Evaluation of TRMM Multisatellite Precipitation Analysis (TMPA) and Its Utility in Hydrologic Prediction in the La Plata Basin

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ABSTRACT

Satellite-based precipitation estimates with high spatial and temporal resolution and large areal coverage provide a potential alternative source of forcing data for hydrological models in regions where conventional in situ precipitation measurements are not readily available. The La Plata basin in South America provides a good example of a case where the use of satellite-derived precipitation could be beneficial. This study evaluates basinwide precipitation estimates from 9 yr (1998–2006) of Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; 3B42 V.6) through comparison with available gauged data and the Variable Infiltration Capacity (VIC) semidistributed hydrology model applied to the La Plata basin. In general, the TMPA estimates agreed well with the gridded gauge data at monthly time scales, most likely because of the monthly adjustment to gauges performed in TMPA. The agreement between TMPA and gauge precipitation estimates was reduced at daily time scales, particularly for high rain rates. The TMPA-driven hydrologic model simulations were able to capture the daily flooding events and to represent low flows, although peak flows tended to be biased upward. There was a good agreement between TMPA-driven simulated flows in terms of their reproduction of seasonal and interannual streamflow variability. This analysis shows that TMPA has potential for hydrologic forecasting in data-sparse regions.

1. Introduction

Precipitation is the most important atmospheric input to land surface hydrology models, and therefore accurate precipitation inputs are essential for reliable hydrologic prediction. However, in many remote parts of the world and particularly in developing countries, ground-based precipitation measurements are either sparse or nonexistent, mainly because of the high cost of establishing and maintaining infrastructure. For rivers that cross international boundaries, inconsistencies in instrumentation and administrative limitations to data access further hamper the effective use of hydrology models in support of reliable flood and drought diagnosis and prediction. Both of these limitations are true for the La Plata basin, which covers parts of five South American countries (Fig. 1; Mechoso et al. 2001; La Plata Basin Regional Hyroclimate Project 2005). Coverage of the La Plata basin by surface networks is highly variable; eastern portions of the basin in Brazil and Uruguay have relatively dense networks, and most of the rest of the basin is poorly represented by surface gauges (Fig. 2). Furthermore, even in those locations where surface networks appear to be relatively dense, station records often are sparse, with single missing days and longer gaps spread throughout the time series (B. Liebmann and D. Allured 2007, personal communication).

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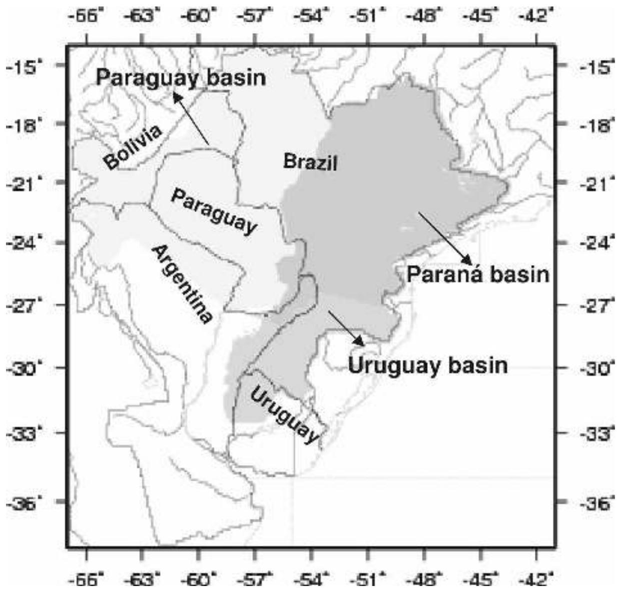

FIG. 1. The La Plata basin and the five South American countries through which it drains. Shaded areas represent the three major subbasins of La Plata: the Paraná, Uruguay, and Paraguay basins.

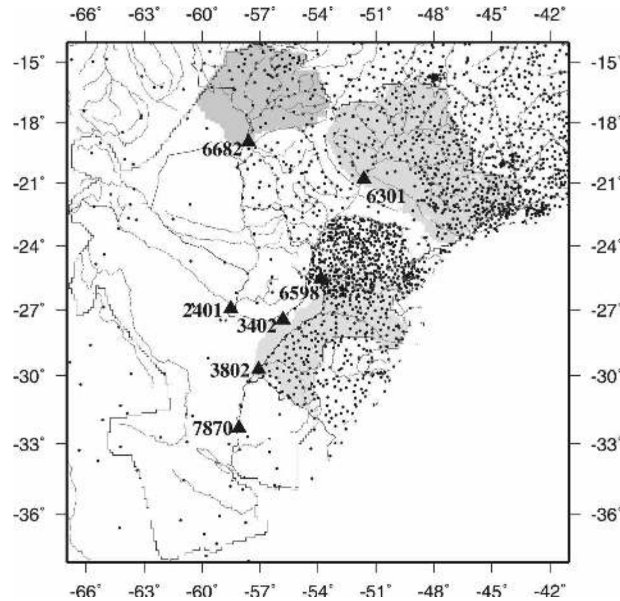

FIG. 2. Rain gauge distribution in 2005. Triangles are streamflow stations. Numbers are station IDs and also represent the basin upstream of the station. Shaded areas highlight four subbasins with relative dense station coverage.

Satellite-based precipitation estimates with high spatial and temporal resolution and large areal coverage provide a potential alternative source of forcing data for hydrological models in regions where conventional in situ precipitation measurements are not readily available. The La Plata basin in South America provides a good example of a case where the use of satellite-derived precipitation could be beneficial, and this is our motivation for selecting it as a case study.

In the past several years, a number of quasi-global high-resolution satellite precipitation products have been developed (e.g., Turk and Miller 2005; Joyce et al. 2004; Kidd et al. 2003; Sorooshian et al. 2000). In 1997, the Tropical Rainfall Measuring Mission (TRMM) satellite was launched. The objective of the TRMM mission was to provide accurate global tropical precipitation estimates by using a unique combination of instruments designed purely for rainfall observation (Simpson et al. 1996; Kummerow et al. 1998, 2000). In the 10 yr since the launch of TRMM, a series of high-resolution, quasi-global, near-real-time, TRMM-based precipitation estimates has been available to the research community (http://daac.gsfc.nasa.gov/data/datapool/TRMM/01_Data_Products/02_Gridded/index.html).

The proposed Global Precipitation Measurement (GPM) mission, which would be the successor to the TRMM, envisions providing global precipitation products with temporal sampling rates ranging from 3 to 6 h and a spatial resolution of 25–100 km^2 (Smith et al. 2007; see also http://gpm.gsfc.nasa.gov). A major GPM science objective is to improve prediction capabilities for floods, landslides, freshwater resources, and other hydrological applications. However, given the perceived retrieval errors in the satellite-based precipitation estimates (Huffman 1997; Bell and Kundu 2000; McCollum et al. 2002; Steiner et al. 2003; Hossain and Anagnostou 2004; Hong et al. 2006), the suitability of satellite-derived precipitation for hydrological prediction remains an open issue. Hossain and Lettenmaier (2006) argue that conventional assessment frameworks for satellite precipitation estimates are inadequate for GPM hydrologic purposes such as flood prediction. They stress that hydrological and land surface models need to be included in the assessment framework for GPM products.

Numerous satellite precipitation validation studies (e.g., "ground truthing") have been implemented with a view to providing both users and providers information about the quality of satellite precipitation estimates (Krajewski et al. 2000; Adler et al. 2001; McCollum et al. 2002; Gottschalck et al. 2005; Brown 2006; Ebert et al. 2007). Comparatively little work has been done to evaluate the suitability of existing satellite precipitation products as input for hydrologic models. Yilmaz et al. (2005) investigated the use of the Precipitation Estimation from Remotely Sensed Information using Artificial

Neural Networks (PERSIANN) satellite precipitation algorithm (Sorooshian et al. 2000) in streamflow forecasting with a lumped hydrologic model over several medium-size basins in the southeastern United States. Artan et al. (2007) evaluated a satellite rainfall product for streamflow modeling with a spatially distributed hydrologic model over four subbasins of the Nile and Mekong Rivers. Both studies demonstrated improved performance of remotely sensed precipitation data in hydrologic modeling when the hydrologic model was calibrated with satellite data. Other studies have been conducted either over very small basins (Hossain and Anagnostou 2004) or with satellite products that are not widely available (Tsintikidis et al. 1999; Grimes and Diop 2003; Wilk et al. 2006).

Given the likely greater availability of satellite precipitation data at fine spatial scales in the next few years, the anticipated availability of GPM data for hydrologic applications, and the global decline of in situ networks for hydrologic measurements (Stokstad 1999; Shiklomanov et al. 2002), there is currently an urgent need to better assess the utility of these satellite products for hydrologic prediction. In this study, we evaluate precipitation estimates from 9 yr (1998–2006) of TRMM Multisatellite Precipitation Analysis (TMPA) (Huffman et al. 2007) with available gauged data and a semidistributed hydrology model over the La Plata basin. Our objective is to assess the effectiveness of TMPA for streamflow forecasting. This initial hydrologic effectiveness assessment should provide useful insights into the potential utility of GPM products for hydrologic prediction in large river basins.

