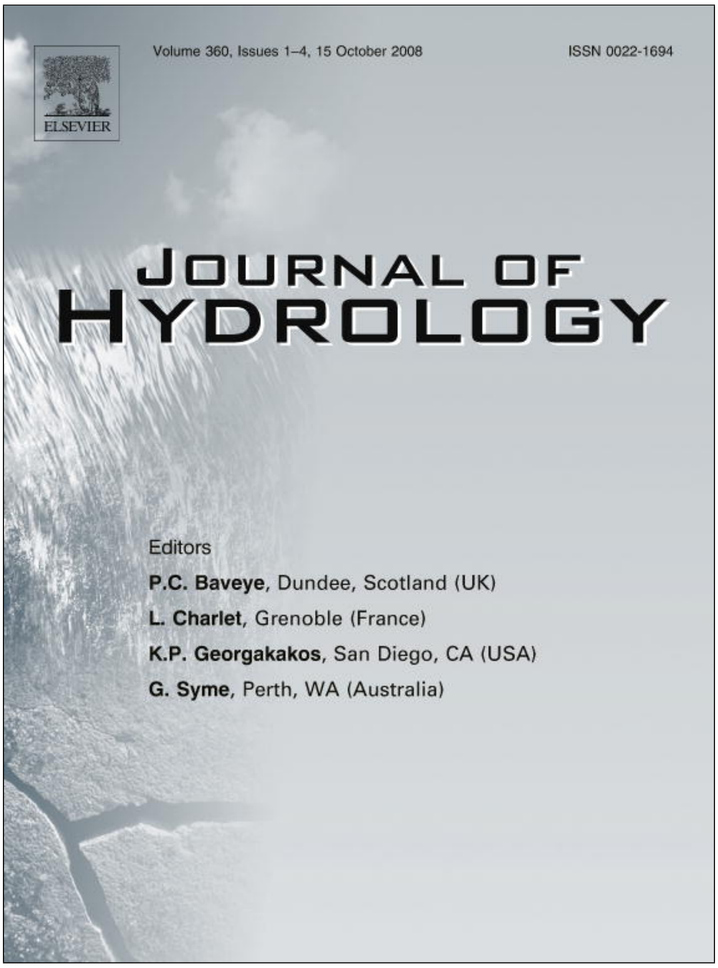
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Daily hydrological modeling in the Amazon basin using TRMM rainfall estimates

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Summary Rainfall measurements by conventional raingauges provide relatively accurate estimates at a few points of a region. The actual rainfield can be approximated by interpolating the available raingauge data to the remaining of the area of interest. In places with relatively low gauge density such interpolated rainfields will be very rough estimates of the actual events. This is especially true for tropical regions where most rainfall has a convective origin with high spatial variability at the daily level. Estimates of rainfall by remote sensing can be very useful in regions such as the Amazon basin, where raingauge density is very low and rainfall highly variable. This paper evaluates the rainfall estimates of the Tropical Rainfall Measuring Mission (TRMM) satellite over the Tapajós river basin, a major tributary of the Amazon. Three-hour TRMM rainfall estimates were aggregated to daily values and were compared with catch of ground-level precipitation gauges on a daily basis after interpolating both data to a regular grid. Both daily TRMM and raingauge-interpolated rainfields were then used as input to a large-scale hydrological model for the whole basin; the calculated hydrographs were then compared to observations at several streamgauges along the river Tapajos and its main tributaries. Results of the rainfield comparisons showed that satellite estimates can be a practical tool for identifying damaged or aberrant raingauges at a basin-wide scale. Results of the hydrological modeling showed that TRMM-based calculated hydrographs are comparable with those obtained using raingauge data.

Introduction

Predictions from rainfall–runoff models are often unsatisfactory because spatial variability in rainfall is poorly represented in regions where data are scarce; furthermore the catch of conventional raingauges is representative of only

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a small radius around the instrument. For more detailed monitoring of extense areas, a dense raingauge network is needed. Such a network is often not feasible in mountainous regions or remote areas such as the Amazon. According to Wilheit (1986), even in technologically advanced nations, sampling by raingauges is marginal at best, and in less-advanced regions the gauges are sparsely distributed and often considered unreliable. The uncertainties of areal precipitation estimates increase with the decrease of rain gauges density, especially for local convective events. Better estimates of rainfall spatial distribution can be obtained by radars which, however, have limited coverage in most developing countries.

More recently, several efforts have been directed to the use of satellite images to estimate rainfall. Various methods for estimating rain rates from satellite images have been proposed (Dingman, 2002), from several bands of the eletromagnetic spectrum. Probably the most popular are derived from the Geoestationary Operational Environmental System (GOES) series and the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al., 2000), this one with the specific goal of measuring precipitation over the oceans and tropics.

In this paper, TRMM satellite-estimated precipitation fields were evaluated in the Tapajós river basin, one of the major tributaries of the Amazon, through direct comparison with raingauge precipitation fields and through the calculation of streamflow hydrographs using a large-scale hydrological model. Furthermore, streamflows were calculated using rainfields interpolated from raingauge data and obtained from the TRMM satellite, and these were compared with observed hydrographs. The main purpose of this paper is therefore to examine whether TRMM rainfall estimates are useful as input to rainfall–runoff models applied to tropical basins, focusing on the use of rainfall estimates for runoff prediction rather than on the development of the rainfall estimates themselves.

The main motivation for evaluating remote sensing rainfall estimates by running hydrological models is to obtain an integration of rainfall effects over large areas in terms of river discharge.

