Estimation of the Surface Water Budget of the La Plata Basin

FENGGE SU
Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington, and Universities Space Research Association at NSSTC NASA MSFC, Huntsville, Alabama

DENNIS P. LETTENMAIER
Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington

(Manuscript received 17 September 2008, in final form 11 March 2009)

ABSTRACT

The Variable Infiltration Capacity (VIC) land surface hydrology model forced by gridded observed precipitation and temperature for the period 1979–99 is used to simulate the land surface water balance of the La Plata basin (LPB). The modeled water balance is evaluated with streamflow observations from the major tributaries of the LPB. The spatiotemporal variability of the water balance terms of the LPB are then evaluated using offline VIC model simulations, the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40), and inferences obtained from a combination of these two. The seasonality and interannual variability of the water balance terms vary across the basin. Over the Uruguay River basin and the entire LPB, precipitation \( P \) exceeds evapotranspiration \( E \) and the basins act as a moisture sink. However, the Paraguay River basin acts as a net source of moisture in dry seasons (strong negative \( P - E \)). The annual means and monthly time series of ERA-40 \( P \) are in good agreement with gauge observations over the entire LPB and its subbasins, except for the Uruguay basin. The \( E \) estimates from VIC and inferred from the ERA-40 atmospheric moisture budget are consistent in both seasonal and interannual variations over the entire LPB, but large discrepancies exist between the two \( E \) estimates over the subbasins. The long-term mean of atmospheric moisture convergence \( P - E \) agrees well with observed runoff \( R \) for the upper Paraná River basin, whereas the imbalance is large (28%) for the Uruguay basin—possibly because of its small size. Major problems appear over the Paraguay basin with negative long-term mean of atmospheric moisture convergence \( P - E \), which is not physically realistic. The computed precipitation recycling in the LPB (for \( L = 500 \) km) exhibits strong seasonal and spatial variations with ratios of 0%–3% during the cold season and 5%–7% during the warm season.

1. Introduction

The La Plata Basin (LPB) spans about 24° of both latitude and longitude (Fig. 1) and covers a variety of landscape and hydroclimatic regimes (Mechoso et al. 2001). Significant changes in both precipitation and streamflow of major tributaries of the LPB have been observed over the last few decades (Genta et al. 1998; García and Vargas 1998; Barros et al. 2000; Saurral et al. 2008). Many studies have shown the strong effects of ocean conditions on the hydroclimatology of the LPB (Robertson and Mechoso 1998; Camilloni and Barros 2000; Barros and Silvestri 2002; Berri et al. 2002), given the dominance of oceans over land area in the Southern Hemisphere. The uniqueness of the basin’s climate and hydrology has led to the LPB being designated as a Global Energy and Water Cycle Experiment (GEWEX) Continental Scale Experiment (CSE; Berbery et al. 2005). Understanding the hydrological cycle and the land surface–atmosphere interactions within the LPB is a subject of interest for both scientific and practical reasons and is also one of the fundamental issues to be addressed by the GEWEX LPB project (Berbery et al. 2005). Estimating the water and energy fluxes and evaluating the implications for budget closure of various data sources will help to better understand the nature and cause of hydroclimate changes in the basin.

Corresponding author address: Fengge Su, Department of Civil and Environmental Engineering, University of Washington, 112 Wilson Ceramics Laboratory, Box 352700, Seattle, WA 98195-2700.
E-mail: fgsu@hydro.washington.edu

DOI: 10.1175/2009JHM1100.1

© 2009 American Meteorological Society
Among the components of the hydrologic cycle, the river response to climatic signals is of special interest because streamflow represents a complex synthesis of precipitation, evapotranspiration, and other components of the hydrological cycle. In this study, we address the following questions: 1) How predictable are runoff and streamflow in the LPB? 2) What is the spatiotemporal variability of the water balance terms of the LPB? 3) How well can the water budgets be closed using independent estimates of the major state variables and fluxes? and 4) How much moisture is recycled within the LPB, and how does the recycling ratio vary seasonally?

The surface and upper-air observational networks in the La Plata region are sparse, and for this reason, in situ observations alone cannot provide the comprehensive information needed to develop adequate water balance estimates. Therefore, we have to rely on atmospheric and hydrologic models and gridded reanalyses such as the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF; Uppala et al. 2005) reanalyses to supplement in situ observations. A template for an approach that exploits data sources other than in situ observations is provided by the GEWEX Water and Energy Budget Studies (WEBs), performed over the Mississippi River basin with a suite of climate models, global reanalysis, observations, and macroscale hydrologic model (Roads and Chen 2000; Roads and Betts 2000; Roads et al. 2002, 2003; Maurer et al. 2001).

Despite the errors inherent in models and analyses, they provide qualitative features that emulate many aspects of the observations. Models close the water budget by construct because they are based upon fundamental mass and energy conservation laws. Comprehensive land surface models capable of representing the dynamics of land–atmosphere water and energy exchanges have been used to simulate historical land surface conditions when provided with realistic forcings (Nijssen et al. 2001; Maurer et al. 2002; Qian et al. 2006; Zhu and Lettenmaier 2007). The Variable Infiltration Capacity (VIC) land surface hydrology model was used in the WEBS study (Roads et al. 2003). The VIC model is intended to reproduce observed streamflow, and by closure it is constrained to balance other terms in land surface water and energy budgets. Therefore, in cases where the VIC model has been calibrated to observed streamflow, its simulated surface fluxes provide a benchmark for the evaluation of flux predictions (e.g., evapotranspiration and runoff) and storage (soil moisture, snow water equivalent) from the reanalyses and the climate models (Maurer et al. 2001; Roads et al. 2003; Su et al. 2006).