2. Data sources and methodology

a. La Plata basin

The La Plata basin, with an area of 3.2×10^6 km^2, is the fifth-largest river basin in the world and is second only to the Amazon in South America. It drains parts of five South American countries (Argentina, Brazil, Paraguay, Uruguay, and Bolivia; Fig. 1), and plays a key role in the economies, water resources, agriculture, energy production, and transportation of the region. The La Plata basin spans about 24° of both latitude and longitude (38°–14°S, 67°–43°W) and covers a variety of landscapes and hydroclimatologies (Mechoso et al. 2001). The mean annual rainfall varies from 1800 mm in the maritime uplands along the Brazilian coast to 200 mm along the western boundary of the basin. The La Plata River has three large tributaries, the Paraná, Paraguay, and Uruguay Rivers (Fig. 1). Precipitation station density is highest in the Paraná and Uruguay basins, and the station coverage is very poor in the Paraguay and lower La Plata basins (Fig. 2). Large parts of the Uruguay and the middle and lower Paraná margins are frequently subject to extended floods, which cause considerable damage (Anderson et al. 1993; Camilloni and Barros 2003; Camilloni 2005). Improved flood forecasts could have considerable practical benefit, and given the unequal distribution of surface gauges, there appears to be potential for the use of satellite precipitation estimates in flood forecasting.

b. TMPA

TMPA is a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales (0.25° × 0.25° and 3-hourly; Huffman et al. 2007). The goal of TMPA is to provide the "best" estimate of precipitation in each grid box at each observation time. TMPA has been computed for the entire TRMM period and is available both in real time (January 2002–present) and as a postprocessed product (January 1998–present), based on calibration by the TRMM Combined Instrument (TCI) and TRMM Microwave Imager (TMI) precipitation products, respectively. The real-time and retrospective data are referred to as the RT and research products, respectively. The research product system has been developed as the version 6 algorithm for the TRMM operational product 3B42 (3B42 V.6).

Huffman et al. (2007) presented two important differences between the real-time and research products. First, the RT product uses TMI precipitation as the calibrator and the research product (3B42 V.6) uses the TCI, which is considered to be better but is not available in real time. Second, the research product rescales the monthly sums of the 3-hourly fields to a monthly gauge analysis, but such a rescaling is not available in real time. The Climate Assessment and Monitoring System (CAMS) 0.5° × 0.5° monthly gauge analysis is used to adjust the initially processed (IP) TMPA estimates; the Global Precipitation Climatology Center (GPCC) 1.0° × 1.0° monthly monitoring product is used to adjust the reprocessed (RP) TMPA (D. Bolvin 2007, personal communication). Currently, the RP TMPA begins 1 January 1998 and ends March 2005. The IP TMPA starts in April 2005 and continues to the present. The gauge adjustment only applies to the research product; the real-time TMPA is currently not corrected. The final TMPA product is the 3B42 V.6, with a 0.25° × 0.25° spatial resolution and 3-hourly time step (0000, 0300, . . . 2100 UTC) within the global latitude belt 50°S to 50°N. Daily TMPA estimates are accumulations of the 3-hourly values from 1200 to 1200 UTC. In this paper, we mainly evaluate the TMPA research product 3B42 V.6 for the entire TRMM period (1998–2006).

c. Hydrology model and observation inputs

The Variable Infiltration Capacity (VIC) model (Liang et al. 1994, 1996) was used to evaluate the potential use of TMPA in streamflow forecasting in the La Plata basin. The VIC model is a grid-based land surface scheme that parameterizes the dominant hydrometeorological processes taking place at the land surface–atmosphere interface. The model was designed both for inclusion in the general circulation models (GCMs) as a land–atmosphere transfer scheme and for use as a stand-alone macroscale hydrology model. The model solves both surface energy flux and water balances over a grid mesh. The VIC model uses a mosaic representation of land cover and a subgrid parameterization for infiltration, which accounts for subgrid-scale heterogeneities in land surface hydrologic processes. The soil column is composed of three soil layers, which allows the representation of the rapid dynamics of soil moisture movement during storm events and the slower deep interstorm response, which is controlled by the bottom layer. The VIC model uses the variable infiltration curve (Zhao et al. 1980) to account for the spatial heterogeneity of runoff generation. It assumes that surface runoff from the upper two soil layers is generated by those areas for which precipitation, when added to soil moisture storage at the end of the previous time step, exceeds the storage capacity of the soil. The formulation of subsurface runoff follows the Arno model conceptualization (Todini 1996). The VIC model has been widely used in hydrologic modeling and streamflow forecasting over continental or global river basins (Nijssen et al. 2001; Maurer et al. 2002; Su et al. 2005; Wood and Lettenmaier 2006). The reader is referred to Nijssen et al. (1997) for details and examples of its application to large river basins.

The VIC model was implemented over the La Plata basin at a spatial resolution of 0.125°. The model domain consists of 18 641 computational grid cells. A 0.125° × 0.125° river network based on a 1-km digital elevation model (DEM) was developed over the entire La Plata basin for purposes of defining the model's river routing scheme using the method of Lohmann et al. (1996, 1998), which takes daily VIC surface and subsurface runoff as input to obtain model-simulated streamflow at the outlets of the study basins.

The meteorological input data for the VIC model include daily precipitation, maximum temperature (T_{max}), minimum temperature (T_{min}), and wind speed.

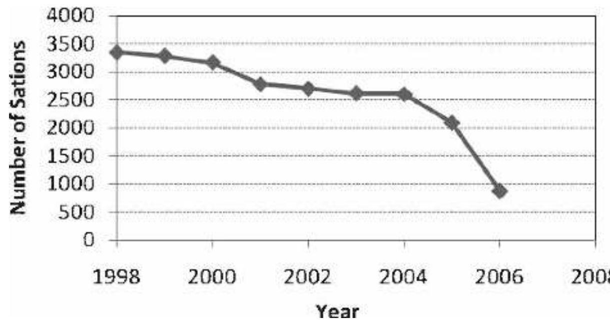

FIG. 3. Numbers of precipitation gauge stations used to produce the 0.25° gridded data for the La Plata basin for 1998–2006.

Observed daily precipitation for 1998–2006 was from South American gridded daily precipitation, which was constructed from daily meteorological stations (Liebmann and Allured 2005). Daily gridded precipitation for South America on 1° and 2.5° grids is available on the Web (http://www.cdc.noaa.gov/people/brant.liebmann/south_america_precip.html). At our request, Drs. Liebmann and Allured produced a high-resolution gridding (0.25°) specifically for the La Plata basin, which they derived directly from the daily station data. The gridded fields were constructed by averaging all available stations within a specified radius of each 0.25° grid point. If there were no station observations within the sampling radius, a missing value was assigned to that grid point. The 0.25° gridded data were then interpolated to 0.125° grids (by us) using the SYMAP method [Shepard (1984); also applied by Nijssen et al. (2001) and Maurer et al. (2002)], which uses the weighted average of all records in the neighborhood of a grid cell. We acknowledge that the spatial interpolation of the 0.25° gridded data inevitably lead to uncertainties in data-sparse regions. Figure 2 shows the spatial distribution of rain gauges in 2005. The rain gauge information was provided by Drs. Liebmann and Allured, together with the 0.25° gridded data. The number of stations used for gridding is different for each year (Fig. 3), but generally the spatial pattern is similar to 2005. The number of rain stations ranges from about 2000–3400 for the years 1998–2005, with a significant drop in 2006 (only 875 stations), probably because not all station records had been updated.

There almost certainly is some overlap of gauges between the daily gridded precipitation for South America that we used for model simulations and the monthly gauge analysis used to adjust the TMPA, although they are different datasets. Unfortunately, detailed information about the gauges used in the GPCC and CAMS products that are used to adjust the TMPA was not available to us.

Daily wind speed and temperature observations are very limited in the La Plata basin. Therefore, the daily 10-m wind speed, $T_{\max}$, and $T_{\min}$ fields for 1998–2006 were obtained from NCEP–NCAR reanalysis (Kalnay et al. 1996). Downward solar and longwave radiation and surface humidity were estimated from the daily temperature and temperature range using methods described in Maurer et al. (2002). All the forcing data were eventually interpolated to 0.125° grids. Soil texture information and soil bulk densities were derived from the 5-min Global Soil Data Task (2000). Vegetation types were obtained from the University of Maryland's (UMD's) 1-km Global Land Cover product (Hansen et al. 2000), which has a total of 14 different land cover classes. The observed streamflows used to validate the model results were partly provided by the Brazilian Water Resources Agency (Agência Nacional de Águas; http://hidroweb.ana.gov.br) and partly by the Argentine Department of Hydrology.

d. Performance indicators

The primary objective of this study is to evaluate the TMPA product in comparison with gauge-derived estimates. Nine years of basin-averaged precipitation from TMPA and gauge estimates were compared at both daily and monthly time scales. To evaluate streamflow prediction implications of the two datasets, the VIC model was forced by the daily TMPA and gauged precipitation over the entire La Plata basin. The simulated streamflow results were compared with each other and with available streamflow observations. Several statistical criteria were used to evaluate the precipitation estimates and streamflow simulations. The quantitative accuracy of satellite precipitation estimations was assessed by normalized root-mean-square error (Nrmse), correlation coefficient (R^2), and bias (BIAS). The VIC model performance evaluations were based on visual inspection, bias (mean differences), and the Nash–Sutcliffe coefficient of efficiency (NSE). These criteria are defined as follows:

$$\text{Nrmse} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_{s_i} - P_{g_i})}}{\frac{1}{n}\sum_{i=1}^{n}P_{g_i}}, \quad (1)$$

$$\text{BIAS} = \frac{\sum_{i=1}^{n}(P_{s_i} - P_{g_i})}{\sum_{i=1}^{n}P_{g_i}} \times 100\% \quad \text{and} \quad (2),$$

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(Q_{o_i} - Q_{s_i})^2}{\sum_{i=1}^{n}(Q_{o_i} - \overline{Q_o})^2}\right], \quad (3)$$

where P_s and P_g denote satellite and gauge basin-wide precipitation estimates, Q_s and Q_o are simulated and observed streamflow; $\overline{Q_o}$ is the observed mean annual runoff, and n is the number of daily or monthly precipitation or streamflow pairs in the analysis.

