during summer months (Nigam and Ruiz-Barradas 2006). But if this is the case over other regions and seasons too, then the long-term mean difference P - E, and as a result runoff, are underestimated in Fig. 1. A way to verify this is to compare NARR runoff with an independent data set. Figure 2 displays the annual mean and annual cycle of observed river discharge and composite runoff (i.e., runoff constrained by observed river discharge from the UNH/GRDC data set). Annual mean river discharge mostly highlights the Pacific northwest basin, the California basin, and the Mississippi, Ohio, Tennessee, Missouri, and Arkansas central river basins with a maximum of 1.5 mm day^{-1} over the central basins. The annual cycle of the river discharge along the California basin and the eastern portion of the central basins peaks in late winter but in the central portion of the central basins it peaks in spring. The composite runoff shows similar features but also adds maxima along the Pacific northwest coast and Mexico. Comparison between NARR's runoff (Fig. 1e) and observed and composite runoff (Figs. 2a-b) indicates that indeed runoff is underestimated in NARR, and its annual cycle is much weaker, especially east of 100°W. As a result, the surface wetness P - E is also underestimated. This confirms the assertion that E is larger than needed for an accurate representation of the water balance over North America in the regional reanalysis.

b. Global Reanalyses

It was shown as part of the analysis of the atmospheric water cycle that NCEP/NCAR and ERA-40 reanalyses have wet and dry bias, respectively, along the eastern half of the US (Nigam and Ruiz-Barradas 2006). These biases are explored now from the perspective of the terrestrial water balance. In addition, the new JRA-25 reanalysis is also used here to assess its capabilities in representing hydroclimate over North America. The annual mean and annual cycle of the terrestrial water cycle fields P - E, change in water storage, and runoff from global reanalyses ERA-40, NCEP/NCAR, and JRA-25 are displayed in Fig. 3. All reanalyses tend to balance the difference P - E with runoff in the long-term mean[3]. It is clear that ERA-40 has the dryer surface among the reanalyses while JRA-25 has the wettest surface. All reanalyses capture the annual mean wetness of the surface (P - E > 0), and corresponding runoff, along the Pacific northwest, but have varied representations of the wetness over the eastern half of the US and over Mexico. Mean annual runoff along the Gulf states of the US is only evident in JRA-25, but its westward expansion is too wide when compared to NARR and UNH/GRDC runoff. It is interesting to point out that both JRA-25 and NCEP/NCAR display mean annual wetness along the western Sierras of Mexico (i.e., the Sierra Madre Occidental and Sierra Madre del Sur) that are not captured by NARR and only in a minimal way by UNH/GRDC. An indication of the unbalanced budgets in ERA-40 and NCEP/NCAR reanalyses is given by the spurious negative difference of P - E over Mexico and central US, respectively, that implies a negative mean annual runoff.

The annual cycle of surface wetness P - E, presents a heterogeneous success in global reanalyses if compared with NARR. The winter peak along the western coasts is well captured by all of them, but it is off the mark over the southeastern US where NCEP/NCAR and JRA-25 peak

[3]A perfect terrestrial water balance would be evident if the annual mean maps of P-E were identical to those of runoff.

earlier in late summer rather than in early winter as ERA-40 does. The annual cycle over central US, judging by the lack of arrows, seems flat in NCEP/NCAR and JRA-25 and well defined in ERA-40. Regarding the annual cycle over Mexico, global reanalyses show it peaking during summer as in NARR, but it is (at least) twice stronger than in NARR.

The annual cycle in runoff also presents some challenges for global reanalyses, even though the winter peak along the Pacific northwest is reasonably captured. ERA-40 practically has none (or very little) seasonal variability over the eastern half of the US. NCEP/NCAR reasonably displays a peak in late winter/early spring over eastern US but it misses a similar peak along the Gulf states when compared to UNH/GRDC. On the other hand, JRA-25 has less marked seasonal variability in runoff over the eastern US, and it is in the wrong season, summer, along the Gulf states of the US.

The annual cycle of the rate of water storage, S, in global reanalyses shows the broad features displayed by NARR, however, the corresponding amplitude varies among them. ERA-40 fairly displays the early winter peak over the western US but its magnitude is smaller than in NARR; similarly, the summer peak over Mexico is reasonably depicted. The seasonal changes over the eastern US are almost non existent in ERA-40, but well defined in both NCEP/NCAR and JRA-25; however, the peak is in late fall in NCEP/NCAR and JRA-25, and no early winter as in NARR. It is clear that the amplitude of the annual cycle over western US and Mexico is accentuated in NCEP/NCAR and particularly JRA-25.

c. Offline Models

In spite of the unidirectional strategy to simulate the terrestrial branch of the hydrological cycle, one has high expectations on these models because of the fact that they are forced by surface meteorological observations. The annual mean and annual cycle of P - E, rate of water storage, and runoff for GSWP-2, and VIC models are displayed in Fig. 4. The long-term average of the difference P - E tends to be balanced by runoff in both VIC and GSWP-2. In general, both offline models are very similar in reproducing the mean surface wetness P - E, and runoff, along the Pacific northwest, and southeastern US, however, differences are also evident. Maxima in P -

E and runoff are evident along the Wyoming Rockies in both VIC and GSWP-2, but only along the Colorado Rockies in VIC. On the southeastern side of the US it is also clear that the maxima in P - E and runoff, are closer to the Gulf of Mexico coast in VIC than in GSWP-2. Thus, runoff from VIC is closer to the observationally constrained runoff from UNH/GRDC than GSWP-2 over the Pacific northwest and the Rockies, but it is the other way around when representing the maximum runoff over the southeastern US. The structure of runoff over southeastern Mexico is well captured by GSWP-2, although its magnitude is smaller when compared against the UNH/GRDC product. VIC's domain does not extend beyond the US.