In this study, we describe an application of the VIC model forced by gridded observed precipitation and temperature for the period 1979–99 to simulate the land surface water balance of the LPB and its major tributaries. The modeled water balance is evaluated with streamflow observations from the major tributaries of the LPB. The predictability of LPB runoff and streamflow is investigated. The surface water budget of the LPB and its tributaries is then examined using the 40-yr ECMWF Re-Analysis (ERA-40; Uppala et al. 2005), VIC-simulated surface water fluxes, and available observations. The mean annual, seasonal, and interannual variations of water balance terms in different datasets are characterized, and long-term imbalances of the moisture flux between land surface and atmosphere of the regions are explored. Finally, precipitation recycling is examined to understand the effect of the land surface on the LPB’s hydrologic regime.

2. Data and methodology
a. La Plata Basin

The LPB consists mainly of three main subbasins, which are defined by the major tributaries of La Plata: the Paraná, Paraguay, and Uruguay Rivers (Fig. 1). The Uruguay River does not have a direct connection with
the Paraná River; its only coincidence being its confluence with the Paraná where it joins the La Plata main stem. The Paraguay flows directly into the Paraná River, a few kilometers upstream of Corrientes City (station 8 in Fig. 1), constituting the Paraná system. The Paraná River (excluding the Paraguay basin) makes up about half of the LPB area. It is usually divided into three sections: the upper, middle, and lower Paraná. On the basis of the available stream gauge stations, we define here the upper Paraná basin as upstream from Posadas (station 5 in Fig. 1), the Paraguay basin as upstream from Bermejo (station 7 in Fig. 1), and the Uruguay basin as upstream from Concordia (station 2 in Fig. 1).

b. The VIC model and inputs

The VIC model (Liang et al. 1994, 1996) is a grid-based land surface scheme that parameterizes the dominant hydrometeorological processes taking place at the land surface–atmosphere interface. The model solves both surface water and energy balances over a grid mesh. The VIC model uses a mosaic representation of land cover and a parameterization for infiltration that accounts for subgrid-scale heterogeneities in land surface hydrologic processes. The sources of the land surface characteristics required by the VIC model, which include soil data, topography, and vegetation characteristics, are the same as in Su et al. (2008), to which the reader is referred for details. The meteorological input data for the VIC model include 21 yr (1979–99) of daily precipitation, maximum temperature (Tmax), minimum temperature (Tmin), and wind speed, among which only precipitation and temperature were taken directly from surface observations. Daily 10-m wind speed was obtained from NCEP–NCAR reanalysis (Kalnay et al. 1996). The other meteorological and radiative variables were derived based on relationships with precipitation, daily mean temperature, and the daily temperature range described in Nijssen et al. (2001) and Maurer et al. (2002).

Daily precipitation and Tmax and Tmin for the years 1979–99 were taken from the National Climatic Data Center (NCDC) Global Daily Climatology Network (GDCN; available online at http://www.ncdc.noaa.gov/oa/climate/research/gdcn/gdcn.html) and NCEP Climate Prediction Center (CPC) stations (available online at http://dss.ucar.edu/datasets/ds512.0/). Precipitation station coverage is best in the Uruguay and upper Paraná tributaries, whereas data coverage is very poor for large parts of the Paraguay and lower Paraná basins. Temperature stations are sparse for the entire Plata basin. Figure 2 shows the spatial distribution of gauge stations for precipitation and temperature in 1986. The number of stations used for gridding is different for each year (Fig. 3), but the spatial pattern is generally the same as in 1986. In this study, we ran the VIC model at a 3-hourly time step and at a 0.125° spatial resolution over the entire LPB. The raw precipitation and temperature data were gridded to 0.125° using the same method as in Su et al. (2008). Daily precipitation was apportioned equally to each 3-h time step. Temperatures at each time step were interpolated by fitting an asymmetric spline function through the daily maximal and minimal. The 3-hourly wind speeds were made identical to the daily values.

Observed monthly streamflow data used to calibrate and evaluate the VIC model results were partly provided by the
Brazilian Water Resources Agency (Agencia Nacional da Água; available online at http://hidroweb.ana.gov.br), and partly from the Argentine Department of Hydrology. The name and location of the selected streamflow stations are given in Table 1 (see also Fig. 1). There are two stations from the Uruguay basin (stations 1 and 2), three from the Paraná basin (stations 3–5), and two from the Paraguay River (stations 6 and 7). The VIC simulated runoff was calibrated by adjusting the soil parameters to match the observed monthly hydrograph and annual flow volume at the strategic outlet points. Detailed calibration strategy for the VIC model can be found in Nijssen et al. (2001) and Su et al. (2005).

c. ERA-40 reanalysis

The ERA-40 reanalysis (Uppala et al. 2005) was produced using a static version of the ECMWF numerical weather prediction model on an N80 reduced Gaussian grid with about 1.125° latitude–longitude spacing. The ERA-40 archive essentially includes the same land surface variables produced by VIC, including surface fluxes of both water and energy, as well as atmospheric moisture flux and storage at multiple levels, which can be vertically integrated to produce a gridded atmospheric water balance. The ERA-40 data cover the 45-yr period from September 1957 to August 2002. We used 21 yr of monthly averages of precipitation, evapotranspiration, runoff, and soil moisture obtained from NCAR for the period 1979–99. These variables are derived entirely from the ECMWF data assimilation system and have no direct relationship to observations. The archived ERA-40 gridded data were interpolated to the 0.125° grid using an inverse distance interpolation.