For quantitative verification of the daily TMPA accumulations in detecting rainy events at different precipitation thresholds over different basins, the frequency bias index (FBI), probability of detection (POD), false alarm ratio (FAR), and equitable threat score (ETS) were computed, based on a 2 × 2 contingency table [*a*: satellite yes, observation yes; *b*: satellite yes, observation no; *c*: satellite no, observation yes; and *d*: satellite no, observation no; Wilks 1995). All these indicators were calculated based on basin average precipitation. The FBI [$=(a + b)/(a + c)$] is the ratio of the number of estimated to observed rain events; it can indicate whether there is a tendency to underestimate (FBI $<$ 1) or overestimate (FBI $>$ 1) rainy events. It ranges from 0 to infinity with a perfect score of 1. The FAR [$=b/(a + b)$] measures the fraction of rain detections that were actually false alarms. It ranges from 0 to 1 with a perfect score of 0. The POD [$=a/(a + c)$] gives the fraction of rain occurrences that were correctly detected. It ranges from 0 to 1 with a perfect score of 1. The ETS [$=(a - H_e)/(a + b + c - H_e)$] measures the fraction of observed and/or detected rain that was correctly detected, adjusted for the number of hits H_e that could be expected due purely to random chance, where $H_e = (a + c)(a + b)/N$ and N is the total number of estimates. A perfect score for the ETS is 1. The ETS is commonly used as an overall skill measure by the numerical weather prediction community, whereas the FBI, FAR, and POD provide complementary information about bias, false alarms, and misses. To evaluate the skill of the daily TMPA estimates for light and heavy rainfall events, the FAR, FBI, POD, and ETS were calculated for precipitation thresholds of 0.1, 0.5, 1, 2, 5, 10, and 20 mm day^{-1}.

3. Evaluation of satellite precipitation estimates

In this study, TMPA was evaluated at both daily and monthly time scales for a 9-yr evaluation period from 1998 to 2006. The evaluation aims to assess the skill of the satellite estimates in detecting the amount and timing of rainy events at basin scales and to provide some

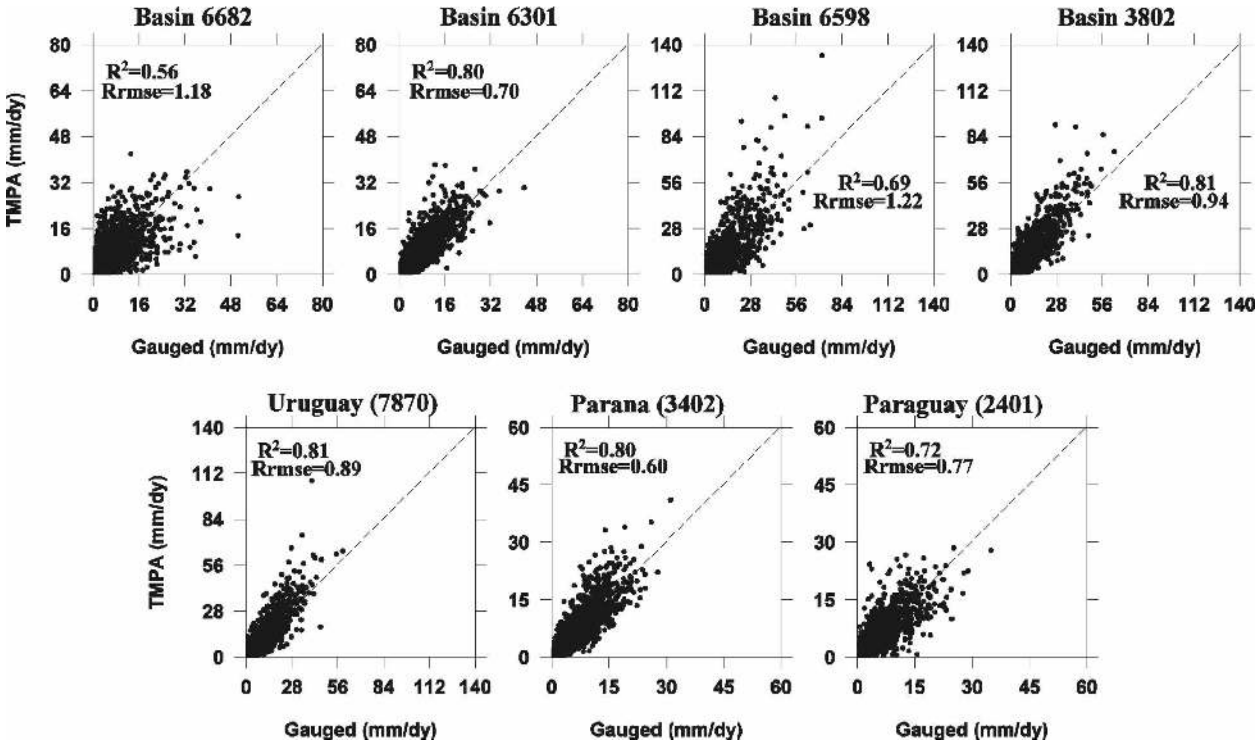

FIG. 4. Scattergrams of daily basin-averaged precipitation from TMPA and gauged estimates over seven subbasins in the La Plata basin for January 1998–August 2006.

information about the accumulated precipitation errors.

a. Daily estimates

The dots shown in Fig. 2 are rain gauge stations, and the triangles are stream gauge stations. The corresponding stream station numbers also represent the basins upstream of those stations. Four subbasins (6682, 6301, 6598, and 3802) with relatively dense rain gauge coverage are highlighted in Fig. 2. The basins upstream of stations 2401, 3402, and 7870 are the three major tributaries of the La Plata, the Paraguay (2401), Paraná (3402), and Uruguay (7870), respectively. Precipitation evaluations were focused on the four highlighted subbasins and the three major tributaries.

The scatterplots in Fig. 4 result from daily basin-averaged precipitation estimates from gauge and TMPA for the period January 1998–August 2006. The results show significant correspondence between the two daily estimates for almost all the basins with R^2 of 0.56–0.81 and Nrmse of 0.6–1.22 (Table 1), with basin 6682 having the worst agreement ($R^2 = 0.56$). There are a number of high-rain-rate days (>56 mm day^{-1}) on which the precipitation is considerably higher for TMPA relative to the gauge product, particularly over the Uruguay (3802, 7870) and Paraná basins (6598). In general, the scatterplots for the entire Uruguay (7870), Paraná (3402), and Paraguay (2401) show less scatter and lower Nrmse than their upstream tributaries, despite the large areas with sparse rain gauges (Fig. 2), indicating greater smoothing of precipitation variation and errors with the increase in upstream area (Nijssen and Lettenmaier 2004).

Daily time series of precipitation over each basin (not shown) indicate that the TMPA and gauge estimates agree on the occurrence of most daily precipitation events at basin scale, although the TMPA tends to overestimate most of the high rain rates.

Figure 5 shows the verification results for FBI, FAR, POD, and ETS for the four subbasins highlighted in Fig. 2 for the period 1 January 1998–31 August 2006. The performance of the satellite data varies among the four basins. Over basin 6301, both TMPA and the gridded rain gauge product detect almost the same frequency of rain events for thresholds up to 5 mm with FBI close to one (Fig. 5a), although there is an increasing overestimation of the frequency of rain events at all thresholds greater than 5 mm. The frequency of rain events is overestimated by the satellite at all thresholds for basin 6682 (FBI > 1). For basins 6598 and 3802, FBI is smaller than 1 at thresholds less than 5 mm but more than 1 for thresholds greater than 20 mm.

TABLE 1. Statistical summary of the comparison between TMPA and gauged precipitation estimates over seven subbasins in La Plata for January 1998–August 2006.