The annual cycle of the difference P - E from the offline models is very much like that in NARR, although it is larger in the offline models, especially over the Pacific northwest. The winter maxima along both the western coasts and southeastern US are similarly captured by both models. The weak annual cycle over central US is also shown by the models, but VIC's pattern is closer to NARR. The annual cycle over Mexico peaks in the summer months and it is similar in both GSWP-2 and NARR.

The annual cycle in runoff is also very similar in both offline models, and in both cases closer to UNH/GRDC than to NARR. The winter maximum along the Pacific northwest is reproduced but with a larger magnitude than in UNH/GRDC data set. The late winter/early spring peak over eastern US is reasonably captured by both models when compared to UNH/GRDC. The late spring peak in runoff over the Colorado and Wyoming Rockies is better represented by VIC than by GSWP-2. The late summer/early fall peak of runoff over southeastern Mexico displayed in the UNH/GRDC data set is well captured by GSWP-2 although it is weaker in the latter.

The annual cycle of the rate of water storage, S, in both GSWP-2 and VIC models show the same features than in NARR, although their amplitudes are weaker than in NARR. This is expected because if the annual cycle of runoff is underestimated, then the annual cycle of S should compensate for this and be overestimated in NARR. Both off-line models display a winter peak over the western and southeastern US, and a late fall peak over eastern US, but with a weaker magnitude than in NARR; the summer peak over Mexico in GSWP-2 is similar to the peak in

NARR.

4. Terrestrial Water Cycle over the Great Plains

The terrestrial water cycle is further scrutinized by analyzing its month to month changes. The Great Plains region will be the focus of the following analysis for consistency with previous studies of the authors (Ruiz-Barradas and Nigam 2005; Nigam and Ruiz-Barradas 2006). This region, outlined in Figs. 1c-e, covers a surface of $1\text{x}10^{6}$ km^{2} over the 100°-90°W, 35°-45°N domain and, in addition to experiencing the largest interannual variability of summer rainfall over the country, it is at the center of the debate on land-surface-atmosphere interactions[4]. Areal averages over the Great Plains of the components of the terrestrial water cycle are displayed in Fig. 5. The same vertical scale is used for all the terms to facilitate a visual comparison.

The difference P - E (Fig. 5a) evolves similarly in GSWP-2, VIC, NARR, and ERA-40 in that for all of them P-E is positive in the early part of the year, negative during summer, and again positive at the end of the year; in other words, water is recharged during the cold season months and expended during the warm season months. However, important differences among those data sets are evident too. While for the hydrological models P - E is negative from June to August with absolute values smaller than 0.6 mm day^{-1} , the negative difference P - E is doubled and last longer in NARR and ERA-40. Negative values in NARR appear in May, but for ERA-40 negative values span six months from April to October. Based on the previous findings on NARR excessive evaporation, and since summer evaporation is comparable in both NARR and ERA-40 (see Nigam and Ruiz-Barradas 2006), it is reasonable to conclude that excessive evaporation is behind the large negative values of P - E in the warm-season. On the other hand, it must be noticed that NARR and VIC monthly evolution is the closest among the different data sets, having maximum positive values in March and November, and a minimum negative value in July; VIC's values are at least twice as large as those in NARR from March to August! This is likely due to the excessive

[4] The analysis of the atmospheric branch of the hydrological cycle over the Great Plains suggests that the enhanced land-surface-atmosphere interactions are more of an artifact in some models than a real feature at both seasonal-to-interannual scales (Ruiz-Barradas and Nigam 2005; Nigam and Ruiz-Barradas 2006).

evaporation in NARR. It should also be noted that the difference P - E is larger in GSWP-2 than in VIC in fall, winter and spring, while it is smaller in absolute value in summer. The evolution of the difference P - E is completely deficient in NCEP/NCAR and JRA-25: while it is negative from spring to fall in the former, it is positive through the year in the latter.

In general, the data sets exhibit their largest runoff (Fig. 5b) during the spring months, then it decreases through the summer until reaching a minimum during fall; a secondary maximum in runoff is also apparent in early winter. NARR and ERA-40 display the lowest magnitudes, barely reaching 0.4 mm day^{-1}, while JRA-25 has the largest values exceeding 1 mm day^{-1}. It is interesting to note that UNH/GRDC's composite runoff is larger than the purely observed river discharge from January to May, but it is smaller from July to December; they are practically the same in June. The composite runoff peaks one month earlier in spring (1.1 mm day^{-1} in April), than the purely observed river discharge (0.8 mm day^{-1} in May). If the observationally constrained composite runoff from the UNH/GRDC data set is assumed as the best representation of the regional runoff, then not a single product reproduces it. Runoff from VIC is the closest to the composite runoff from January to June but NARR is the closest from July to December. It is worth noticing that VIC's runoff is virtually the same as the observed river discharge from June to August, and about the same with the composite runoff in June.

The UNH/GRDC runoff products are the most reliable observations and estimates one can have at the regional-to-continental scales. As a result, the range of uncertainty they provide indicates that runoff over the Great Plains from NARR, and ERA-40 are very low, especially during the spring and early summer months. It is also clear that VIC does a reasonable good simulation, while GSWP-2 is a bit higher, and peaks later in spring (May). Both GSWP-2 runoff, and UNH/GRDC observed river discharge peak in May, but considering that the river discharge lacks any spatial information about the surface runoff over the domain, this peak cannot be an accurate representation of the mean runoff over the Great Plains. Excessive runoff is depicted by the global reanalysis JRA-25 through the whole year, but only for late winter/early spring by NCEP/NCAR; NCEP/NCAR runoff is very low and comparable to that from NARR from May to December.