Satellite-estimated rainfall and its use in rainfall–runoff simulation

Daily sampling raingauges are the main source of rainfall data in Brazil as in other South American countries. Meteorological radars are rare, and concentrated around the most populous cities. Satellite derived rainfall estimates will probably be very useful in the near future in several applications such as operational hydrology, meteorology and agriculture. In the Amazon region, satellite rainfall estimates will probably be the only available information over large areas for a long time. The quality of satellite-based precipitation estimates therefore needs to be evaluated.

Satellite images are a source of information for several water cycle components. Even before the launch of the first meteorological satellite (the Television and Infrared Observation Satellite – TIROS 1), in April 1960, it was hypothesized that the occurrence, and even the intensity, of rain might be inferred from the appearance of the parent cloud systems (Pretty, 1995).

The basic principle of estimates based on visible wavelength bands is the fact that the brightness of reflected sunlight from clouds is an indication of their thickness and, therefore, of their likelihood to produce rain. Similarly, low reflectances in infrared (IR) bands are associated with low cloud top temperature and consequently with higher rain intensity.

However, it was soon found that by no means all bright clouds precipitate, nor do all clouds having cold IR tops. Conversely, not all rain clouds are bright or cold. Perhaps more frustrating of all, some parameters, such as radiance thresholds, needed to optimally discriminate rainfall were found to vary markedly from one situation to another (Pretty, 1995). Being an observation only of the top of the clouds, these estimates have significant limitations.

A great improvement in satellite-based rainfall estimates came with the use of passive microwave sensors. For clouds over the oceans, microwave radiation can be directly related to the amount of water in the cloud through Planck's law. Over the continents, the relation is not as directly obtained but needs to be determined by the use of parameters such as ice content, and results are generally worse than over the oceans. Nevertheless, even on the continents, estimates based on high-frequency (85.5 GHz) microwave sensors, are more accurate than those obtained from infrared images (Ramage et al., 2003).

The Tropical Rainfall Measuring Mission (TRMM) is a satellite built and operated jointly by the USA NASA and JAXA, the Japanese Aerospatial Agency; it was launched in November 1997 and has provided rain estimates since January 1998. Its purpose was to get a better understanding of the precipitation in the tropics and its influence on global climate (Kummerow et al., 2000). The low-orbit of the satellite and the short translation period (91 min) allow relatively high temporal and spatial resolution. Instruments onboard the satellite include passive sensors for microwave, visible and infrared bands and a meteorological radar.

In 2001 the initial original 350 km orbit was modified to 403 km, in order to reduce fuel consumption and extend the observation period.

Several different rainfall estimates are obtained by combining data from the different TRMM sensors. These estimates are termed products, according to the combination of instruments used in the estimation algorithm (http://daac.gsfc.nasa.gov/data/ NASA's online database). Research product 3B42 (Huffman et al., 2007), which is used in this work, uses precipitation estimates obtained from TMI, the microwave sensor, adjusted with information about the vertical structure of the cloud, obtained from PR, the onboard precipitation radar.

Estimates are integrated to accumulated monthly values, generating the product known as 3B31. This product has a good spatial resolution of 0.25°, but an inadequate temporal resolution due to the low sampling frequency. Monthly totals are finally used to adjust infrared precipitation estimates from the Geostationary Operational Environmental System (GOES) series, which have a temporal resolution of 3 h. By this means, a product – called 3B42 realtime, or RT – that combines both high temporal and spatial resolution is obtained. Finally, the 3B42 research product is obtained by scaling the 3-h RT values in order to match the monthly sums of a $1^\circ \times 1^\circ$ rainfall grid derived from GPCC raingauge data (Huffman et al., 2007). Due to this adjustment, 3B42 research product is only available with a 10–15 days delay.

These TRMM precipitation estimates are believed to be considerably more reliable than those obtained from other satellites (Barrera, 2005; Nicholson, 2005). However, only a few evaluations of the TRMM rainfall estimations have hitherto been published.

Reports in the literature on the evaluation of satellite-derived rainfall can be divided basically into two major groups. Most present some form of comparison between precipitation estimated by satellite to raingauge data, both in terms of local and area average analysis. Several articles in this group refer to evaluations over the African continent, as in Hughes (2006) and Nicholson (2005). The latter, as well as evaluating satellite-estimated rainfall from TRMM over the African Sahel, reached important conclusions about the long-term variability of rainfall in this region. In South America, Barrera (2005) developed a technique called Hydroestimator, based on images of geostationary satellites, and Araújo and Guetter (2005), who compared low-orbit satellite estimates with ground rain data over the Iguazu river basin, both with encouraging results.

Publications in the second group approach the evaluation of satellite-derived rainfall by comparing observed sequences of river streamflow with estimated sequences derived from rainfall–runoff models, in the two cases when rainfall inputs are (a) derived from raingauge networks and (b) estimated from satellite measurements. This group has rather examples than the first. Guetter et al. (1996) and Yilmaz et al. (2005), used GOES-based estimates as input to the Sacramento hydrological model over medium-scale basins (~5000 km^2) in the USA, obtaining satisfactory results, although poorer than those obtained from conventional rainfall–runoff simulation. Hughes et al. (2006) used monthly TRMM precipitation estimates as input to the Pitman model applied to the Okavango river basin in Africa, although on a monthly basis. More recently, Su et al. (in press) evaluated the TRMM 3B42 research product as input to the VIC model applied to the La Plata basin, for both monthly and daily time steps. They concluded that agreement between satellite-based and observed rainfall was much better for monthly than daily scales; they also found that TRMM-driven daily simulations perform well at low flows, although peak flows tended to be overestimated.