			Daily		Monthly			Mean rain rate (mm day^{-1})		Conditional rain rate (>0.5 mm day^{-1})	
Basin ID	River/station	Drainage area (km^2)	R^2	Nrmse (%)	R^2	Nrmse (%)	BIAS (%)	Gauged	TMPA	Gauged	TMPA
6682	Paraguay/Ladario	459 990	0.56	118	0.95	23	13	3.39	3.81	6.09	6.52
6301	Parana/Jupia	478 000	0.80	70	0.99	13	8	3.78	4.07	6.20	6.87
6598	Iguazu/Estreito	62 236	0.69	122	0.90	17	3	4.96	5.11	8.43	10.98
3802	Uruguay/Paso de los Libres	189 300	0.81	94	0.95	16	10	4.83	5.32	7.95	10.32
7870	Uruguay/Concordia	240 000	0.81	89	0.96	14	10	4.63	5.08	7.52	9.34
3402	Parana/Posadas	975 000	0.80	60	0.98	10	6	3.96	4.19	5.51	6.16
2401	Paraguay/Bermejo	1 100 000	0.72	77	0.97	12	−1	3.02	2.99	4.69	4.76

Basins 3802, 6301, and 6598 show very low values of FAR (<0.1) for thresholds up to 2 mm (Fig. 5b), with a roughly linear increase at thresholds greater than 5 mm, reaching values of 0.37–0.58 for precipitation thresholds greater than 20 mm. Basin 6682 provides consistently worse scores of FAR than the other three basins for all the thresholds.

Rain occurrence was best detected for thresholds of 0.1–2 mm for the two northern basins 6682 and 6301 (with POD scores of 0.85–0.93), and the skill drops rapidly with increasing precipitation thresholds, to as low as 0.36–0.63 (Fig. 5c). The two central basins (6598 and 3802) show lower POD scores (0.71–0.84) than the two northern basins for the thresholds less than 2 mm; however, POD does not change much with the increase of precipitation thresholds.

Figure 5d shows the ETS scores for the different subbasins for a range of precipitation thresholds. For the two northern basins (6301 and 6682), the observed rainy events were best detected at thresholds less than 2 mm, with ETS scores of 0.55–0.75, while the ETS deteriorated rapidly to 0.18–0.32 with the increasing precipitation thresholds. The satellite estimates show better performance over basin 6301 than basin 6682, which is consistent with the results from FBI, FAR, and POD. For the two central basins (6598 and 3802), the ETS only shows minor changes for thresholds from 0.5 to 20 mm (with ETS from 0.51 to 0.66).

Our general conclusion is that for the two northern basins (6301and 6682), the TMPA estimates perform well for low and medium precipitation thresholds (0.1–5 mm). However, the satellite estimates tend to

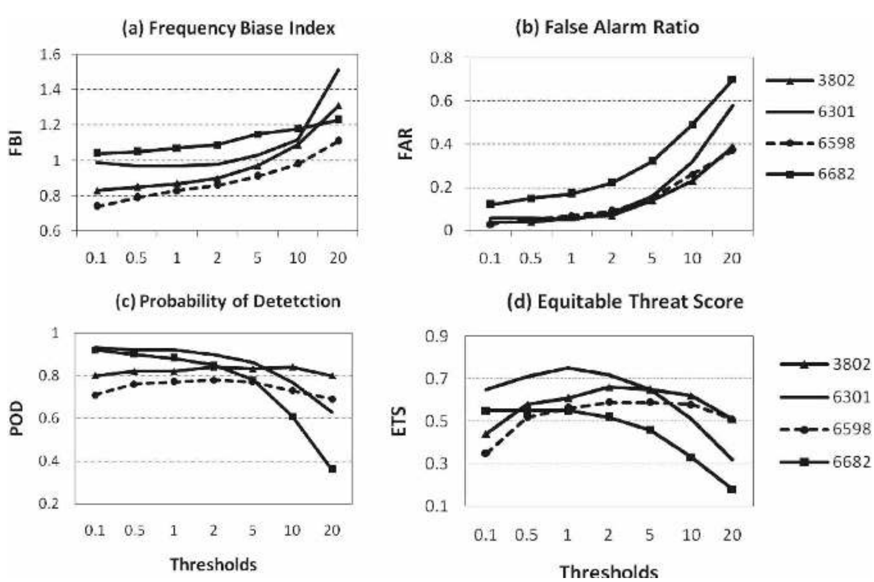

FIG. 5. (a) FBI, (b) FAR, (c) POD, and (d) ETS, all calculated for seven daily precipitation thresholds (mm day^{-1}) over four subbasins in La Plata.

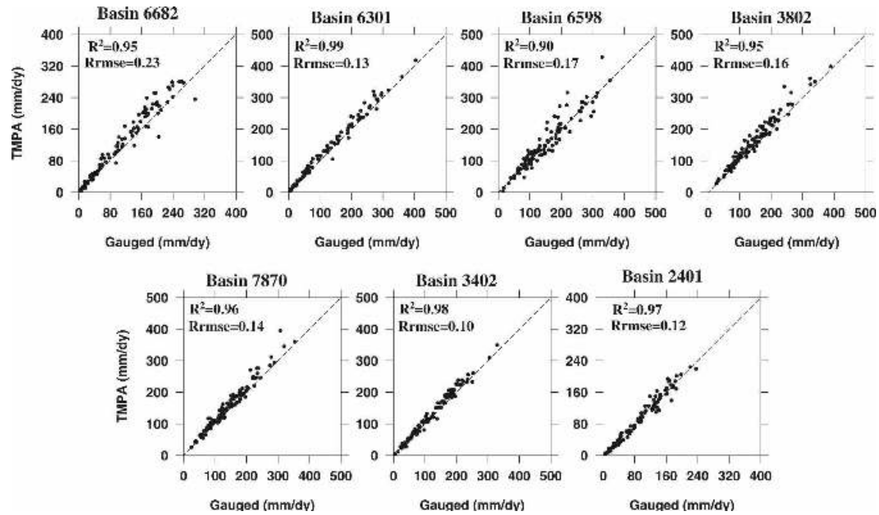

FIG. 6. Same as Fig. 4, but for monthly basin-averaged precipitation.

overestimate the frequency of rain events relative to the gauge estimates and show low POD and ETS and high FAR with the increase of precipitation thresholds. Katsanos et al. (2004) examined the performance of the early version of the RT TMPA product with daily gauged data in the eastern Mediterranean region. They found that the RT TMPA performed best for low and medium precipitation thresholds but was biased upward for the high precipitation rates, a finding which is consistent with our results in basins 6301 and 6682. The two central basins (6598 and 3802) also show significant increasing values of FAR and FBI with the increase of thresholds; however, the POD and ETS do not change much for different precipitation thresholds.

b. Monthly estimates

Figure 6 shows the scatterplots of monthly accumulations of gauged and TMPA estimates for all the selected basins. Strong correlations are apparent between the two estimates (R^2 of 0.9–0.99), and low bias (Nrmse of 0.1–0.23) on monthly time scales. Plausible performance of TMPA on monthly scales was also found in Huffman et al. (2007), the most likely reason for which is that the TMPA product is constrained by monthly gauge analysis. In spite of the high R^2 in Fig. 6, close inspection reveals that more points lie to the left of the 1:1 line, which is interpreted as mostly reflecting the climatological undercatch correction applied to TMPA (Huffman et al. 2007). Table 1 lists the corresponding statistics of R^2, Nrmse, and BIAS for each basin at both daily and monthly time scales. The basin average rain rate (mm day^{-1}) and conditional rain rate ($>$0.5 mm day^{-1}) from both gauge and TMPA estimates are also provided in Table 1. TMPA overestimated total precipitation by 3–13% for all the basins, except for the Paraguay basin (2401; $-$1%).

Monthly time series of precipitation from gauges and TMPA for the period January 1998–August 2006 over different subbasins are shown in Fig. 7. The La Plata basin has two well-defined precipitation regimes: one toward the northern boundary (basins 6301 and 6682) and the other over the central part (basins 6598 and 3802). The monthly mean precipitation over the northern region (Figs. 7a,b) peaks during austral summer; on the other hand, precipitation over the central part (Figs. 7c,d) can peak in different times in the seasonal cycle. TMPA follows the interannual variations and seasonal cycle of observations very well for all the basins. The TMPA monthly estimates show better agreements with the observations with increasing upstream area (Figs. 7f,g). The TMPA estimates in general overestimate observations throughout the study time period for the Paraná and Uruguay basins and for upstream of the Paraguay basin. Notable overestimation of precipitation by the TMPA was observed in basin 6682 for all seasons (total of 13%) and in the central basins for most of the months with high rainfall.

4. Evaluation of streamflow predictions

This section investigates the performance of TMPA estimates in hydrologic modeling in terms of the overall statistical measures of BIAS and NSE and the visual examination of hydrographs. The analysis mainly focuses on the basins upstream of the flow stations shown in Fig. 2.