The rate of change in water storage S (Fig. 5c) evolves similarly in NARR, VIC and GSWP-2: after positive values from January to March, S decreases to a negative minimum in July for NARR and VIC and in June for GSWP-2, and then it reaches a secondary maximum in November; the sudden decrease in S and P-E from September to October in GSWP-2 is very strange. The range in the rate of change in water storage in NARR goes from -1.5 to 1.1 mm day^{-1}, it is smaller in VIC (-1.1 to 0.9 mm day^{-1}) and comparable in GSWP-2 (-1.2 to 1.3 mm day^{-1}). While the global reanalyses NCEP/NCAR and JRA-25 exhibit very large ranges, especially NCEP/NCAR (-1.7 to 3.4 mm day^{-1} , and -1.4 to 1.6 mm day^{-1}, respectively), ERA-40 displays the smallest range (-0.4 to 0.7 mm day^{-1}). Water storage and its rate of change is difficult to compare among the different data sets because the different design of the soil layers that define the column soil moisture. For instance, VIC and JRA-25 use soil layers of different depths and they add up to 2m only in some parts of the US. In turn, the GSWP-2 multi-model mean has fixed depths that only add up to 1.5m; the other reanalyses (ERA-40, NCEP/NCAR and NARR) have layers with a total column of 2m. In spite of those differences, there is some coherence in the month to month evolution of S between NARR and the two hydrological model simulations from GSWP-2 and VIC, although the winter and summer values are much larger in NARR than in the hydrological models.

The nature of the terrestrial water balance is examined now by displaying the residual P-E-R-S (Fig. 5d). As expected, VIC closes the balance through the year if the whole column, in excess of 2m, is considered (not shown). However, in this case where the soil column is limited to 2m a tiny imbalance is noticeable in April[5]. The terrestrial water budget in GSWP-2 is practically closed too[6]. According to Dirmeyer et al. (2006a), imbalances in the GSWP-2 multi-model mean arise due to deficiencies “in the handling of snow “but those errors (figure 1 in Dirmeyer et al. 2006a) are minimized when calculating the regional area-averaged means. NARR closes the annual balance

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[5] If the rate of storage of surface water, S, is calculated from monthly values using centered differences, as in the reanalyses, the water budget is not closed in VIC.

[6] The water budget is not closed at all if the storage of surface water is calculated from monthly means in GSWP-2. Differences in the annual cycle of S from VIC and GSWP-2 data sets, among other things, arise due to the way the corresponding groups have calculated them. While VIC’s uses centered differences, GSWP-2's uses backward differences.

better than the global reanalyses: while the long-term mean for NARR does not reach a tenth of a mm day^{-1}, the corresponding means for ERA-40, JRA-25 and NCEP/NCAR are -0.2, -0.3,-0.3 and -0.7 mm day^{-1} respectively. However, in spite of the long-term balance in NARR, it is also clear that seasonal imbalances are larger in spring and fall. Large evaporation and low runoff seem to be at the center of the seasonal imbalances in NARR from spring to fall. Large seasonal imbalances in ERA-40 from summer to early fall are dominated by the small runoff and change in surface water during those seasons. On the other hand, the large seasonal imbalances in JRA-25 arise from the lack of an annual cycle in the difference P -E and the large runoff. Not only do the large rates of water storage contribute to the large imbalance in NCEP/NCAR during winter, but so does the elevated evaporation through the year; this large evaporation also contributes to negative P - E values through the year.

5. Seasonal Variability

The seasonal apportioning of the difference P - E, and runoff is analyzed next, but for space considerations, this discussion is limited on NARR, VIC and UNH/GRDC data sets for the contrasting seasons of winter and summer; these are the seasons of water storage and consumption, when evaporation is at its minimum and maximum respectively.

The seasonal means of P - E and runoff are displayed in Fig. 6. It is clear right away that NARR underestimates both the difference P - E and runoff in both winter and summer, especially to the east of the continental divide. Surface wetness (P-E>0) and runoff over the western US in winter (Figs. 6a-e) are in better agreement among the data sets, even though NARR does not capture the broad extension of surface wetness as in VIC. However P-E is around a fourth smaller in NARR than in VIC over southeastern US. Although winter runoff over the east extends a bit further to the west in VIC, when compared with the UNH/GRDC product, the underestimation of NARR's winter runoff is very drastic.

Regions of surface dryness (P-E<0), wetness (P-E>0), and runoff in NARR do not compare well with those fields from VIC and UNH/GRDC during summer (Figs. 6f-j). Again, the difference P-E compares well over the western US, and over northwestern Mexico (where it changes sign), but it is quite different over the southeastern US compared to VIC. Although there is a hint of surface wetness (P-E>0) along the southeastern and the states along the Gulf of Mexico in NARR, this is not as extended as in VIC; additionally, the surface dryness (P-E<0) in NARR over the central US is three times larger than in VIC. While VIC and UNH/GRDC products agree on the distribution of runoff over the western mountains and the central and southeastern regions of the US during summer, runoff is practically absent in NARR (except for runoff along the Colorado and Wyoming Rockies). The seasonal mean P - E is largely balanced by the change in water storage in NARR, but not in VIC or the multi-model mean from GSWP-2 (not shown).

Annual, winter and summer mean differences of P-E and runoff between NARR and VIC (not shown) indicate that NARR fields are significantly smaller, at the 95% level, than the corresponding fields in VIC.

Considering that observed precipitation is very well assimilated in NARR, it is apparent that the shortage in water for runoff in the regional reanalysis is caused by excessive evaporation, that also leads to large changes in water storage (not shown); this is particularly evident over the southeastern US.

Excessive evaporation in NARR seems to be rooted in the NARR's Noah land-surface model. Additional comparisons (not shown) of the climatological net solar and downward longwave radiation at the surface in VIC and NARR reveal that both land-surface models, VIC and NARR's Noah, receive comparable energy so the discrepancies in received energy cannot be considered as the source of the large evaporation. On the other hand, surface air temperature and winds do not present significant bias in NARR (Mesinger et al. 2006) so the remaining option is the land-surface model. Indeed, evaluations at NCEP indicate that the land-surface model Noah had a large positive bias in summer evaporation over regions of non-sparse vegetation cover, such as the eastern US, and that the bias was related to canopy resistance parameters in the model (Mitchell et al 2005; http://www.emc.ncep.noaa.gov/gc_wmb/Documentation/TPBoct05/T382.TPB.FINAL.htm).