The atmospheric branch of the water balance can be expressed as

$$-\frac{dW_a}{dt} - \mathbf{V} \cdot \mathbf{Q} = P - E,$$  \hspace{1cm} (1)

where $P$ is precipitation, $E$ is evapotranspiration, $\mathbf{V} \cdot \mathbf{Q}$ is the horizontal divergence of vertically integrated atmospheric vapor flux, and $W_a$ is precipitable water in the atmosphere. Here

$$W_a = \frac{1}{g} \int_0^p q dp \quad \text{and} \quad (2)$$

$$Q = \frac{1}{g} \int_0^p q \mathbf{v} dp, \hspace{1cm} (3)$$

where $q$ is specific humidity, $p$ is pressure, $p_s$ is the pressure at the ground, $\mathbf{v}$ is the horizontal wind velocity, and $g$ is gravitational acceleration. The two terms on the left-hand side of Eq. (1) were computed at NCAR from ERA-40 wind, moisture, and surface pressure fields (which are strongly linked to observations) to produce fields of $P - E$ for the period 1958–2001 using methods outlined by Trenberth and Guillemot (1995). The $P - E$ fields were subsequently interpolated to the 0.125° grid. We combined $P - E$ with the gridded observed $P$ to compute the residual of the two (the residual is denoted as “implied $E$” hereafter). The implied $E$ was compared with $E$ simulated directly by the VIC model and the $E$ values from the ERA-40 reanalysis data.

The water balance for the terrestrial branch of the climate system can be written as

$$\frac{dS}{dt} = P - E - R,$$  \hspace{1cm} (4)

where $S$ represents the terrestrial water storage and $R$ is total runoff. Assuming that changes in storage in both the atmosphere and soil can be neglected in the long-term (e.g., a year) means, the following equation results from combining (1) and (4) for multiyear averages:

$$\overline{R} \approx \overline{P - E} \approx - \mathbf{V} \cdot \mathbf{Q}. \hspace{1cm} (5)$$

Equation (5) indicates that in the long-term means, the net horizontal flow of water vapor into a region is balanced by the total runoff out of the region. This approach of relating terrestrial and atmospheric water budgets has been widely used to study terrestrial water

---

**Fig. 3.** Number of gauge stations for (a) precipitation and (b) temperature for the years 1979–99.
storage, regional $E$, and the agreement between the terrestrial and atmospheric water cycles (Roads et al. 1994; Oki et al. 1995; Yeh et al. 1998; Yeh and Famiglietti 2008; Oki 1999; Seneviratne et al. 2004; Marengo 2005; Su et al. 2006).

3. Streamflow simulations with the VIC model

The streamflow regime varies widely between the subbasins of the LPB (García and Vargas 1996). In this section, we describe the streamflow simulations with the VIC model for the selected river basins in Table 1 and focus particularly on the Uruguay, upper Paraná, and Paraguay Rivers. Figure 4 shows the mean monthly simulated and observed streamflow at selected stream gauges in the LPB. Monthly time series of the simulated and observed streamflow at the corresponding stations are presented in Fig. 5. The Nash–Sutcliffe efficiency ($E_f$), which describes the prediction skill of the modeled monthly streamflow as compared to observations and

<table>
<thead>
<tr>
<th>Station ID</th>
<th>River/station</th>
<th>Drainage area (km$^2$)</th>
<th>Data period</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Nash–Sutcliffe efficiency $E_f$</th>
<th>Relative $E_r$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Uruguay/Paso de los Libres</td>
<td>189 300</td>
<td>1979–99</td>
<td>−29.73</td>
<td>−57.08</td>
<td>0.9579</td>
<td>2.59</td>
</tr>
<tr>
<td>2</td>
<td>Uruguay/Concordia</td>
<td>240 000</td>
<td>1979–99</td>
<td>−32.23</td>
<td>−58.02</td>
<td>0.9254</td>
<td>5.93</td>
</tr>
<tr>
<td>3</td>
<td>Paraná/Jupiá</td>
<td>478 000</td>
<td>1979–99</td>
<td>−20.80</td>
<td>−51.62</td>
<td>0.6949</td>
<td>3.49</td>
</tr>
<tr>
<td>5</td>
<td>Paraná/Posadas</td>
<td>975 000</td>
<td>1979–99</td>
<td>−27.45</td>
<td>−55.80</td>
<td>0.0953</td>
<td>5.68</td>
</tr>
<tr>
<td>6</td>
<td>Paraguay/Ladario</td>
<td>459 990</td>
<td>1979–90</td>
<td>−19.00</td>
<td>−57.59</td>
<td>&lt;0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Paraguay/Bermejo</td>
<td>1 100 000</td>
<td>1979–96</td>
<td>−26.93</td>
<td>−58.51</td>
<td>&lt;0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Paraná/Corrientes</td>
<td>2 051 720</td>
<td></td>
<td>−27.48</td>
<td>−58.83</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AUGUST 2009 S U A N D L E T T E N M A I E R 985

Fig. 4. Average annual cycle of the simulated and observed streamflow at selected gauging stations in LPB. The periods covered by the data are indicated in Table 1.
the relative error (Er) between simulated and observed mean annual runoff, are also summarized in Table 1.

a. Uruguay River

The streamflow regime of the Uruguay River is characterized by the absence of marked seasonality, a short duration of floods, a quick response to precipitation, and a high variation in monthly flow, which are associated with the steep topography and irregular precipitation characteristics within the basin (García and Vargas 1996). Despite the high variability in hydrographs, the VIC model shows good performance in reproducing the seasonal and interannual variations of observed streamflow for the Uruguay basin, as shown by results for the Uruguay at Paso de los Libres with a drainage area of 189,300 km² (station 1 in Fig. 4, see also Fig. 5a) and the Uruguay at Concordia (240,000 km²; Table 1). The model efficiencies based on the monthly streamflow (1979–99) exceed 0.9 for the both Uruguay stations, with relative errors less than 6% (Table 1). Tucci et al. (2001) and Collischonn et al. (2005) also reported similar results over the upper Uruguay basin (tributaries with drainage areas less than 75,000 km²) using a hydrology model that is similar in many respects to VIC. There are a few reasons that might explain the good performance of the hydrology models over the Uruguay basin in addition to the runoff generation mechanism in the models: good coverage of precipitation gauging stations (Fig. 2a), modest effects of human development, relatively high runoff (a runoff ratio of 0.44), and the physical characteristic (relatively steep topography) of the basin.