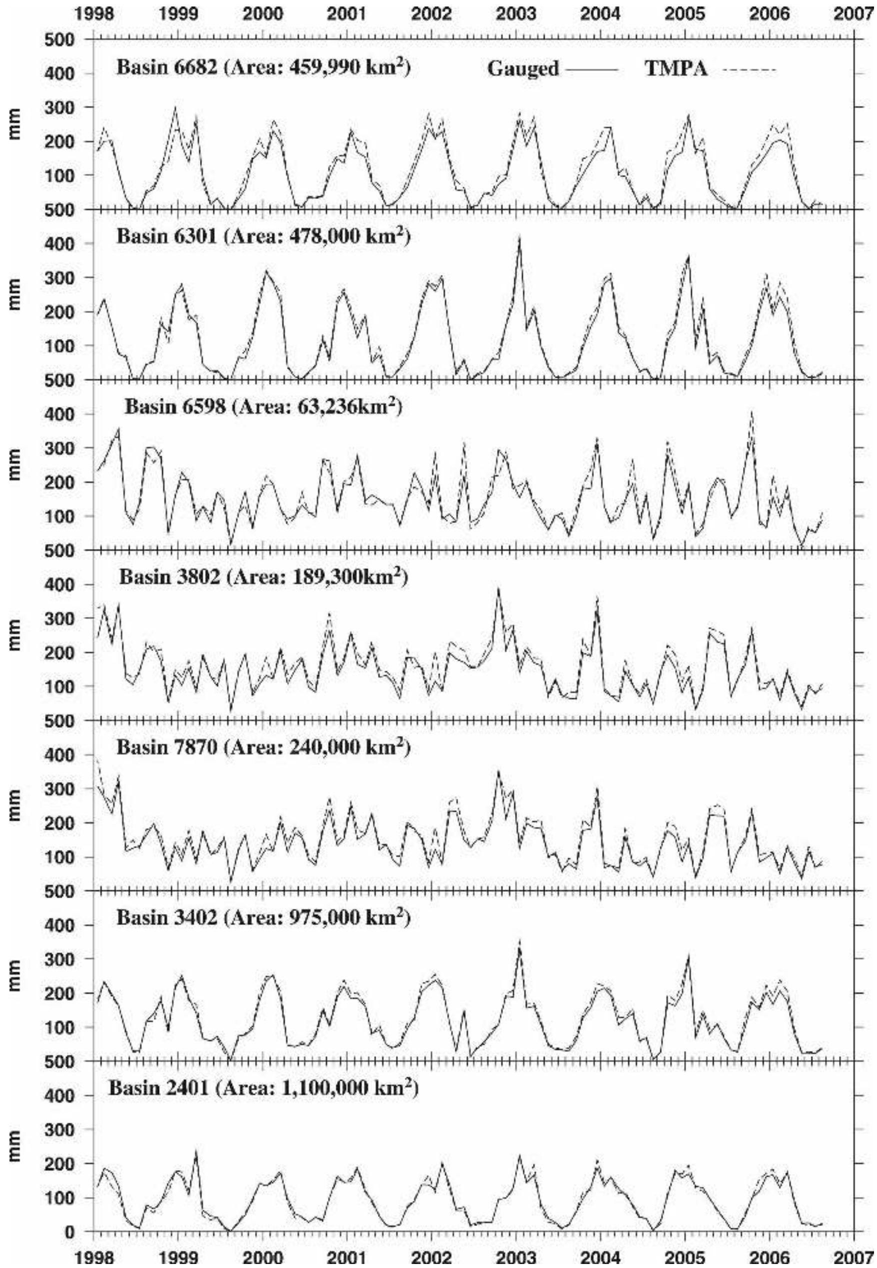

FIG. 7. Same as Fig. 6, but for monthly time series of precipitation.

a. Daily streamflow

The VIC model uses physically based formulations to calculate land surface energy fluxes and a conceptual scheme to represent runoff production. Several model parameters, especially those related to soil properties that control infiltration and subsurface moisture storage, must be calibrated by matching predicted and observed streamflow. We used such a procedure for 1979–99 to estimate VIC parameters for the three major tributaries of La Plata. The observed precipitation used to calibrate the VIC model for 1979–99 was gridded from observed daily station data (which was taken from slightly different data sources than those used in the precipitation assessment in section 3). In this study, we used the calibrated VIC model, without any further adjustment of parameters, with the VIC model forced with the gridded station data described in section 2c and the TMPA data for 1998–2006.

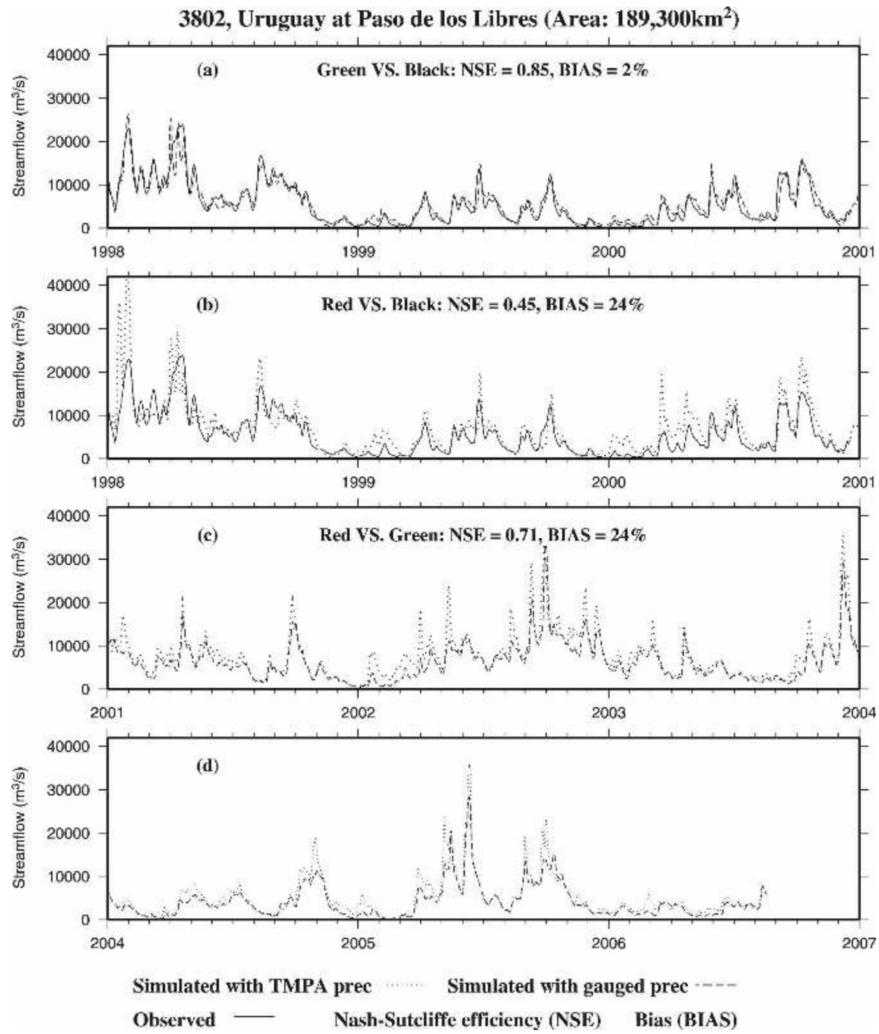

FIG. 8. Daily streamflow for station 3802 (Uruguay at Paso de los Libres), with forcings of (a) observed and VIC model simulated streamflow with the gauged precipitation for 1998–2000, (b) observed and simulated streamflow with the TMPA for 1998–2000, (c) simulated streamflow with TMPA and gauged precipitation as forcings for 2001–03, and (d) the same as (c) but for 2004–06.

Figure 8 shows predicted and observed daily streamflow for station 3802 (the Uruguay River at Paso de los Libres), with a drainage area of 189 300 km^2. The Uruguay River basin experiences precipitation with irregular characteristics, which are reflected in the annual streamflow regime. Daily observed streamflows for station 3802 were only available for 1998–2000. Three-year (1998–2000) observed daily hydrographs and the simulated streamflows (from the VIC model forced with gridded gauge precipitation) are shown in Fig. 8a, which confirms both that floods in the Uruguay can occur in any season and that the river's flood response to precipitation is quite fast for a river of this size. Figure 8a also shows that the VIC model was able to capture the daily observed hydrograph quite well in both timing and magnitude when forced with gridded gauge precipitation for basin 3802 (model efficiency of 0.85 and BIAS of 2%).