Upgrades to the Noah model, including the correction of the evaporation bias, were implemented in middle 2005, almost two years after the completion of NARR at the end of 2003.

6. Concluding Remarks

The present study is focused on the assessment of the seasonal variability of the terrestrial water balance over North America and the Great Plains in particular. Outputs from hydrological models are compared to reanalyses and observationally constrained data sets. The model outputs analyzed come from the GSWP-2 hydrological multi-model mean, and VIC hydrological model, which are forced with observed meteorology. The reanalyses products analyzed are the regional reanalysis NARR and the global reanalyses NCEP/NCAR, ERA-40, and JRA-25. Special attention is paid on how NARR compares against the offline models, and the new Japanese reanalysis JRA-25 compares against the other global reanalyses. Observed river discharge and observationally constrained runoff from UHN/GRDC provide the needed independent data set in order to establish some uncertainties in the reanalyses and simulations, including the diagnosis of evaporation from NARR. The main findings are as follows:

- In the long-term average, the different products largely balance the surface wetness P - E with runoff but substantial differences exist in both P - E and runoff among the data sets. While all products reasonably simulate the long-term means along the Pacific northwest, they are challenged when trying to reproduce the structures over the mountain ranges of the west, over the eastern half of the US (to east of the continental divide), and over Mexico.
- The off line land-surface model simulations are the closest among the different products, while the reanalyses have varied representations of the wetness of the surface: very dry in NARR and ERA-40, dry and wet in NCEP/NCAR and JRA-25, respectively. The long-term mean of runoff in the hydrological models is closer to the long-term mean of

observationally constrained runoff from UNH/GRDC (~2.0 mm day^{-1}) than any other product, especially over the eastern US. ERA-40 and NARR have very little runoff, NCEP/NCAR has around half of the observed runoff, and JRA-25 has comparable magnitude to the observed runoff but its spatial structure extends farther to the west.

- Since the long-term mean of runoff in NARR is a fourth of that in the observationally constrained UNH/GRDC data set, and in the hydrological models, the long-term mean of the surface wetness P - E must be low as well. This implies that evaporation in NARR is larger than needed in order to have a tighter terrestrial water balance; this confirms the authors' previous finding regarding NARR's excessive evaporation in the context of the atmospheric branch of the water cycle (Nigam and Ruiz-Barradas 2006). Thus, the long-term mean of the difference P - E should have a structure similar to the one depicted in the hydrological models.
- NARR and VIC depictions of the winter and summer means of P - E and runoff over the US differ importantly. VIC's runoff is closer than NARR's to the observationally constrained runoff in UNH/GRDC. Runoff is larger in winter than in summer over the US, and the largest differences exist to the east of the continental divide. While NARR's surface wetness (P - E > 0) over the southeastern US during winter is around 30% smaller than VIC's, NARR's runoff is around 70% smaller than VIC's. The surface dryness (P - E < 0) over the same region during summer is three times larger in NARR than in VIC; although runoff is at its minimum in VIC and UNH/GRDC in summer, it is practically absent in NARR. Contrary to the US, runoff over Mexico is larger in summer than in winter in the UNH/GRDC data set, but it is pretty much absent from the region in NARR.
- The annual cycle of the components of the terrestrial water cycle peaks at different times of the year and over distinctive regions: the Pacific northwest, the western mountain ranges, and the southeastern/eastern regions over the US, and western and southeastern Mexico. This picture is particularly consistent through VIC, GSWP-2 and NARR. However, because the mentioned problems in evaporation and runoff in NARR, the annual cycles of

P-E and runoff are underestimated, and the annual cycle of the change in water storage is overestimated. Comparisons with the annual cycle of the observationally constrained runoff from the UNH/GRDC product, give some credence to the offline land-surface models and validate the notion of a weak annual cycle of runoff in NARR . Global reanalyses depict reasonable (considering their coarse resolution) annual cycles of P-E and runoff over the Pacific northwest, but are challenged over the eastern half of the US and over Mexico, and when portraying the annual cycle of the change in water storage.

- Examination of the terrestrial water cycle over the central Great Plains (100°-90°W, 35°-45°N) indicates some problems in reanalyses. Seasonal imbalances in NARR from spring to fall are due to the highlighted errors in runoff and evaporation. Among the global reanalyses, JRA-25 has the largest seasonal imbalances, although its annual imbalance is comparable to that in ERA-40 and it is almost half of that in NCEP/NCAR. Seasonal imbalances in JRA-25 are due to overestimations in P - E, the change in water storage, and runoff as well as the almost nonexistent annual cycle in P - E and runoff. Even when NARR and ERA-40 have some common features in P - E and runoff, ERA-40 has larger imbalances from spring to fall due to the small and almost uniform change in water storage during those seasons. The evolution of the UNH/GRDC observationally constrained runoff is only realistically reproduced by VIC.

It is clear that reanalyses have some problems in reproducing the terrestrial water cycle over North America, particularly the global products. The most recent global reanalysis, the Japanese reanalysis, does not improve the representation of the climatological features of the terrestrial water cycle over North America. On the other hand, the regional reanalysis NARR severely overestimates evaporation that leads to the underestimation of runoff. Excessive evaporation in NARR is rooted in canopy resistance parameters within the Noah land-surface model.

Differences apart between the surface models in VIC and NARR, a critical aspect seems to be also the observationally constrained runoff imposed in VIC, but not in NARR, which keeps runoff on check and favorably impacts evaporation and water storage in this model. These results make clear the need for a correction in the assimilation process in NARR in which some observational constraints on the land-surface part are needed to generate realistic hydroclimate fields.