b. Parana River

The upper Paraná flows mostly in areas with steep terrain that favors runoff production and contributes more than one-half of the total runoff flowing in the La Plata River system. The upper Paraná and its tributaries are regulated by a number of dams with a total storage capacity of 240 km³ (around 50% of the annual flow of the upper Paraná; ICOLD 2003), including one of the
world’s largest reservoirs, Itaipú. There is a well-defined streamflow regime above Jupia (station 3 in Fig. 4) with floods occurring between December and March and a dry season between June and September. The 21-yr model simulations show consistency with the observations in seasonal and interannual variations; however, the model generally overestimates the austral summer peaks in February and March (station 3 in Fig. 4, see also Fig. 5b), which might be partly explained by reservoir effects for which the VIC model does not account. The overall overestimation of the peak flows at Jupia results in a moderate model efficiency of 0.7 and a positive bias of 3.5% (Table 1). The Iguazu River (station 4 in Fig. 4) shows similarities with the Uruguay River, with very irregular streamflow regimes and floods of short duration at any time of the year. The VIC model simulations reasonably match the observed seasonal variations; however, the model tends to underestimate the peak flows with a mean negative bias of 9%. Despite the underestimation, the simulations closely follow the high variation of the observed monthly hydrograph at the Estreito (Fig. 5c), with a high model efficiency of 0.84 (Table 1).

The behavior of the Paraná River at Posadas (station 5 in Fig. 4) represents the spatially integrated response of the upper Paraná. Observed runoff at Posadas was observed to have a smaller range in annual cycle of river discharge after about 1980 relative to the periods 1902–40 or 1930–80 (Genta et al. 1998; Camilloni and Barros 2000). The 21-yr (1979–99) VIC model simulations at Posadas show higher austral summer flow and lower winter season flow than the observations. The difference is most likely due to reservoir effects (which tend to reduce the summer maximum and increase the winter flows), which are reflected in the observed streamflow. Although the monthly simulated hydrograph does not agree well with the observed, there is a good agreement between the simulated and observed annual runoff (not shown), indicating that reservoir regulation might change the seasonality of streamflow, but they have negligible effects on yearly flows (García and Vargas 1996).

c. Paraguay River

The Paraguay River has a different rainfall–runoff response from the Uruguay and Paraná basins because of its extremely small main stem gradient (0.05 m km⁻¹) and the existence of a large area of the Pantanal wetlands (Fig. 1). The wide extent and low gradients of the Paraguay basin enhance evapotranspiration, resulting in a low runoff ratio of only 0.14. There is about a half-year lag between the discharge peak at the basin outlet and the austral summer precipitation in the upper Paraguay (Camilloni and Barros 2000). The simulated seasonal and monthly streamflow at Ladario (the outlet of Pantanal), are shown in Fig. 4 (station 6) and Fig. 5d. The discharge at Ladario exhibits only one hydrograph peak per year because of the low conveyance and discharge reduction in the Pantanal, with the maximum appearing in May. The simulations show a consistent pattern, with observations in the seasonal cycle after the adjustment of the velocity parameter in the offline VIC routing model (in most of the previous VIC model applications, the parameters in the routing model were not calibrated). The default value of the velocity in the routing model is 1–1.5 m s⁻¹ based on the suggestion in Lohmann et al. (1996). The default values work well for the basins with marked slope like the Uruguay and upper Paraná; however, the velocities are too high for the low relief Paraguay basin (the peak flow at Ladario would appear in March when using the velocity of 1 m s⁻¹). Therefore, we adjusted the velocity to 0.08 m s⁻¹ for the basin upstream of Ladario by a visual comparison between simulated and observed seasonal hydrographs.

There are very limited observed precipitation and temperature stations over the Paraguay basin, aside from the extreme northern part (Fig. 2). Neither the seasonal cycle nor the interannual variations in runoff at the outlet of the Paraguay basin (station 7 in Fig. 4) are well represented by the VIC model (not shown), although the mean annual runoff error is close to zero as a result of calibration. Aside from uncertainties in the model inputs, the Paraguay basin’s physical characteristics themselves pose some difficulties for rainfall–runoff simulations. In particular, the VIC model in general has been found to perform best in basins with pronounced topography and high runoff ratios than in the basins with flat topography and low runoff ratios (Su et al. 2005).

4. Water balance components

In this section, we examine the spatial fields and seasonal variability of P, E, and R, both for the major tributaries and the entire LPB by comparing the water fluxes from the VIC 21-yr offline simulations and the same variables represented by the ERA-40 reanalysis. Columns 1–3 in Table 2 summarize the expressions for the water balance terms used in this paper and the data sources and approaches from which the terms are derived. There are three P – E estimates: 1) computed P – E, calculated from atmospheric moisture balance using Eq. (1); 2) ERA-40 P – E, calculated from the ERA-40 analyzed P and E; and 3) VIC P – E, calculated from observed P and the VIC simulated E. We compared the three P – E estimates with each other and with observed runoff to investigate water balance closure and the agreement between atmospheric and land surface water
balances in the LPB. We also compared the $E$ simulations from the VIC model and ERA-40 reanalysis with the implied $E$ from observed $P$ and computed $P - E$. The observed $P$ in this analysis refers to the 21-yr daily precipitation dataset, which they derived from gauge observations and used to force the VIC model.

### a. Spatial fields

1) PRECIPITATION

Figure 6 displays spatial fields of annual mean precipitation over the LPB derived from gauge stations and ERA-40 reanalysis data for 1979–99. The general spatial features from observations include two maxima of $P$ (1600–2200 mm)—one over the central portion and one toward the northern boundary—and a dry region in the southwest (200–800 mm). The annual mean $P$ in the LPB shows decreasing trends from north to south and from east to west. These features are consistent with previous studies (Berbery and Barros 2002; Caffera and Berbery 2006) based on the CPC Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997). The northern region has the largest $P$ during summer [December–February (DJF)], whereas the spatial maximum over the central region is present during all seasons (not shown). Previous studies (Horel et al. 1989; Zhou and Lau 1998; Laing and Fritsch 2000; Velasco and Fritsch 1987; Vera et al. 2002; Berbery and Barros 2002) suggest that the precipitation regime over the northern region is related to the southernmost extension of the monsoon system, and the mesoscale convective systems and transient activity account for much of the total precipitation over the central region.