Methodology

The quality of TRMM rainfall estimates was evaluated by comparing several years' daily data with observed catch of ground-level raingauges in the Tapajós river basin shown in Fig. 1. A large-scale hydrological model was also used with a daily time step, with raingauge and TRMM derived rainfall fields as alternative inputs.

The Tapajós region and its available records are briefly described in the section 'The Tapajós river basin and the available data'. The hydrological model is described in the section 'The MGB-IPH large-scale hydrological model'. The interpolation method for daily rainfall is set out in the section 'Generation of rainfields' and the procedure for comparing rainfields in the section 'Comparison of rainfields'. Model calibration and procedures for streamflow compari-

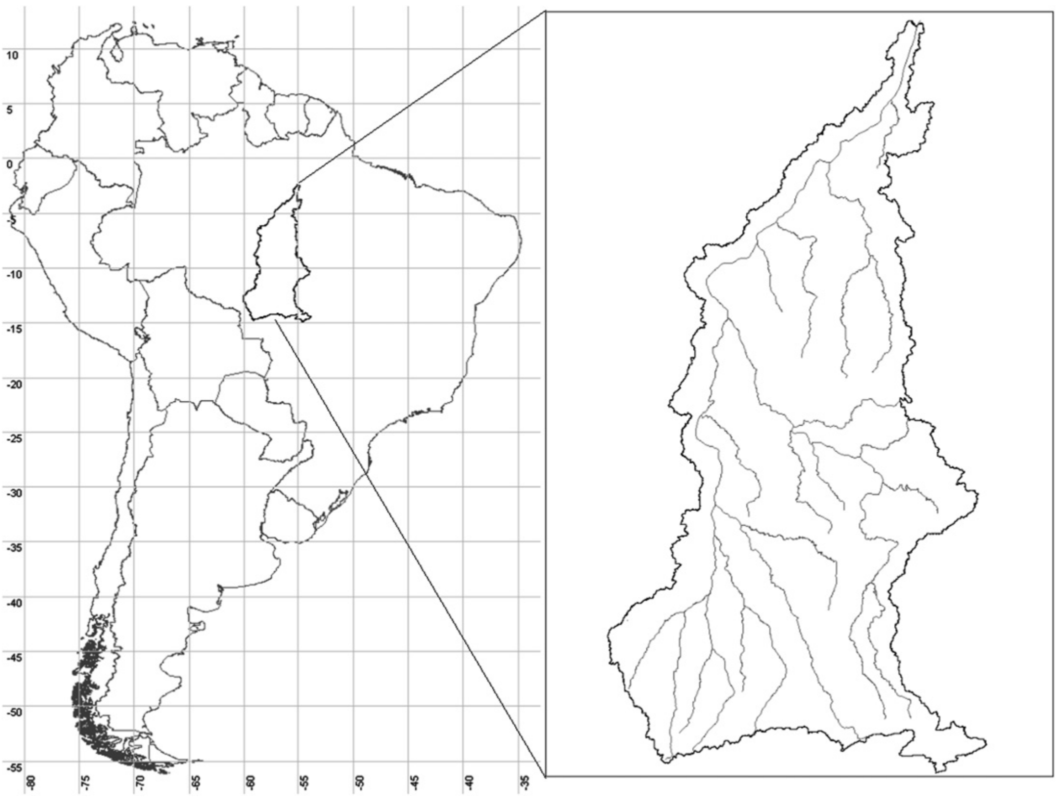

Figure 1 The Tapajós river basin and its location in Brazilian territory.

son are described in the section 'Comparison of streamflow'.

Results of the comparison of rainfields are presented in the sections 'Comparison between mean basin rainfalls' and 'Comparison between rainfields' and results of the comparison of the hydrographs are presented in the section 'Rainfall—runoff simulation'.

The Tapajós river basin and the available data

As already mentioned, the Tapajós River is a tributary of the Amazon river, and its raingauge network density is low. The Tapajós basin lies in the Brazilian mid-west between parallels 2° and 15°S and meridians 53° and 61°W, covering parts of the states of Mato Grosso and Pará (Fig. 1). The Tapajós is one of the most important tributaries of the right margin of the Amazon. The area of the basin at its confluence with the Amazon, near the city of Santarém, is about 500,000 km^2. In terms of climate, the basin is dominated by the Intertropical Convergence Zone (ITCZ), the low-pressure region characteristic of areas near to the Equator. Annual rainfall is high, varying between 1800 and 2300 mm. Most of the rain falls in a well-defined wet season between October and April.

Despite the absence of serious water-use conflicts, due to high average flows and low water demand, the Tapajós river basin is increasingly a matter of concern because it includes the so-called ''Brazilian agricultural border'': the southern part of the basin is experiencing rapid land-use change with rainforest replaced mostly by pasture but also by crops and sugarcane, with presumed hydrological impact.

The MGB-IPH large-scale hydrological model

The rainfall—runoff model used in this study is the distributed Large Basin Simulation Model, called MGB-IPH (Collischonn et al., 2007a). Its structure is based on that of the models LARSIM (Ludwig and Bremicker, 2006) and VIC (Wood et al., 1992). Evapotranspiration is calculated after Shuttleworth (1993) and flow is routed through the Muskingum-Cunge model. According to the classification proposed by Beven (2001), the MGB-IPH is a hydrological response unit model. It uses input data derived from Geographical Information Systems giving information on basin characteristics including land use, topography, vegetation cover and soil types, which guide the calibration of parameter values. It has modules for calculating the soil water budget; evapotranspiration; flow propagation within a cell, and flow routing through the drainage network. The drainage basin is divided into elements of area — normally on a square grid with cells of the order of 10×10 km — connected by channels, with vegetation and land use within each element categorized into one or more classes, the number of vegetation and land-use types being at the choice of the user. The Grouped Response Unit (GRU) (Kouwen et al., 1993) approach is used for hydrological classification of all areas with a similar combination of soil and land cover without consideration of their exact locality within the grid (or cell). A cell contains a limited number of distinct GRUs, soil water budget is computed for each GRU, and runoff generated from the different GRUs in the cell is then summed and routed through the river network.