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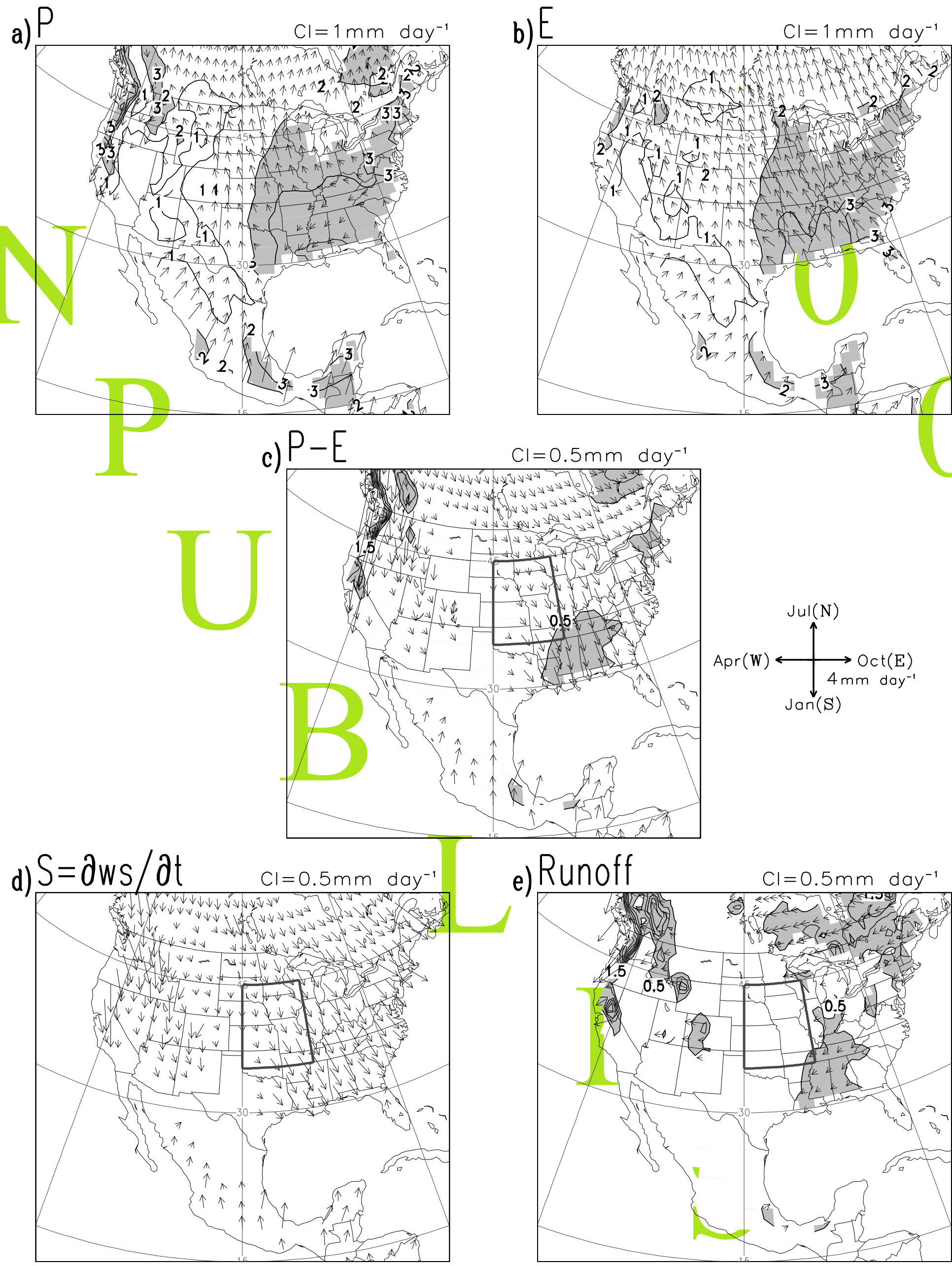

Figure 1. Annual cycle and annual mean of surface fields in NARR for the 1979-1999 period: (a) precipitation, P; (b) evaporation, E; (c) precipitation minus evaporation, P-E; (d) change in water storage, S=∂ws/∂t; and (e) runoff, R. Vectors represent the annual cycle through the first harmonic while background isolines display the annual mean of the fields in mm day^{-1}. The insert vectors to the right of the central panel indicate the scaling of the magnitude in mm day^{-1} and the phase of the annual-cycle: vectors pointing to the south indicate a maximum on 1 January, pointing toward the west means a maximum on 1 April, pointing to the north a maximum on 1 July, and pointing to the east a maximum on 1 October. Only magnitudes of the annual cycle larger that 0.5 mm day^{-1} are displayed for all fields. Annual means are contoured at 1 mm day^{-1} for P, and E, while it is 0.5 mm day^{-1} for P-E, S, and R; the zero contour line is omitted. Shading indicates annual means equal or larger than 2 mm day^{-1} for P, and E, and |±0.5| mm day^{-1} for P-E, S, and R; positive/negative values are shaded dark/light. The box over central US outlines the Great Plains region (100°-90°W, 35°-45°N).