The ERA-40 $P$ roughly captures the maximum areas and the spatial pattern shown in gauge estimates. A questionable feature is the elongated maximum along the Andes (up to 2200 mm), which is not observed in the

gauge estimates and satellite estimates (Berbery and Barros 2002). Zeng (1999) found a similar problem along the Andes in the Amazon basin from the Goddard Earth Observing System-1 (GEOS-1) reanalysis and suggested that it was likely due to the model’s orographic enhancement of precipitation (e.g., Trenberth and Guillemot 1995). The effect is more obvious in the moisture convergence fields (computed $P - E$) as moisture divergence occurs over the front valley east of the Andes (Fig. 8c). Given the very sparse gauge network density in the western part of the basin, the gauge estimates in those regions are open to question as well.

2) EVAPOTRANSPIRATION

Figure 7 shows annual mean evapotranspiration from the VIC model, ERA-40 reanalysis, and implied $E$. Here $E$ from VIC (Fig. 7a) decreases from northeast to southwest from 1000–1400 mm to 200–600 mm. The VIC model has the highest $E$ values along the Paraguay River and areas defined as potential lakes/wetlands in Lehner and Döll (2004). The annual $E$ from ERA-40 (Fig. 7b) shows less spatial variation than the VIC estimates and is higher than the VIC $E$ almost everywhere in the LPB (by 13% for the entire basin; Table 2). The apparent overestimation of $E$ in ERA-40 has been recognized in previous studies over the Mississippi River, Arctic river basins, and other global river basins (Betts et al. 2003a,b; Hagemann et al. 2005; Su et al. 2006); it appears to be mostly attributable to the structure of the land surface scheme used in ERA-40 and the analysis increments that continually restore moisture fields to observed levels. On the other hand, ERA-40 appears to reasonably represent the strongest $E$ over the Paraguay basin, particularly over the upstream where there are large areas of wetlands (Pantanal).
The implied $E$ values are unrealistically high (1600 mm) over the upper Paraguay and the adjacent Paraná basin and the western boundary of the LPB (Fig. 7c). Both the fields of observed $P$ and the computed $P - E$ contribute to the large-scale patterns of implied $E$. The high values of implied $E$ appear to result from the negative computed $P - E$ (Fig. 8c).

3) RUNOFF

Figure 8 shows the fields of annual mean runoff simulated by the VIC and ERA-40 land surface models and the annual atmospheric moisture convergence (computed $P - E$) for 1979–99. The VIC $R$ (Fig. 8a) is high ($\sim$500–800 mm) across the Uruguay, upper Paraná, and the headwaters area of the Paraguay basin, with the maximum area of runoff ($\sim$900–1200 mm) in the central part of the LPB, where $P$ is also high (Fig. 6a). Low-runoff ($\sim$0–200 mm) regions include the western Paraguay basin and the west and south border, where runoff contributes very little to the flow of LPB. Because the VIC model is forced by the observed $P$ and is tuned to produce the observed streamflow at the outlets of the major tributaries (section 3), the VIC model may provide the most reliable geographic distribution of runoff, at least for the Uruguay and Paraná basins. Given the sparse rain gauge stations and issues noted above in areas of low relief, the VIC simulated $R$ might not be as realistic in the low-runoff regions.

The ERA-40 $R$ (Fig. 8b) shows roughly the same distributions of high and low runoff as the VIC $R$; however, the ERA-40 $R$ is generally lower than the VIC $R$ in the Uruguay and the upper Paraná basins (see also Table 2). The ERA-40 $R$ is extremely high (up to 1200 mm) in the western boundary (Andes Mountains), where the VIC $R$ is moderate (200–400 mm), and the computed $P - E$ is negative (Fig. 8c). Because of the lack of observations in these mountainous areas (with elevation up to 5000–6000 m) and the strong orographic enhancement in the ERA-40 reanalysis, large uncertainties exist in the $R$ estimates, both from the ERA-40 reanalysis and the VIC model.

Long-term $P - E$ from reanalysis atmospheric water balance has been used to study the continental discharge and river inflow to the world oceans (Dai and Trenberth 2002; Oki et al. 1995), although there can be considerable differences between $P - E$ and surface runoff. Trenberth et al. (2007) identified the major problems in $P - E$ derived from ERA-40 atmospheric water balance.
over land in the subtropics, including too strong evapotranspiration (exceeding the actual moisture supply in some cases), and thus large areas with negative $P - E$. The LPB is mostly located in tropical and subtropical regions. Figure 8c indicates that negative values of $P - E$ mostly appear in the Paraguay basin and the western and southern boundaries, where runoff is generally low. Our previous studies (Su et al. 2006) of Arctic river basins also indicated that the annual moisture convergence $P - E$ from ERA-40 tended to be negative in low-runoff regions. Here $P - E$ (Fig. 8c) corresponds reasonably with high-runoff areas in the central portion and

![Annual Avg. Evaporation, mm](image)

**Fig. 7.** Spatial fields of annual mean $E$ (mm) from the (a) VIC model, (b) ERA-40 reanalysis, and (c) atmospheric water budget estimates for LPB (1979–99).