Calibration of the model is in three stages. First estimates of parameter values come from physical considerations and prior applications in similar basins or basins nearby. Then model results are improved by manual calibration of the parameters using a trial-and-error procedure. After this stage the overall volume of runoff obtained from calculated and observed hydrographs should be in agreement, and calculated peaks and recessions should be of the same order of magnitude as those observed. During the third and final stage, the MOCOM-UA (Yapo et al., 1998) algorithm is used to obtain the final calibration, based on ranges of parameter values defined *a priori*, and considering three objective functions: the Nash—Sutcliffe coefficient of efficiency; the Nash—Sutcliffe coefficient of efficiency of logarithms of streamflow; and relative volume errors. A more comprehensive description of the model is given by Collischonn et al. (2007a) and further applications are presented by Collischonn et al. (2007b), Allasia et al. (2006), Collischonn et al. (2005) and Tucci et al. (2003).

To apply the MGB-IPH model, the whole Tapajós river basin was divided into 3917 square cells measuring 6 min of latitude and longitude, which gives an element of approximately 120 km^2 of area. The low resolution (6×6 min) discretized drainage network was generated from the relatively high resolution (90 m) SRTM DEM using specially developed algorithms (Paz et al., 2006; Paz and Collischonn, 2007) followed by careful visual revision. GRUs for the basin were determined based on a crossing of land use maps, which were obtained from the classification of 30 m-LANDSAT 7 TM imagery, and soil maps, which were obtained from surveys done by the Brazilian Mining Ministry.

The basin was also divided into 23 sub-basins determined by the location of stream gauges and the availability of discharge data during the period of analysis (1998—2006). Discharge time-series were obtained from the National Water Agency (ANA) database (http://hidroweb.ana.gov.br/), and from the HYBAM project (http://www.ore-hybam.org/). Time series for temperature, wind velocity, pressure, humidity and insolation, needed for the estimation of potential evapotranspiration, were obtained from only two monitoring stations in the whole basin. The model MGB-IPH was then used with two separate rainfall inputs: using rainfall interpolated from ground-level gauges; using the 3B42 research product, generated from the TRMM project; Calibration of the model was repeated for each of these data sources and for each of the sub-basins, as described in the section 'Comparison of streamflow'.

Generation of rainfields

Rain data were gridded to a point mesh that corresponds to the center of the cells of the distributed hydrological model. For both raingauge and satellite sources, rain data were interpolated using the inverse distance squared method. Data interpolated from the existing raingauge network was termed the PLU dataset, and the model using it was denoted by MGB-PLU.

The hydrological model uses a spatial discretization of 0.1° cells. TRMM 3B42 data, however, have a spatial resolution of 0.25°, being downscaled into a 0.1 grid degree for modeling and comparison purposes. The dataset derived from TRMM 3B42 research estimates was termed the SAT dataset and the model using it as input is termed MGB-SAT. Moreover, 3-h estimates from the 3B42 product were summed to 1-day rainfall to allow comparisons with raingauge data.

At the end of this step, an interpolated rainfall series was obtained on a 0.1° grid, in the form of a matrix with 3917 cells and 3287 time intervals, stored in binary data form, for both PLU and SAT data. As well as being the main input to the rainfall–runoff models, these matrices also allowed PLU and SAT data to be compared directly.

Comparison of rainfields

Before the rainfall–runoff simulation, the performance of TRMM 3B42 research estimates was evaluated by direct comparison with raingauge data. Differences between them were evaluated both in terms of averages and spatial differences. For each time interval, mean basin rainfall was first calculated for the 3917 cells and the mean rainfall time series for PLU and SAT were compared. Correlation coefficients between the interpolated PLU and SAT time series were then calculated for each 0.1° cell. This generated a map of correlation coefficients, showing regions where PLU and SAT were more or less similar. The relative differences between mean PLU and SAT rainfalls were also calculated for each cell, generating a map of relative differences.

Comparison of streamflow

The hydrological model was calibrated using both PLU and SAT data sources, and results were compared by means of statistics commonly used in hydrological studies: namely the Nash–Sutcliffe coefficient, the log-Nash–Sutcliffe coefficient and the relative bias, as given below:

$$NS = 1 - \frac{\sum_{t=1}^{nt}(Q_{obs}(t) - Q_{cal}(t)^2)}{\sum_{t=1}^{nt}(Q_{obs}(t) - \overline{Q_{obs}})^2} \quad (1)$$

$$NS_{log} = 1 - \frac{\sum_{t=1}^{nt}(\log(Q_{obs}(t)) - \log(Q_{cal}(t)))^2}{\sum_{t=1}^{nt}(\log(Q_{obs}(t)) - \overline{\log(Q_{obs})})^2} \quad (2)$$

$$\Delta V = \frac{\sum_{t=1}^{nt}(Q_{cal}(t)) - \sum(Q_{obs}(t))}{\sum_{t=1}^{nt}(Q_{obs}(t))} \quad (3)$$

where t indicates time interval; nt is the number of time intervals; V is the runoff volume (m^3); ΔV is the relative error of this volume (bias); Q_{cal} is the calculated flow at the gauge ($m^3\,s^{-1}$); Q_{obs} is the observed flow at the gauge ($m^3\,s^{-1}$); and $\overline{Q_{obs}}$ is the mean observed flow ($m^3\,s^{-1}$).