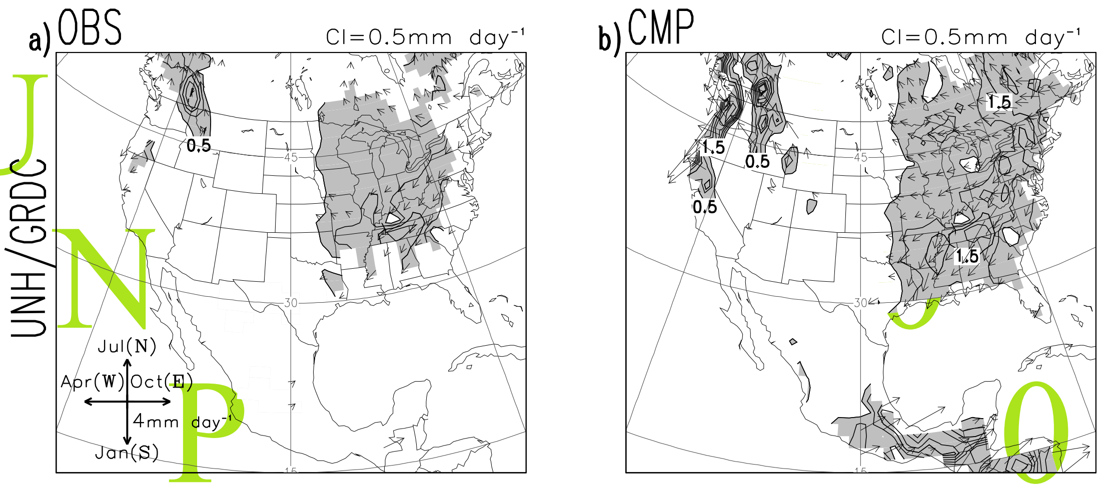

Figure 2. Annual cycle and annual mean of runoff from the UNH/GRDC data set. (a) Observed river discharge, (b) composite from observed river discharge and simulated runoff. Vectors, shades and contours are as in Fig. 1.

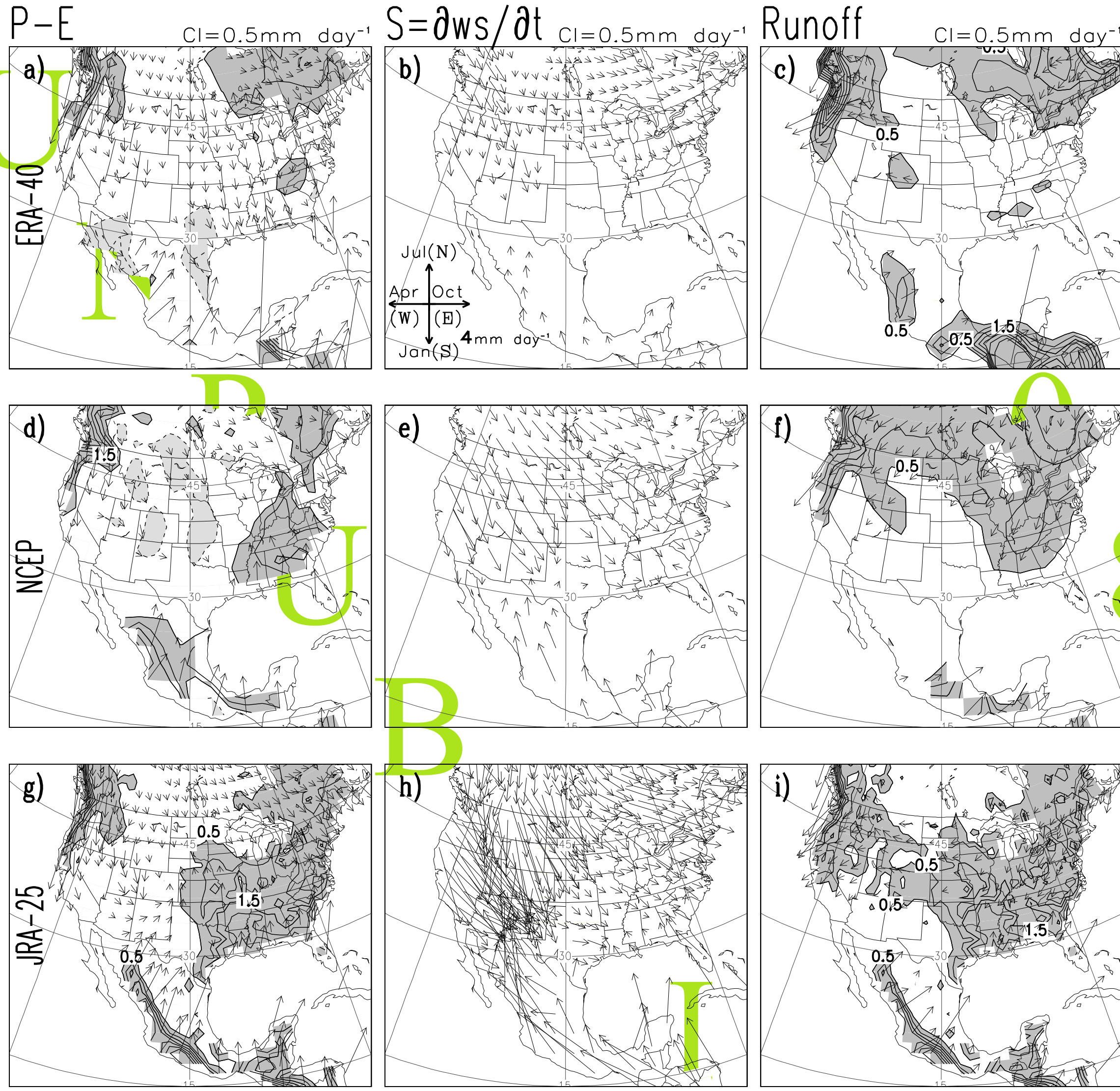

Figure 3. Annual cycle and annual mean of surface fields: (a)-(c) ERA-40; (d)-(f) NCEP; and (g)-(i) JRA-25 for the 1979-1999 period: (a), (d), (g) precipitation minus evaporation, P-E; (b), (e), (h) change in water storage, S=∂ws/∂t; and (c), (f), (i) runoff, R. Vectors, shades and contours are as in Fig.1.