The TMPA-driven model simulations are compared with daily observed discharge in Fig. 8b; they capture the flood events well, but tend to overestimate most flood peaks. The NSE decreases to 0.45 for the same period (1998–2000), mainly because of the substantial overestimation of streamflow during January–February 1998. The TMPA-driven simulated streamflow has a large positive BIAS (up to 24%), which is mostly explained by the upward bias in the satellite precipitation estimates (about 10%; see Table 1 and Fig. 4). The VIC

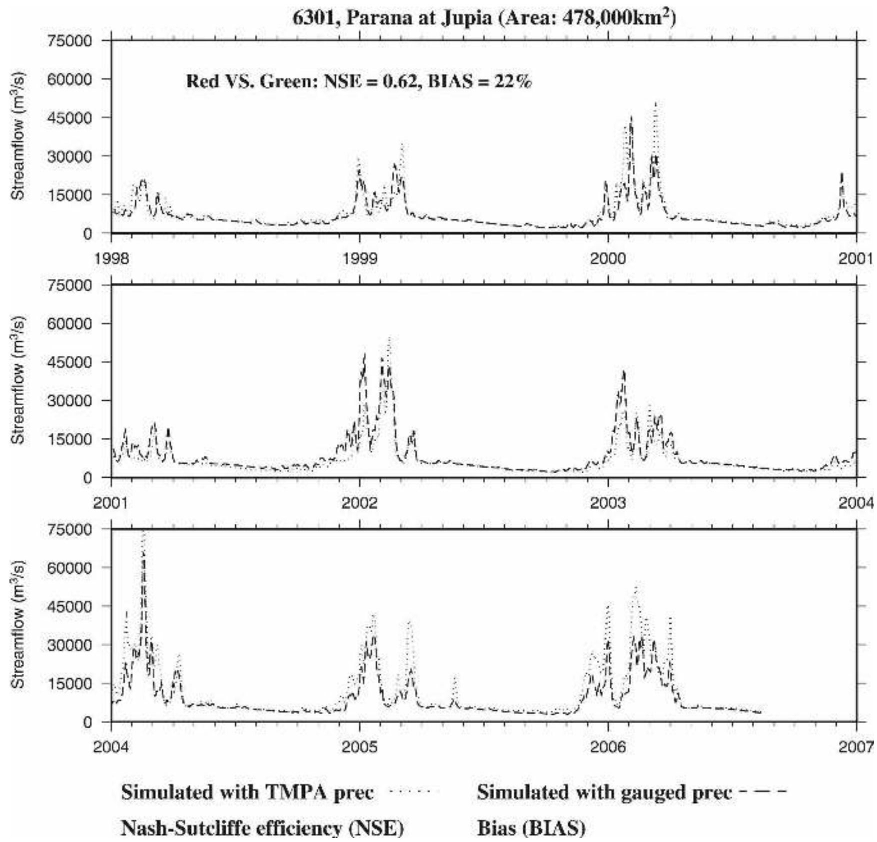

FIG. 9. Simulated daily streamflow for station 6301 (Paraná at Jupia) with the TMPA and gauged precipitation estimates as forcings for 1998–2006.

simulated streamflow as forced with gauge and TMPA precipitation for 2001–06 is shown in Figs. 8c,d. Given the plausible performance of the VIC model in Fig. 8a and the lack of observed daily streamflow, the VIC simulated streamflow as forced by gridded observations is treated as a reference for 2001–06. There is good agreement between the two sets of daily simulated streamflows (NSE of 0.71). The TMPA-driven simulations seem to represent high flows reasonably well for basin 3802, although high flows are generally higher than those predicted by the VIC model forced with gridded observations.

Observed daily streamflow is not available for stations other than 3802 for any years from 1998 to 2006, so the observation-driven VIC simulated streamflow is used as the reference. The river upstream of station 6301 (Paraná at Jupia; see Fig. 2) is known as the upper Paraná, with a drainage area of 478 000 km^2. There is a well-defined streamflow regime above Jupia; floods occur during December and March with a dry season between June and September. The maximum discharges during February and March are associated with copious austral summer rainfall over the upper Paraná basin resulting from intense convection organized in the South Atlantic convergence zone. Figure 9 shows daily simulated hydrographs for station 6301 with TMPA and gauge precipitation estimates as forcings for 1998–2006. The two daily simulations are consistent in their predicted low flows and in the timing of high-flow peaks. There are some differences in peak flow events identified by the two datasets; the VIC model simulations forced with gridded observations predict some peak events not resulting when the TMPA forcings are used, and vice versa. For those events predicted using both forcing datasets, the TMPA forcings tend to results in higher simulated peak flows in austral summer. The relative model efficiency is 0.62; there is a positive BIAS of 22% for TMPA forcings for the entire period relative to the observation-driven simulated streamflow.

Basin 6598 (Iguazu at Estreito; Fig. 2), with a drainage area of 63 200 km^2, is a tributary of the Paraná River that flows from the east. The Iguazu River shows similarities with the upper Uruguay River, with quite irregular streamflow regimes and floods of short duration at any time of the year. Nine-year daily streamflow

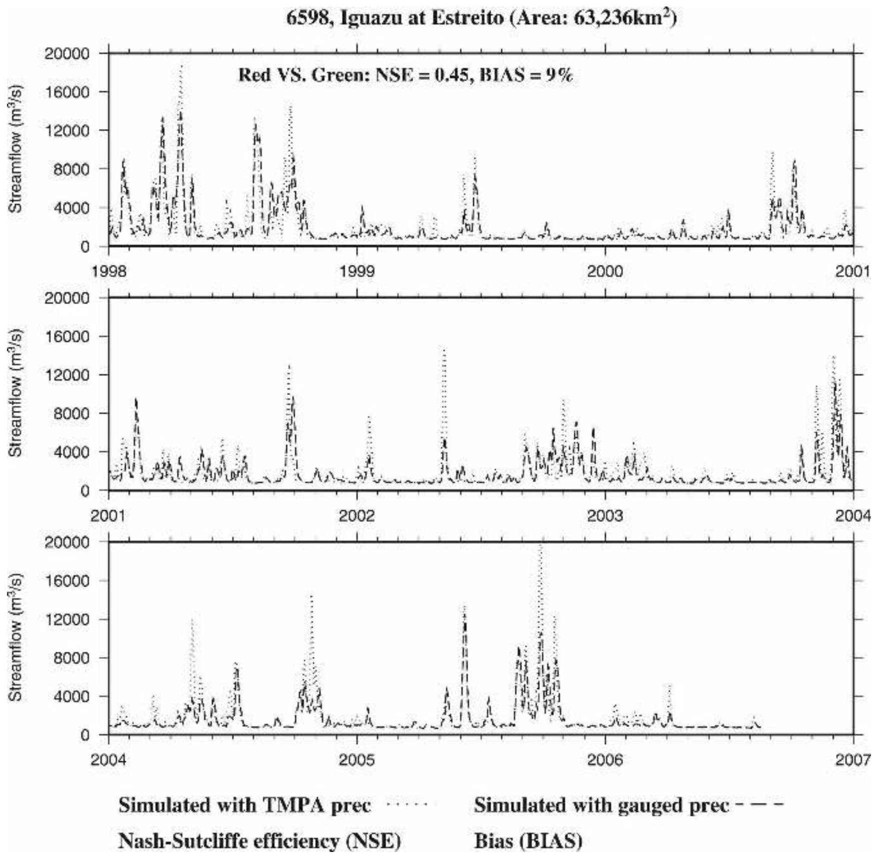

FIG. 10. Same as Fig. 9, but for basin 6598 (Iguazu at Estreito).

simulations driven by both gauge and satellite precipitation for the Iguazu at Estreito are shown in Fig. 10. The two simulations agree well in the occurrence of most flooding events, despite the high variability in the daily hydrographs. Statistics show a slight positive BIAS (9%) for the whole period for TMPA versus gridded forcings, and a low relative model efficiency (NSE = 0.54) is mostly due to the overestimation of some peak discharge events. For instance, the TMPA-driven simulations yield a peak flow of 14 800 $m^3 s^{-1}$ on 22 May 2002, while the observation-driven model result is 5530 $m^3 s^{-1}$ on the same day.

The Paraguay River regime is highly regular, with well-defined high and low flow periods. Results for the Paraguay River at Ladario (6682; 460 000 km^2) are shown in Fig. 11. Although the two simulated hydrographs show the same periods for the high and low flows, the TMPA-driven simulations are consistently higher than the observation-driven simulations for almost the entire period (1998–2006). The summary statistics show a high positive BIAS for TMPA (relative to gridded observed forcings of 48%) and negative model efficiency.

b. Monthly streamflow

Monthly time series of simulated streamflow forced by both TMPA and gauge precipitation estimates at seven locations within the La Plata basin (triangles in Fig. 2) for the period January 1998–August 2006 are shown in Fig. 12. Given the overall agreement between the two monthly precipitation estimates (Fig. 7), the seasonal and interannual variations of the TMPA-driven simulated flows show unsurprising consistency, with the observation-driven simulations for all the stations with NSE (based on the monthly streamflow) ranging from 0.54 to 0.8. The Paraguay at Bermejo (2401; Fig. 12g) shows good relative results in terms of the NSE (0.78) and BIAS (7%) despite the large portions of the basin with few rain gauges, which may well be the result of smoothing and cancellations of errors in both precipitation and streamflow within such a large basin (1 100 000 km^2).