For each dataset, the MGB model was calibrated using data from the period January 1998 to December 2006. This period was chosen because TRMM estimates are available since late 1997, and ground rainfall and discharge data were obtained only up to December 2006. All comparisons therefore refer to the period from 1/1/1998 to 31/12/2006. As mentioned above, calibration of the MGB-IPH model follows three phases. After good initial guesses were found for the parameters, the final phase is the automatic calibration using the MOCOM-UA (Yapo et al., 1998) algorithm. This phase was repeated for both PLU and SAT rainfall data sets.

In the MGB-IPH structure, parameters are related to GRUs and in ideal applications of the model the same parameter values are adopted for each GRU, regardless of where it lies within the basin (Collischonn et al., 2007). However, in the case of the Tapajós river basin, each sub-basin was calibrated separately, so that different parameter values for the same GRU were found for different sub-basins. The MOCOM-UA algorithm was applied using a population of 100 parameter sets and the final solution was chosen arbitrarily between the three with best NS coefficients. Time series from 23 flow gauges were used for calibration, so that there were 46 model calibrations in total: 23 for the MGB-PLU and 23 for the MGB-SAT models. Since the purpose of the study was to compare the utility of alternative sources of input (rainfall) data, there was no reason to define separate periods for model calibration and verification. It is assumed that the input dataset which gives best results during calibration period will also perform best during verification.

Results

Comparison between mean basin rainfalls

Rainfall grids for PLU datasets were derived from the time series of 118 raingauges, maintained by the Brazilian Water Agency (ANA) and by the Brazilian Meteorological Service (INMET). This represents an average coverage of only one rain gauge per 4200 km^2. In practice, the actual density is lower still because for several gauges there are long periods when data are missing. Grids of the SAT dataset, by their turn, were obtained from the 1581 TRMM 3B42 pixels covering the Tapajós river basin. Fig. 2 shows accumulated rainfall curves for PLU and SAT datasets during the period of analysis.

Fig. 2 shows that TRMM estimates are very close to those from the raingauge record, when averaged over the entire basin. Moreover, results are very similar also in terms of total amounts of rain during the 9-year period. TRMM 3B42 shows a slight tendency to underestimate rainfall, but this should not be overstated since comparisons are based on a very sparse raingauge network. It can also be seen that the SAT dataset also represents very well the seasonal

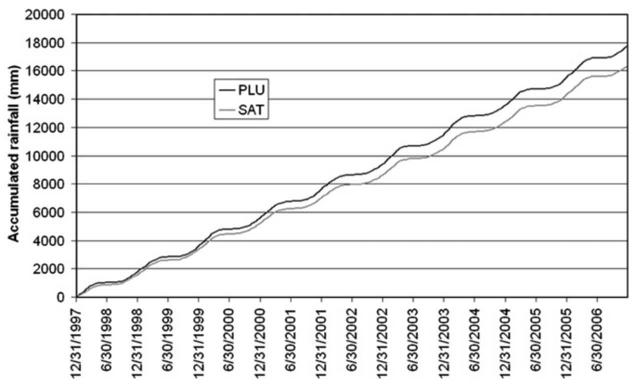

Figure 2 Accumulated mean daily rainfall over the Tapajós river basin for PLU and SAT datasets, period from 1/1/1998 to 31/12/2006.

variability between dry and wet periods, which is very pronounced in most parts of the Amazon region. Moreover, although the TRMM 3B42 estimation algorithm suffered some changes during the last 10 years, such as the inclusion of new sensors and a change of the satellite's flying altitude, from 350 to 403 km in 2001, no remarkable changes of trend can be noted.

Basin-average rainfalls were also compared on a monthly basis to explore whether seasonality exists in the differences, and Fig. 3 shows monthly rainfall from both datasets during the period of analysis.

Fig. 3 shows that TRMM 3B42 tends to underestimate rainfall during the wet season (October–April), while during the dry season (May–September), monthly totals are slightly higher than those from raingauges. However, overall seasonal variations of rainfall are very well distinguished by the TRMM-based estimates.

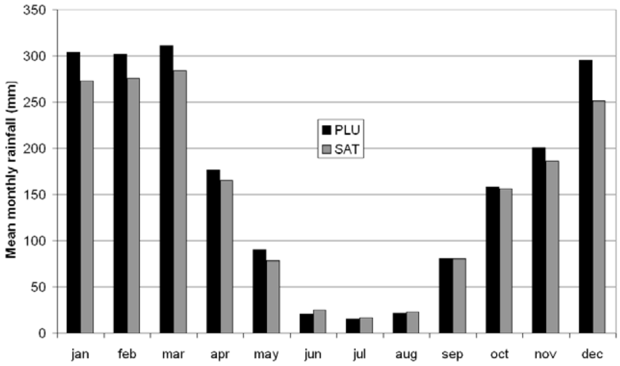

Figure 3 Averaged monthly rainfall over the Tapajós river basin, derived from both rain gauges and TRMM 3B42 data.

Comparison between rainfields

Fig. 4a shows the map of spatial differences between rainfall totals of the SAT and PLU datasets. White and light gray pixels represent 0.1° cells where SAT was higher than PLU, while dark grey to black pixels show cells where the opposite occurs.