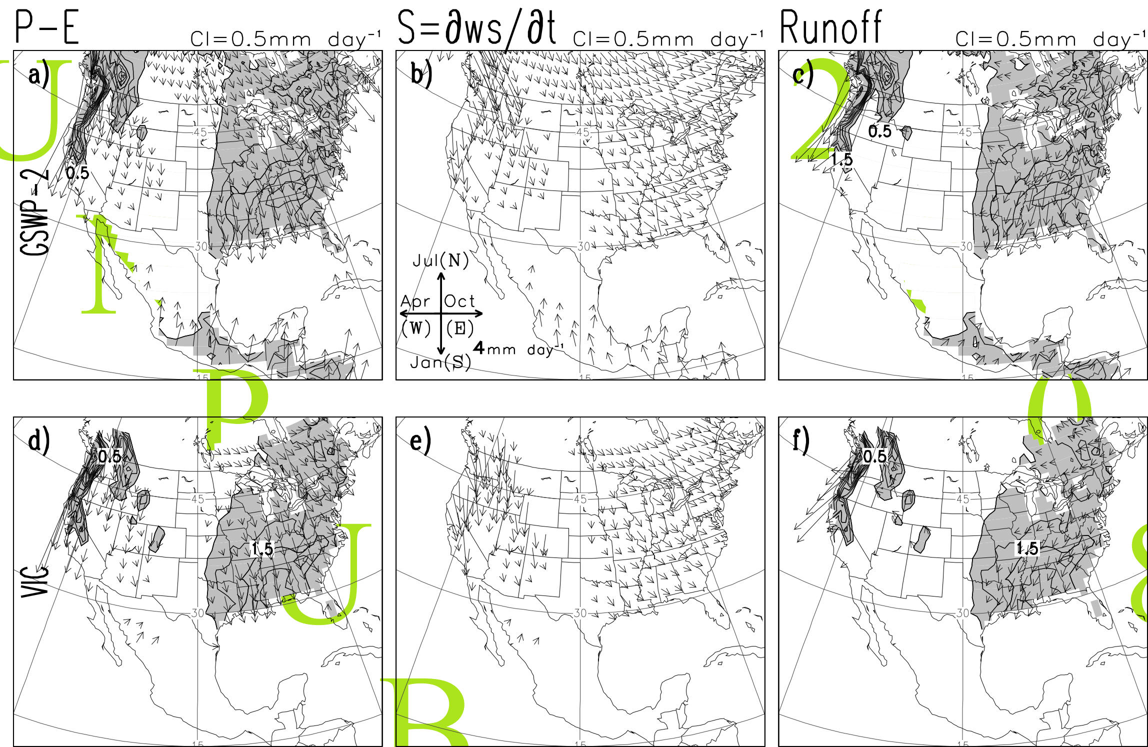

Figure 4. Annual cycle and annual mean of surface fields: (a)-(c) GSWP-2 for the 1986-1995 period; (d)-(f) VIC for the 1979-1999 period: (a), (d) precipitation minus evaporation, P-E; (b), (e) change in water storage, S=∂ws/∂t; and (c), (f) runoff, R. Vectors, shades and contours are as in Fig. 1.