In spite of the good agreement in seasonality of discharge, the TMPA-driven simulations consistently overestimate the observation-driven simulated flows, mostly because of the apparent overestimation of high

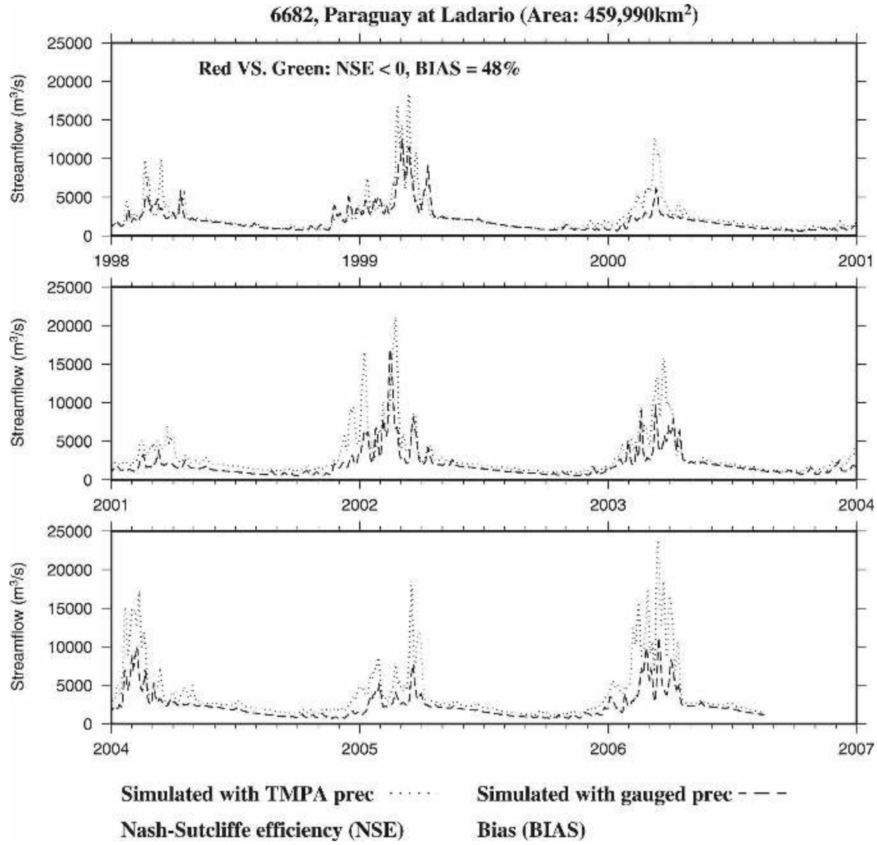

FIG. 11. Same as Fig. 9, but for the basin 6682 (Paraguay at Ladario).

precipitation by TMPA. According to Tables 1 and 2, the bias in the precipitation inputs was amplified in the simulated streamflow. For instance, the BIAS in precipitation ranges between −1% and 13%, while the range of the BIAS in the corresponding simulated streamflow is 7%–48%. For basin 6682, a positive BIAS of 13% in precipitation results in a positive BIAS of 48% in the simulated streamflow (and thus a negative NSE). In the case of basin 2401, there is a small negative BIAS (1%) in precipitation but there is a 7% positive BIAS in the simulated streamflow, indicating the strong nonlinearities in land surface hydrological process parameterizations in the VIC model. The amplification of the precipitation signals in the river flow of La Plata basin was also noted by Berbery and Barros (2002) based on observed data.

Two years (1998–99) of observed monthly streamflow are available at stations 6301, 6596, 3802, and 7870 (black lines in Figs. 12b–e). The streamflow predictions driven by the satellite- and gauge-based precipitation both track the interannual variations of observed flows very well during those two years. The hydrograph predictions driven by the gauge-based precipitation match the observed flows better than those obtained from satellite precipitation estimates for the Uruguay basins (Figs. 12d,e). Streamflow is considerably overestimated by the TMPA-driven model, particularly in February 1998, as a result of higher short-term precipitation estimates for TMPA relative to the gridded observations.

5. Discussion

a. Uncertainties in precipitation estimates

It is worth noting that there are several factors that could contribute to the differences between the TMPA and gauge precipitation estimates other than TMPA retrieval errors. Uncertainties may arise from inadequate spatial representation of the gauge data or the ways in which the gauge data were used to obtain gridded data. Many of the available precipitation station records are not complete, and a substantial number of missing days and gaps throughout the 1998–2006 time series had to be estimated (B. Liebmann and D. Allured 2007, personal communication). On the other hand, many of the results we report are consistent across the subbasins we evaluated, some of which (e.g.,

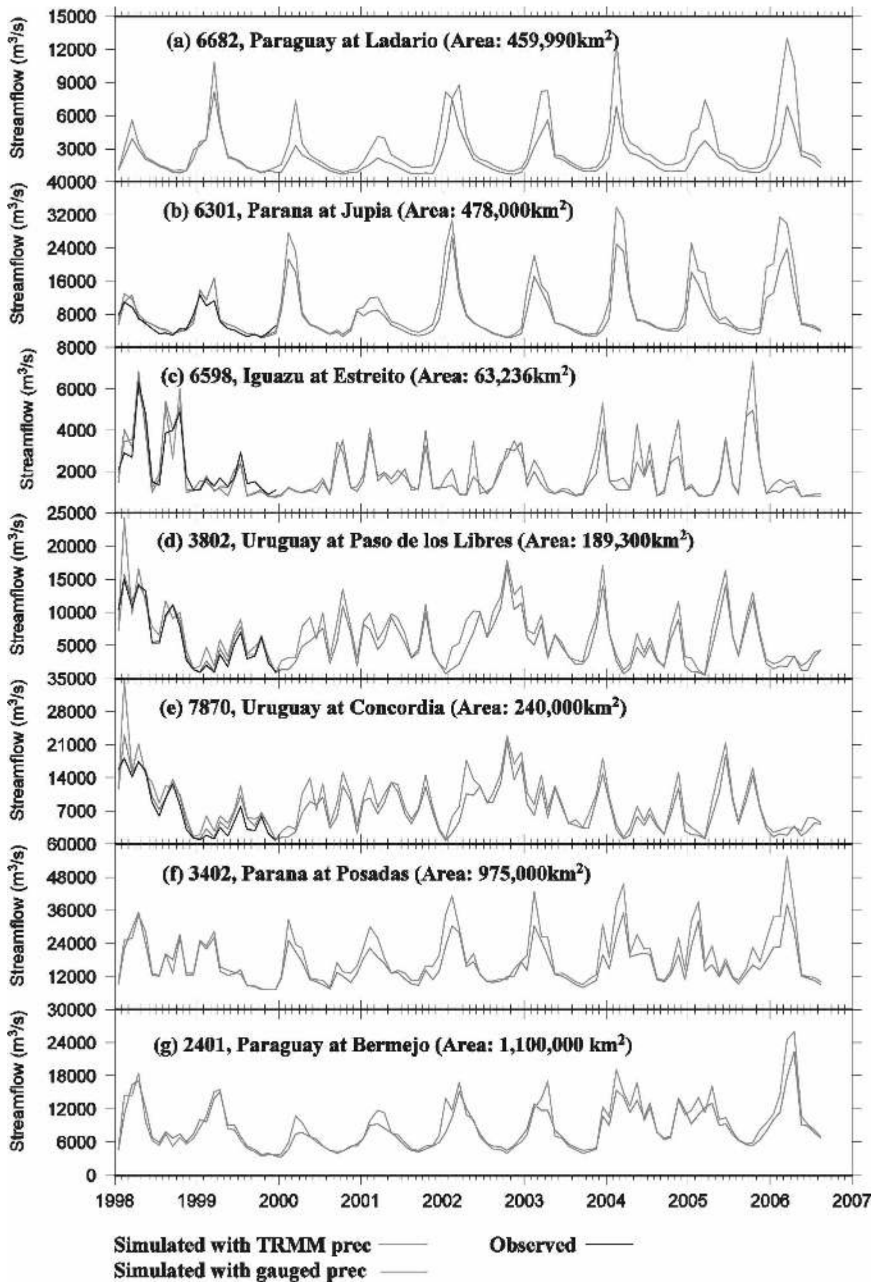

FIG. 12. Monthly time series of streamflow at seven locations within the La Plata basin (see triangles in Fig. 2) for 1998–2006.

the Uruguay) have relatively dense station networks, for which the gridded data are less subject to error.

The positive trends of BIAS in the TMPA monthly values can be mostly explained by the climatological undercatch correction applied to the TMPA, which is not present in the gridded station data. Another possible source of error is that most daily precipitation stations in South America are measured at 1200 UTC, which is consistent with the TMPA daily accumulations (1200 to 1200 UTC); however, some agencies have different observation times, and some times are not currently known (Liebmann and Allured 2005). The inconsistencies in the accumulating times may exert some uncertainties on the daily precipitation comparisons (e.g., Fig. 4); however, the difference is unlikely to cause any substantial effects in the simulated stream-

TABLE 2. Statistical summary of the comparison between the two streamflow simulations when the VIC model was forced by TMPA and gauged precipitation estimates over the seven subbasins for January 1998–August 2006. The observation-driven simulations were treated as the reference.

Basin ID	River/station	Drainage area (km^2)	Daily NSE	Monthly NSE	BIAS (%)
6682	Paraguay/Ladario	459 990	<0	<0	48
6301	Parana/Jupia	478 000	0.62	0.71	22
6598	Iguazu/Estreito	62 236	0.45	0.80	9
3802	Uruguay/Paso de los Libres	189 300	0.71 (2001–06)	0.73	24
7870	Uruguay/Concordia	240 000	0.69	0.77	22
3402	Parana/Posadas	975 000	0.53	0.54	18
2401	Paraguay/Bermejo	1 100 000	0.60	0.78	7

flows, given the large basin sizes and multiday times of travel through the channel system.

b. *Calibration issue and basin response*

We used model parameters that were calibrated based on gridded gauge precipitation and observed streamflow for 1979–99 for all the VIC model runs in this study. As noted in section 4a, the gridded precipitation data used for model calibration used slightly different stations and a slightly different period of record than the period used for model evaluation. For comparison of hydrologic predictions for 1998–2006, our benchmark was the VIC model forced with gridded station data. Yilmaz et al. (2005) and Artan et al. (2007) show that hydrology model performance can be considerably improved if the hydrology model is calibrated to satellite-based precipitation estimates. Although we could have calibrated to the TMPA data, we chose not to for the following reasons: (i) We already had obtained calibration parameters (for other purposes) and it was convenient to use these parameters to produce benchmark simulated streamflows that were consistent with other ongoing work focused on the hydrology of the La Plata basin tributaries. (ii) The observed length of the gridded station data used in our calibration is longer than that of the satellite data and hence provides a basis for evaluating model performance under a wider range of hydrologic conditions. (iii) For the more densely gauged areas, the errors in spatial estimation of rainfall are fairly modest, and hence the gridded gauge data, for purposes of hydrologic simulations, are expected to have errors that in general are smaller than the differences between TMPA and gauge-based estimates, especially at the daily time scale and for basin averages. (iv) Finally, keeping the same model setup (parameters) allows us to investigate how differences between precipitation estimates affect the resulting simulated streamflow.