Relative differences ranged from −39% to +25%. In general, however, differences stayed between −12% and +12%. In some regions, especially around certain raingauges (highlighted with numbers from 1 to 3), there were more significant differences which influenced the interpolated estimates of rainfall in neighbouring cells. Thus, this figure allows raingauges to be identified that deviate from the general trend found elsewhere in the basin. These raingauges may be poorly sited, perhaps close to trees or buildings, leading to biased measurements. In fact, the raingauge highlighted with number one was found to measure about 1200 mm year^{-1} from 1999 to 2003, which is significantly below expected rainfall for the region. After consulting CPRM (Brazilian Mining Research Company), is the agency responsible for collecting rainfall data in the basin, it was found that this gauge was leaking part of its catch, so that rainfall was underestimated; the gauge was replaced in 2004. However, it has not been possible do identify a clear

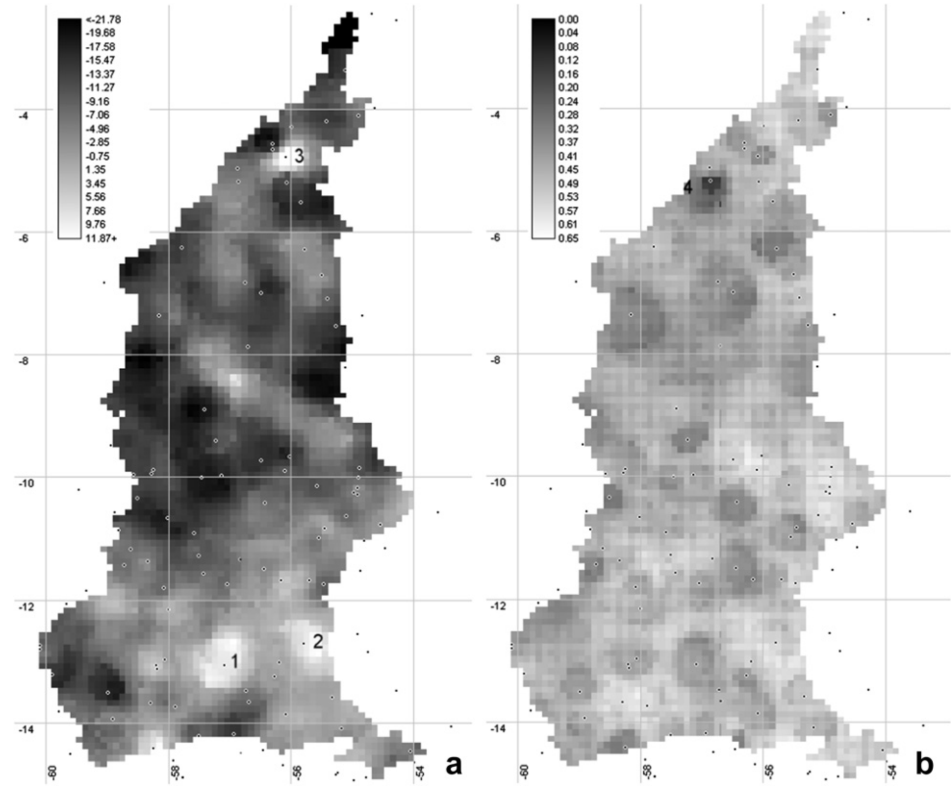

Figure 4 Spatial relative differences (a, in %) and correlation coefficients (b) between SAT and PLU datasets, period from 1998 to 2006. Dots indicate the location of raingauges.

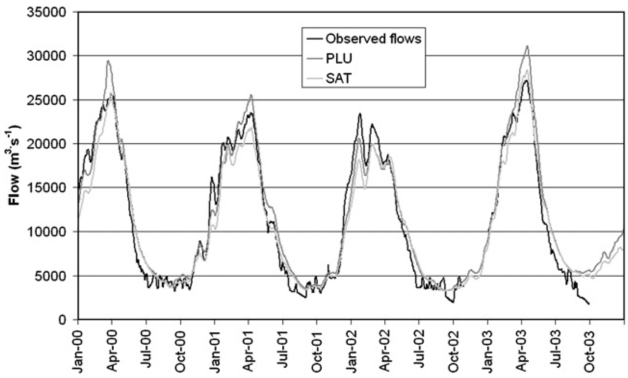

Figure 5 Results of PLU and SAT models at Itaituba flow gauge (460,000 km^2), from January 2000 to December 2003.

cause for the differences shown in Fig. 5a for raingauges marked with numbers 2 and 3.

Since the relative differences between rainfall totals say little about the distribution of errors in time, a map of correlation coefficients between SAT and PLU datasets was also calculated, as shown in Fig. 4b.

Correlation coefficients between SAT and PLU datasets in the 3917 0.1° cells ranged from 0.14 to 0.62. Most cells presented correlation coefficients around 0.4, showing that, on a daily basis, rainfall amounts from TRMM 3B42 pixels differ from punctual raingauge measurements. Again, one can observe an area around a raingauge in the northwestern part of the basin where correlation coefficients are quite low, deviating from the general correlation trend found in the remaining parts of the basin. This raingauge was marked with number 4 in Fig. 5b. Such a lower than normal correlation may be a result of accidental mismatching of rainfall dates, with the start of long periods of rainfall being recorded as beginning a day early or late.

It must be remembered that the 3B42 research product itself contains corrections based on ground raingauges, which would in part explain the relatively good agreement between SAT and PLU datasets. However, this adjustment is based only on gauges providing realtime data. Since only 23 of the 118 raingauges used in the generation of the PLU dataset are realtime, there is a significant difference between both datasets.

Rainfall—runoff simulation

Model calibrations allowed results to be generated for the whole of the Tapajós basin, whose drainage area is almost 500,000 km^2. Model results for the Itaituba flow gauge (460,000 km^2), close to the confluence of the Tapajós river with the Amazon, are shown in Fig. 5.