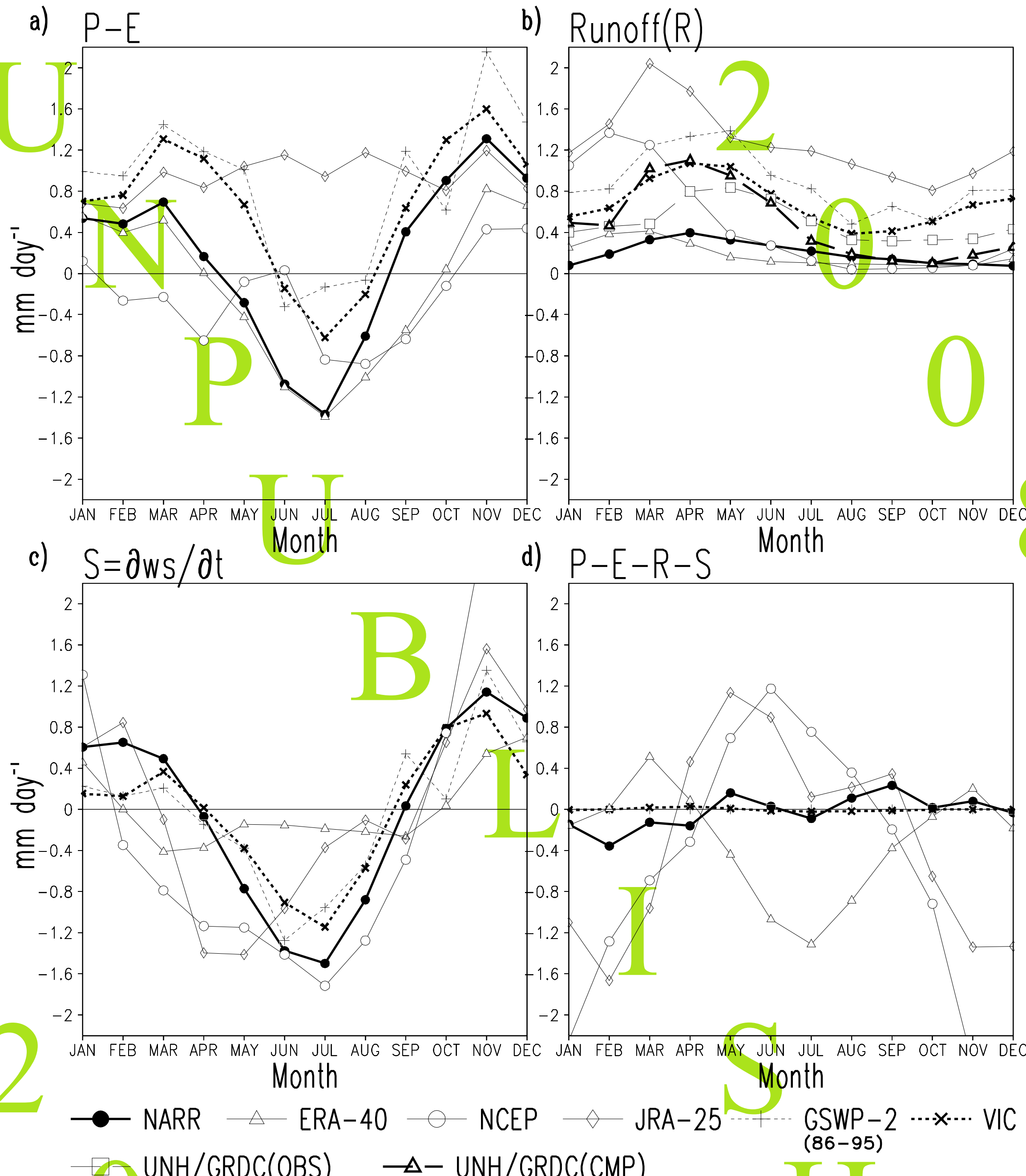

Figure 5. Monthly climatology of the terrestrial water cycle fields over the Great Plains (100°-90°W, 35°-45°N) in mm day^{-1} for the 1979-1999 period. (a) Precipitation minus evaporation, P-E; (b) runoff, R; (c) change in water storage, S=∂ws/∂t; (d) residual, P-E-R-S. NARR: thick continuous line with filled circles; ERA-40 thin continuous line with triangles; NCEP: thin continuous line with circles; JRA-25: thin continuous line with diamonds; GSWP-2: short dashed line with plus signs; VIC: thick short dashed line with multiplication signs; UNH/GRDC (observed river discharge): long dashed line with squares; UNH/GRDC(composite R): thick long dashed line with triangles. Climatology for the GSWP-2 data set covers the 1986-1995 period.

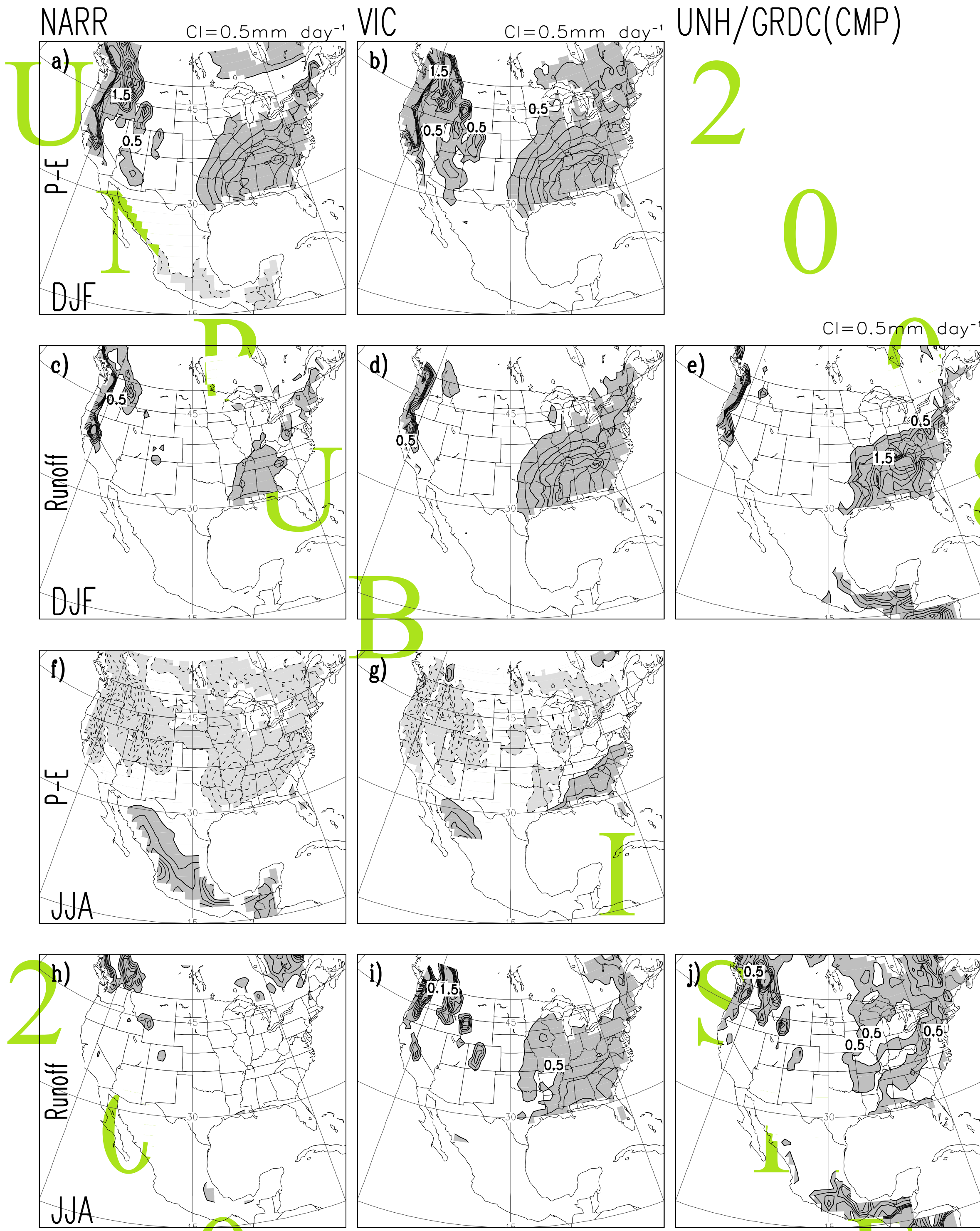

Figure 6. Climatological winter (December-February) and summer (June-August) surface fields for the 1979-1999 period. NARR, left panels (a), (c), (f), (h); VIC, central panels (b), (d), (g), (i); UNH/GRDC right panels (e), (j). Winter precipitation minus evaporation, P-E: (a), (b); winter runoff, R: (c)-(e); summer P-E: (f), (g); summer R: (h)-(j). Shading indicates values larger than |±0.5| mm day^{-1}; positive/negative values are shaded dark/light. Contours are 0.5 mm day^{-1}, and the zero contour line is omitted.