![Annual Avg. Runoff, mm](image)

**Fig. 8.** Spatial fields of annual mean $R$ (mm) from the (a) VIC model, (b) ERA-40 reanalysis, and (c) atmospheric moisture convergence computed $P - E$ for LPB (1979–99).
northern boundary of the basin; however, the extremely high values (1200 mm) at the edge of the Andes Mountains might not be realistic.

b. Seasonal and interannual variations

To assess the seasonal and interannual variability of the water balance components derived from different datasets, the seasonal means and monthly time series of each component were spatially integrated over the three major subbasins (Uruguay, upper Parana, and Paraguay basins) and the entire LPB for the period 1979–99 (Figs. 9, 10).

1) PRECIPITATION

The upper Parana and Paraguay basins have a well-defined annual cycle of $P$ that peaks during austral summer (December–February) with a marked minimum in winter [June–August (JJA)], which is related to the South American monsoon system. On the other hand, the Uruguay basin shows a markedly irregular $P$ regime with only hints of larger $P$ during February–May and September–October. The annual cycle of the Uruguay $P$ can be explained by the precipitation regime over the upper part of the basin. Precipitation over the entire LPB exhibits a similar seasonal pattern to the upper Parana and Paraguay basins, indicating the predominant effect of the monsoon regime over the LPB.

The ERA-40 $P$ shows fairly consistent seasonal variations with the gauge-based estimates over all the subbasins except for the Uruguay, where the ERA-40 $P$ markedly underestimates the observations from late summer to early winter (February–June), resulting in 7% lower values than the gauge-based estimates (Table 2). Apparent underestimation by the ERA-40 $P$ was also observed over the upper Parana, particularly for the

![Fig. 9. Seasonal variability of water budget components over the Uruguay, upper Parana, Paraguay, and the entire LPB for the period 1979–99: (a) $P$, (b) $E$, (c) $R$, and (d) $P - E$ from observations, VIC model and ERA-40 reanalysis, and atmospheric moisture convergence.](image-url)
low-precipitation seasons (April–September), which were about 10% lower than the observation-based estimates. Given the relatively dense station coverage over the Uruguay and upper Paraná basins (Fig. 2a), the gauge-based estimates over these two basins should be accurate. The ERA-40 $P$ shows good agreement with observations in seasonal and monthly variations over the Paraguay and the entire LPB (Fig. 10a) as well, where the stations are sparse in large portions of those basins, indicating the smoothing and cancellations of errors in the $P$ estimates within such large basins.

2) EVAPOTRANSPIRATION

Because the VIC model is forced by observed $P$ and constrained by observed streamflow, the climatology of $E$ from VIC is arguably realistically estimated so long as the observed streamflow is well reproduced by the model and $P$ is accurate (Maurer et al. 2002). Here $E$ estimates from the ERA-40 are roughly consistent with those from the VIC model in the annual cycle and interannual variations, with strong $E$ occurring in warm seasons (October–March) and weak $E$ in cool seasons (April–September; Figs. 9b, 10b). However, the ERA-40 $E$ is consistently larger than the VIC $E$ over all basins, particularly from winter to early summer, which is not surprising for the reasons suggested earlier.

The approach of using residual estimates from atmospheric moisture convergence and observed precipitation provides an alternative for estimating regional $E$ (Ropelewski and Yarosh 1998; Yeh et al. 1998; Serreze et al. 2003; Su et al. 2006). However, the accuracy of the implied $E$ is highly dependent on the size of the area investigated, which can be reflected by the $E$ estimates in Fig. 9b. Large discrepancies exist between the implied $E$ and the VIC $E$ over the three subbasins, whereas the two estimates agree much more closely when integrated over the entire LPB. There is also good agreement in the interannual variations between the $E$ estimates from the VIC model and the atmospheric moisture budget over the entire LPB (Fig. 10b).

3) $P - E$

Seasonal variations of computed $P - E$, ERA-40 $P - E$, and VIC $P - E$ (Fig. 9c) exhibit similar seasonal patterns
over each basin, despite significant differences in annual means (Table 2). All three $P - E$ estimates are positive for all seasons over the Uruguay basin, indicating that the Uruguay basin is an atmospheric moisture sink.

For the Upper Parana, $E$ can exceed $P$ during cool and dry seasons (May–August). The computed $P - E$ (atmospheric moisture convergence) is slightly negative in May, July, and August ($-7$ to $-13$ mm), whereas the VIC $P - E$ is only $-5$ mm in July. Much larger negative values are present in the ERA-40 $P - E$ estimates for May through August ($-10$ to $-27$ mm), which corresponds to lower $P$ and higher $E$ in ERA-40 during those seasons (Figs. 9a,b).

For the Paraguay basin, both ERA-40 $P - E$ and VIC $P - E$ exhibit consistently large negative values during May through August ($-32$ mm in July). The computed $P - E$ has even larger negative values for April through August ($-24$ to $-54$ mm). The annual mean of $P - E$ estimates from ERA-40 and VIC are positive, whereas the annual mean of computed $P - E$ over the Paraguay basin is negative ($-78$ mm; see Table 2). Here $P < E$ during the dry season indicates that the Paraguay basin becomes a source of atmospheric moisture. This is plausible, given the flat topography of the Paraguay basin and the existence of a large area of wetlands, which enhance the rate of $E$ and result in $E > P$ during the season with low $P$. However, it is not reasonable that the Paraguay basin can act as a net source for moisture in the long-term mean, as the estimates based on ERA-40 atmospheric moisture convergence suggest. When integrated over the entire LPB, the three estimates of $P - E$ are more comparable (Fig. 10c), and the entire basin is a sink of moisture.