It is seen that flows calculated from the rainfall—runoff model using the 3B42 data-set as input agree fairly well with observed flows, and are similar to those obtained with the PLU model. For some peak flows, the SAT model was even better; however, the hydrological model used still has limitations. Although seasonal fluctuations were well represented, smaller peaks were dampened by both models. Fig. 6 compares results from model calibrations at the most important Tapajós flow gauges for both datasets. Circles

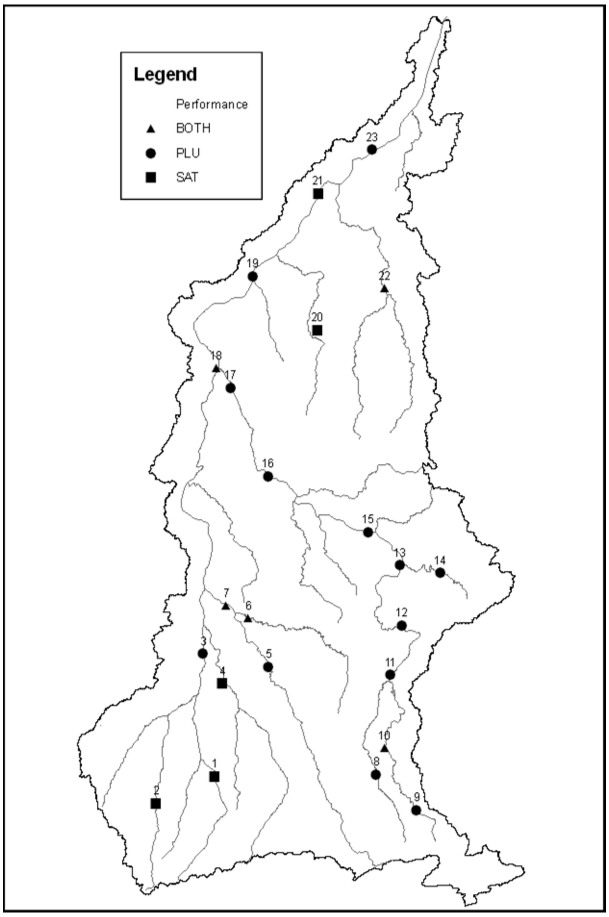

Figure 6 Comparison between results from PLU and SAT models at flow gauges in the basin. The symbol shows which model achieved the best Nash—Sutcliffe coefficient, whether PLU (circles) or SAT (squares). Triangles indicate gauges where both models achieved similar results.

represent gauges were the PLU model obtained better results, and squares represent gauges where the SAT model achieved higher Nash—Sutcliffe coefficients. Numerical values of Nash—Sutcliffe coefficients at each flow gauge are shown in Table 1.

In general, the MGB-PLU model still gave better results at most flow gauges. Even in the central portion of the basin, where raingauge density is lower, PLU gave higher Nash—Sutcliffe coefficients.

Although PLU gave better results at gauges along the main Tapajós channel, the Nash—Sutcliffe for PLU decreased from 0.96 to 0.93 in the reach between gauges Fortaleza and Acará do Tapajós (gauges 19 and 21, Fig. 6). The SAT model, instead, increased from 0.92 to 0.95 in the same reach. This reach is located in a region with low correlation coefficients between PLU and SAT dataset (highlighted with number 4 in Fig. 4b), suggesting that a raingauge in this region is not measuring rain adequately or that its coordinates in the database do not match its actual position. This raingauge strongly influences PLU results in this region, resulting in lower Nash—Sutcliffe coefficients.

The MGB-SAT model gave better results than MGB-PLU in some sub-basins, remarkably in those situated at the south-

Table 1 Nash—Sutcliffe coefficients for PLU and SAT models after calibration for the existing gauges at Tapajós river basin

#	Gauge name	Nash—Suttcliffe coefficients	
		PLU	SAT
1	Fazenda Tucunaré	0.54	0.70
2	Fazenda Satélite	0.62	0.68
3	Fontanilhas	0.89	0.87
4	Fazenda Tombador	0.81	0.87
5	Porto dos Gaúchos	0.91	0.89
6	Rio dos Peixes	0.91	0.91
7	Rio Arinos	0.99	0.99
8	Lucas do Rio Verde	0.89	0.85
9	Porto Roncador	0.90	0.86
10	Teles Pires	0.96	0.96
11	Cachoeirão	0.95	0.94
12	Fazenda Tratex	0.96	0.93
13	Indeco	0.96	0.94
14	Estrada Cuiabá-Sant	0.93	0.86
15	Jusante Foz P.A.	0.97	0.94
16	Santa Rosa	0.96	0.94
17	Três Marias	0.98	0.97
18	Barra do São Manuel	0.96	0.96
19	Fortaleza	0.96	0.92
20	Creporizão	0.74	0.77
21	Acará do Tapajós	0.93	0.95
22	Jardim do Ouro	0.91	0.91
23	Itaituba	0.96	0.94

The numbers correspond to those in Fig. 7.

western part of the Tapajós basin. This region is characterized by rivers with a high contribution of groundwater flows. To illustrate this, results of model calibration are presented for gauge marked as number 4 in the map (Fazenda Tombador on Sangue river). Calibration results for MGB-PLU and MGB-SAT models at this location are shown in Fig. 7.

According to Smakhtin (2001), the ratio between Q_{90} and Q_{50} (Q_{90}/Q_{50}) may be interpreted as an index representing the proportion of streamflow originating from groundwater, excluding the effect of catchment area. For this sub-basin, this ratio was equal to 0.73, indicating a high contribution from groundwater. MGB-PLU achieved a Nash—Sutcliffe coefficient of 0.81, while for MGB-SAT it was 0.87. In fact, Fig. 7 shows that MGB-SAT better represented recession periods, as well as most of the peaks.