Because the VIC model parameters were the same for all the runs, the biases in the simulated streamflow in Figs. 8–12 are attributable entirely to differences in the precipitation inputs. Nijssen and Lettenmaier (2004) found that even unbiased precipitation can give rise to biases in other hydrologic fluxes and states because of nonlinearities in the hydrological cycle. In most cases, the overestimation of the high flow peaks in both daily and monthly hydrographs was associated with the apparent overestimation of high rain rates in the TMPA. The large overestimation of streamflow for the Paraguay River at Ladario (Fig. 11) is mostly attributable to the wet soil conditions in this basin (which has large wetland areas); any positive rainfall bias is transformed into a larger positive bias in the simulated streamflow. The TMPA-driven simulated streamflow is 48% larger than the observation-driven simulated streamflow; however, the difference in the simulated evaporation is only 2%, indicating that excess precipitation primarily contributes to runoff in this basin. In the meantime, the high variability of daily precipitation was attenuated in the simulated streamflow due to the low-pass filter effect of rainfall-runoff processes (Storm et al. 1989). The TMPA-driven model results provide a good representation of low flows (e.g., Fig. 9). One explanation is that the frequent and small anomalous rainfall episodes exert a weak influence on the soil moisture dynamics and are partially attenuated by evaporation losses. Nijssen and Lettenmaier (2004) found that error rates in slow (baseflow) runoff response to error-corrupted precipitation are much lower than for high flows because the low flow response integrates precipitation errors temporally. These features help to understand what level of input accuracy is required for hydrologic prediction.

c. *Potential of TMPA products for hydrology applications*

The objective of this study is to evaluate the utility of satellite-based precipitation estimates (TMPA) as inputs to hydrological models for hydrologic forecasting because they may provide an alternative source of pre-

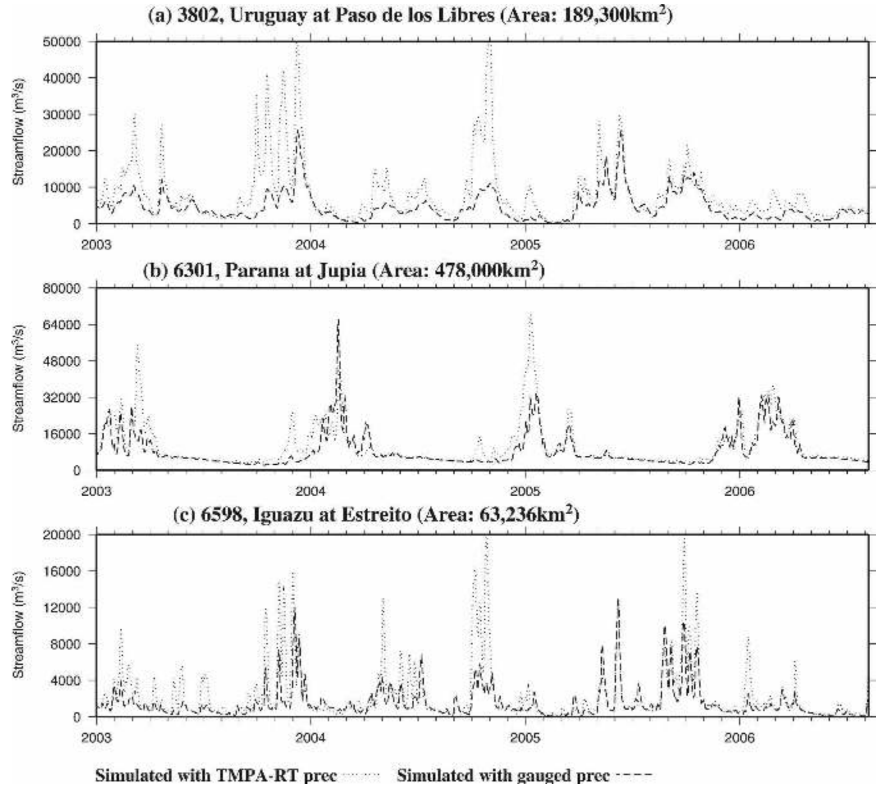

FIG. 13. Daily simulated streamflow with the VIC model forced by TMPA-RT and gauge precipitation estimates for 2003–06 for stations at (a) Uruguay at Paso de los Libres, (b) Parana at Jupia, and (c) Iguazu at Estreito.

cipitation data for areas where ground-based networks are sparse or nonexistent. There is nonetheless concern that the encouraging aspects of the performance of TMPA are substantially attributable to the monthly gauge correction, a correction which requires a reasonably dense gauge network. Of course, dense gauge networks do not exist in many parts of the world where satellite-based estimates would be expected to be most beneficial. On the other hand, although the TMPA is adjusted by the monthly gauge analysis, the information on the daily distribution of precipitation within a month comes mostly from satellite estimates. The consistency between the timings of the TMPA-driven and observation-driven simulated daily streamflows reflected in Figs. 8–10 should indicate some potential utility of TMPA for hydrologic prediction.

The TMPA RT product, which has been accessible in near-real time on the Web since January 2002, uses a different TRMM calibrator (TMI) from the research product and does not currently include any gauge analysis. There is a firm policy that the RT data are not reprocessed, so the data record always reflects the various experimental versions that created the record in real time. Despite the recommendations from the TMPA developers (G. Huffman et al. 2007, personal communication) that research be done with the post-real-time product 3B42, which is consistently reprocessed, we did a limited evaluation of the RT TMPA to further understand the potential utility of the TMPA products for hydrologic prediction. Figure 13 compares the RT-driven daily simulated streamflow and the observation-driven simulations over three La Plata subbasins (3802, 6301, and 6598) for 2003–06. The RT data result in much better hydrologic model performance for the years after 2005 (including 2005) than for the years before (with the observation-driven simulated streamflow as reference) in both timing and magnitude of floods over all the basins. The plausible performance of the RT data in streamflow simulations in recent years suggests that even without the monthly gauge correction, there is considerable potential for hydrologic prediction using satellite precipitation estimates in data-sparse areas.

Although gauge analysis is incorporated into the TMPA research product, its relatively long (for satellite data) records (1998–present) and high spatiotemporal resolutions and quasi-global coverages make its use appealing for global hydrologic prediction. However, further work to reduce the dependence of satellite products such as TMPA on gauge networks is highly desirable. This might be done, for instance, by relying more on gauge climatologies at sparse networks of global index stations (i.e., by trading off spatial density for record length, which becomes increasingly feasible as the satellite record length increases). We hope that the work we report here will improve the communications between the hydrology community and satellite precipitation product developers and will eventually lead to improvements in the accuracy of satellite precipitation estimates for hydrologic applications.

6. Conclusions

Nine-year (1998–2006) basinwide precipitation estimates from the TMPA research product (3B42 V.6) were evaluated with gauge-based precipitation and the VIC land surface hydrology model over the La Plata basin. Our general conclusions are as follows:

(i) The TMPA estimates agree well with the gridded gauge data at monthly time scales for all the subbasins (most likely because of the monthly adjustment to gauges performed in TMPA), although the TMPA tends to provide slightly larger estimates than the gauge data—most likely because of the gauge undercatch correction applied in TMPA but not in the gridded gauge product.

(ii) The agreement between TMPA and gauge precipitation estimates is much less at daily time scales; however, TMPA and gauge estimates often agree on the occurrence of daily precipitation events. TMPA tends to overestimate high rain rates relative to the gridded gauge estimates.

(iii) For the two northern basins 6301 and 6682, TMPA agreement with the gauge product at daily time steps is best for low and medium precipitation thresholds (0.1–5 mm); for high precipitation thresholds (up to 20 mm), the satellite estimates tend to overestimate the frequency of rain events and show high FAR and low POD and ETS. For the two central basins 6898 and 3802, the POD and ETS values do not show significant trends with the increase of precipitation thresholds.

(iv) The TMPA-driven model simulations show a good ability to capture daily flood events and to represent low flows, although peak flows tend to be biased upward. Furthermore, there is a good agreement between TMPA-driven simulated flows in terms of their reproduction of seasonal and interannual streamflow variability. Our analysis demonstrates the potential of TMPA products for hydrologic forecasting in data-sparse regions.

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