4) RUNOFF

The seasonal cycle of streamflow for the major tributaries of LPB based on observations and the VIC model simulations was discussed in section 3. The large differences between the annual cycle of ERA-40 $R$ and VIC $R$ in Fig. 9d are indicative of errors in ERA-40 runoff, particularly over the Uruguay basin where the VIC model reproduced the observed streamflow very well (Figs. 4, 5a). For instance, annual $R$ from ERA-40 is $33\%$ and $24\%$ lower than observations over the Uruguay and Upper Paraná basin, respectively, and $40\%$ higher over the Paraguay basin (Table 2). The poor performance of $R$ in ERA-40 in reproducing observed interseasonal and interannual variations has been noted in previous studies (Betts et al. 2003a,b; Hagemann et al. 2005; Su et al. 2006).

c. Long-term imbalances

Table 2 lists annual means of $P$, $E$, $P - E$, $R$, and nonclosure terms ($P - E - R$) in both VIC and ERA-40 over the three major subbasins and the entire LPB. Because the VIC model balances the surface water budget by construct, the nonclosure term in VIC is generally small (<1% of annual $P$), mostly reflecting the changes in surface storage of lakes and wetlands over the period of simulation.

The annual mean $P - E - R$ values in ERA-40 account for $3\%$–$5\%$ of annual ERA-40 $P$ for all the basins except for the Paraguay, where the imbalance ($-174$ mm) reaches $15\%$ of annual $P$. The ERA-40 soil moisture is available at four levels: 7, 21, 72, and 189 cm (Van den Hurk et al. 2000). On the basis of these four levels soil moisture, we derived the 21-yr (1979–99) average values of total soil moisture change in ERA-40, which are $-3.8$, $-0.8$, 1.3, and $-1.1$ mm for the Uruguay, upper Paraná, Paraguay, and the entire La Plata basins, respectively. These values are much smaller than the total surface imbalances in ERA-40 (Table 2). The imbalance in ERA-40 therefore appears to be mostly attributable to the analysis increment, which corresponds to artificial residual forcings included in the analysis water budget (Betts et al. 2003a,b). Those residual forcings are not part of the natural processes and are only implicitly included to force the analyses’ fluxes to close to observations. As discussed by Roads et al. (2002), although an overall goal of reanalysis data is to produce an analysis with small residuals and accurate estimates for each component of the budgets, there may not be a quick fix for these residual forcings, which are indicative of fundamental errors in the model physical parameterizations.

When the $P$ and $E$ fields from ERA-40 data are commensurate with the left-hand side of Eq. (1) computed from ERA-40 wind, moisture, and surface pressure fields, the dataset is said to be in “hydrologic balance.” Results in Fig. 9c and Table 2 indicate that the ERA-40 reanalysis is not in hydrologic balance. The imbalances between the ERA-40 $P - E$ and computed $P - E$ are $88\%$–$200\%$ over the subbasins (the largest imbalances are in the Paraguay basin), whereas the imbalance is about $12\%$ for the entire LPB. As mentioned earlier, the left-hand side of Eq. (1) is computed from analysis fields that are strongly linked to observations (although not independent of the ERA-40 land surface model). While the ERA-40 $P$ and ERA-40 $E$ are derived entirely from the data assimilation model, they have no direct relationship to the observed data. The insertion of artificial forcings used to prevent analysis model drift may exert large uncertainties on the ERA-40 $E$. Cullather et al. (2000) also found that ERA and NCEP–NCAR reanalysis data were not in hydrologic balance in the Arctic, and they suggested that the imbalance represents the transition from the observationally constrained initial conditions to a climate preferred by the model.
On the basis of Eq. (5), with perfect datasets and no additional sources of sinks of moisture, long-term means of atmospheric moisture convergence (computed $P - E$) and observed $R$ should be equal. The agreement between the computed $P - E$ and the observed $R$ is best over the Upper Parana, with an imbalance of 2%. Given the uncertainties in both computed $P - E$ and observed streamflow, we consider the atmospheric and surface water budgets to be well closed for the upper Parana basin. The computed $P - E$ is 28% more than the observed $R$ for the Uruguay basin. The computations of $P - E$ for larger basins tend to be more accurate as a result of the compensation of errors between subbasins (Rasmusson 1971). The relatively small size of the Uruguay basin (see Table 1) may increase the uncertainties in the integrated $P - E$ over the basin. The long-term mean of computed $P - E$ is unrealistically negative ($-78$ mm) over the Paraguay basin despite the large basin area ($1.1 \times 10^6$ km$^2$). The apparent errors in the computed atmospheric moisture convergence and the significant imbalance in the ERA-40 surface water all occur over the Paraguay basin where there is strong evapotranspiration due to the existence of the Pantanal and its flat topography (see section 3c). It is not clear whether the Paraguay basin’s hydrometeorology and its physical characteristics are related to those apparent errors.

5. Precipitation recycling

The amount of $P$ falling on a region can be partitioned into $P_m$, precipitation associated with water vapor advected into the region by air mass motion, and $P_m$, precipitation associated with water that evaporates from the surface of the region and falls within the same region. The contribution of local evapotranspiration to local precipitation is termed precipitation recycling, which is quantified by the precipitation recycling ratio $\rho$, defined as $P_m/P$ (Brubaker et al. 1993; Eltahir and Bras 1994, 1996; Trenberth 1998, 1999). There is considerable interest in the precipitation recycling in the LPB given the existence of the Pantanal wetland in the basin (Berbery et al. 2005). In this section we investigate moisture recycling over the LPB by estimating its precipitation recycling ratio using the ERA-40 reanalysis data. Following Trenberth (1998, 1999), we employ the approach of Brubaker et al. (1993). This is given as

$$\rho = \frac{P_m}{P} = \frac{EL}{PL + 2F},$$

where $L$ is the length scale of the domain and $F$ is the average horizontal moisture flux ($\text{kg m}^{-1} \text{s}^{-1}$) through the domain. The advantage of formulation (6) is that it allows for the mapping of a recycling ratio at every point as a function of length scale $L$. Trenberth (1998, 1999) discusses the assumptions required by this empirical way of computing recycling and suggests that it may be more appropriate to think of the results as providing an index of recycling.