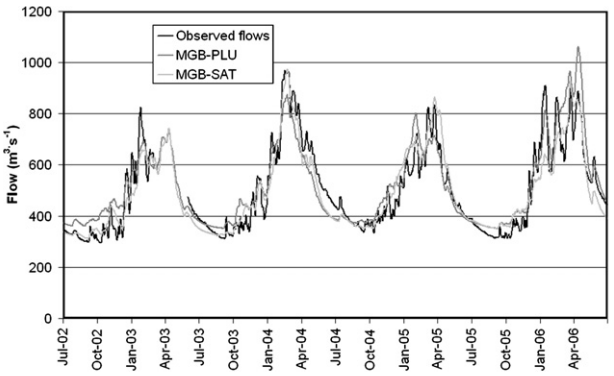

Figure 7 Calibration results for MGB-PLU and MGB-SAT at Fazenda Tombador gauge (area 25,918 km^2) from 01/07/2002 to 30/6/2006.

Similar results were achieved for the gauge at Fazenda Tucunaré on the Juruena river, and the gauge at Fazenda Satélite on the Sacre river, where the Q_{90}/Q_{50} ratios were 0.89 and 0.84, respectively. Results suggest a trend for MGB-SAT to give better results in groundwater-dominated watersheds. This may be because model performance in such watersheds is more sensitive to an accurate representation of spatial distribution of rain, and less sensitive to uncertainties in point rainfall depths, since high infiltration capacity ''buffers'' stronger storms. This hypothesis would explain the better result of MGB-SAT in these sub-basins.

Conclusions

TRMM 3B42 research rainfall estimates can be considered reliable, reproducing the rainfall regime of the Tapajós basin fairly well. Seasonal variability of rain is well represented. The 3B42 research estimates still differ from point measurements but, when averaged over the basin, results are very similar to those obtained from raingauge data.

More extensive tests in other basins are needed to improve experience in combining conventional rain measurements with remote sensing estimates. However, this work has shown that these estimates can represent temporal and spatial patterns of rain in a useful way, at least in Brazilian tropical basins. Results also show that it is possible to use satellite estimates to help in raingauge consistency analysis, since the maps of relative bias generated in this work allow regional bias to be delineated. This is a potential tool for data consistency over the entire basin, assisting the identification of faulty raingauges. Given that TRMM and raingauge data are generally well correlated, any situation where errors were higher than normal should be verified in order to check for the presence of errors in ground measurements resulting from factors affecting gauge catch such as obstacles, location change, equipment failure and timing errors.

Results given in this paper suggest that TRMM 3B42 research estimates can be used as input to distributed rainfall–runoff modeling in tropical South-American basins. In most sub-basins of the Tapajós river basin, the hydrological model driven by rainfall data observed at conventional raingauges still gave better results, suggesting that conventional raingauge measurement is still a more reliable way of quantifying rainfall than satellite estimates; but where there is a severe lack of conventional rainfall data, satellite estimates can be a helpful alternative source of data for rainfall–runoff simulation.

In some specific sub-basins with high contribution from groundwater to streamflow, MGB-SAT achieved results that were better than those from MGB-PLU. That is possibly associated with higher infiltration capacity of soils, so that hydrographs are more dependent on monthly or seasonal rainfall and less sensitive to errors on a daily basis.

The Amazonian region seems to present very good agreements between satellite estimates and gauge data, even on a daily basis. This is not necessarily true for similar studies in other regions, such as the La Plata basin. A possible explanation for this better performance may be the differences in the nature of rainfall in each of those regions; in the Amazon region, there is a predominance of convective rainfall, which tends to form at much higher altitudes, thus producing more ice crystals than the frontal rain which predominates in more temperate regions. The precision of microwave estimates is related to the amount of scattering that microwave radiation suffers when reaching ice crystals, so convective rain tend to be more precisely detected by TRMM.

One of the more promising applications of satellite-based rainfall estimates in Brazil is the coupling of rainfall measured in real time, meteorological forecasts and rainfall–runoff models for flow forecast, since there are very few real-time raingauges in most of the country. More precise, physically based flow forecasts would be useful for reservoir operation of hydropower dams, which account for almost 90% of Brazilian energy supply. For this purpose, however, the 3B42 RT should be tested as input.

It is possible that satellite rainfall estimates will improve in the near future. According to its developers, the TRMM project achieved satisfactory results and significant improvement of knowledge about water and energy budgets (Kummerow et al., 2000). This success is leading to an extension of the project; recent information indicates that the life of the TRMM satellite will be extended until 2010 (http://trmm.gsfc.nasa.gov/). Moreover, TRMM will be followed by GPM-Global Precipitation Measurement (Smith et al., 2007), a constellation of 10 low-orbit satellites to be launched in 2013. GPM is expected to improve sampling frequency, which is still a limiting factor of rainfall estimates derived from circle-orbit satellites such as TRMM, thus improving availability and accuracy of rainfall estimates. Rainfall–runoff simulation with these estimates as input is expected to improve accordingly, perhaps becoming as reliable or even better than simulation with conventional rainfall data.

However, it is very unlikely that remote sensing of precipitation will completely replace ground based measurements. It is possible that the best information for hydrological applications will be the combination of remote sensing and ground data. Since satellite-based rainfall estimates provide a good representation of spatial patterns of rain, but are often not as precise as point ground-level measurements, methods that combine satellite estimates and raingauge data need further development and test.

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