Trenberth (1999) provide global seasonal maps of $\rho$ with a length scale of 500 km. For comparison purposes, we used the same length scale (500 km) for the LPB. For $P$ and $E$ in Eq. (6), we used the observed $P$ (which is used to force the VIC model) and the VIC simulated $E$. Our calculation of $F$ used the ERA-40 vertically integrated moisture fluxes at a reduced Gaussian grid with approximately uniform 125 km for 1979–99. All the $P$, $E$, and $F$ were smoothed to a 500 km $\times$ 500 km grid.

Figure 11 shows the recycling ($\rho$) over the LPB for seasonal mean conditions for $L = 500$ km. There are notable seasonal and spatial variations of recycling $\rho$ over the LPB. The maximum values (5%–7%) occur in southern summer (DJF) for the entire basin and in southern autumn [March–May (MAM)] for the very northeast LPB (with the highest in north Paraguay for both seasons). Here $\rho$ is mostly in the range of 0%–3% during southern winter (JJA) and 3%–5% during southern spring [September–November (SON)]. Despite the strong seasonality of the recycling $\rho$, there is one exception: $\rho$ is high (5%–7%) for all seasons over the north Paraguay basin where the Pantanal exists. Correlation analysis reveals that the spatial variability of $\rho$ over the LPB is mostly tied to $E$. The correlation coefficient ($R^2$) between $\rho$ and $E$ for the four seasons ranges from 0.42 to 0.57, whereas the relationships between $\rho$ and either $P$ or $F$ are weak for all seasons. None of the $R^2$ values exceed 0.3. Here $\rho$ estimates in Trenberth (1999) are generally larger (10%–20%) for the southern parts of South America (south of 10°S, which includes the LPB) for the same $L = 500$ km in all seasons except southern winter. One explanation is that the $E$ in the calculation of $\rho$ in Trenberth (1999) was from the NCEP reanalysis where the moisture budget nonclosure can be large. Previous studies have shown a large overestimation of $E$ in both NCEP and ECMWF reanalyses relative to the VIC model over the Mississippi River basin (Maurer et al. 2001; Roads et al. 2003), which are due, at least in part, to nonclosure in the reanalysis.

6. Conclusions

We evaluated the spatiotemporal variability of the water balance terms of the LPB using the 21-yr offline VIC model simulations, ERA-40 reanalysis, and inferences obtained from a combination of the two. The components of the water budget exhibit different behavior
The annual cycle of streamflow is determined by the physical characteristics of the subbasin and the primary precipitation regime on the locations. The upper Paraná and Paraguay basins have a well-defined annual cycle of \( P \), whereas the Uruguay basin shows a markedly irregular \( P \) regime. The estimates of \( P - E \) from different approaches (VIC \( P - E \), ERA-40 \( P - E \), and computed \( P - E \)) show that the Uruguay basin and the La Plata as a whole behave as atmospheric moisture sink (\( P > E \) for all the seasons). However, the Paraguay basin shows strong negative \( P - E \) values during interseasonal to interannual variations over the three major subbasins.

**FIG. 11.** The recycling (%) for seasonal mean conditions, computed from Eq. (6) for \( L = 500 \) km, and using \( P \) from gridded observations (which are used to force the VIC model), \( E \) from VIC simulations, and \( F \) from ERA-40 reanalysis.
April through August and acts as a net source of moisture in those seasons. For the upper Paraná, $E$ can slightly exceed $P$ during cool and dry seasons.

The annual means and monthly time series of ERA-40 $P$ are in good agreement with gauge observations over the entire LPB and its subbasins (except for the Uruguay). The ERA-40 reanalysis could be a useful resource for depictions of seasonal and monthly variations of precipitation for the LPB. However, the overestimation in $E$ and significant errors in $R$ suggest a need for improvements in the ECMWF land surface model and/or the analysis scheme.

The $E$ estimates from the VIC model agree well with those inferred from the ERA-40 atmospheric moisture budget (as contrasted with those computed directly by the ECMWF land surface scheme) in both seasonal and interannual variations over the entire LPB, although large discrepancies exist between the two $E$ estimates over the three subbasins because of their smaller sizes. Here $P - E$ computed via the atmospheric moisture budget (from analyzed wind, moisture, and surface pressure, which are closely related to observations) provided better estimates of the climatology of $E$ in the LPB than did the values computed directly by the ECMWF land model within the reanalysis.

The ERA-40 moisture budget does not balance for either the atmosphere or the land surface over the LPB. Our estimates show a basin-wide imbalance of about 12% between the computed $P - E$ and ERA-40 $P - E$ over the entire LPB, and the imbalances are as large as 88%–200% over the subbasins, with the largest imbalances occurring in the Paraguay basin. The long-term mean of atmospheric moisture convergence (computed $P - E$) shows good agreement with observed $R$ for the upper Paraná (with the imbalance of 2%), while the imbalance is 28% for the Uruguay basin, possibly because of its small basin size. Major problems appear over the Paraguay basin, which has a negative long-term mean atmospheric moisture flux convergence, which is not physically realistic.

The computed precipitation recycling in the LPB (for $L = 500$ km) exhibits strong seasonal and spatial variations with ratios of 0%–3% during the cold season and 5%–7% during the warm season. The north Paraguay basin shows relatively high recycling ratios (5%–7%) for all seasons, which may indicate the effects of the Pantanal. The recycling results in the LPB provide an indication of the importance of land surface processes on the hydrologic budget.

Acknowledgments. The authors thank Vicente R. Barros, Carlos E. M. Tucci, and Ernesto Hugo Berbery for providing observed streamflow data in the La Plata basin and Joey Comeaux for help getting ERA-40 data. We also thank Kevin E. Trenberth for his advice in the recycling analysis, and William Crosson and two anonymous reviewers for their comments, all of which have improved the manuscript. This work was supported by National Science Foundation Grant EAR-0450209 and by the National Aeronautics and Space Administration Grant NNG04GD12G to the University of Washington.

REFERENCES


