



## How well does the ERA40 surface water budget compare to observations in the Amazon River basin?

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[1] The surface water budget of the Amazon River basin derived from the ERA40 reanalysis is evaluated by comparing it with observed precipitation (P), streamflow/runoff (R), and evapotranspiration (ET) data sets for the period of 1980–2002. The rainfall is averaged over 90% of the Amazon River basin, corresponding to the catchments of the Óbidos and Altamira streamflow gauges. The annual rainfall and the interannual changes from ERA40 fall within the range of the two precipitation data sets. On the seasonal timescale, ERA40 reproduces well the rainfall during the dry and transition seasons, but it underestimates the wet season rainfall by 4–11% when compared with the two precipitation data sets. On the subbasin scale, the disparity in precipitation between ERA40 and observations is as much as  $\pm 40\%$ . The annual runoff integrated over the two catchments is underestimated in ERA40 by 25%. The rain-rates in ERA40, which affect both throughfall and runoff, are comparable to those measured by the Tropical Rainfall Measurement Mission (TRMM 3B42V6), when these are rescaled to the resolution of the  $2.5^\circ$  ERA40 data. However, even the native resolution of ERA40 ( $\sim 1.125^\circ$ ) is greater than the scale of tropical convection. ET in ERA40 appears to be higher than observations by about 20%, although observed ET may have a 10% low bias. The difference between precipitation and runoff, P-R, in ERA40 generally agrees with observations. However, annual ERA40 ET is greater than P-R, because soil moisture nudging adds water to the soil. On the seasonal scale, soil moisture nudging is largest during the dry season, because ERA40 provides only a 45 mm surplus of P-R relative to ET during the wet season, whereas the deficit in the dry season is almost four times greater. This low bias in wet season soil moisture recharge may be caused by the underestimation of wet season rainfall in ERA40. It is possible that the model interception may have a high bias, which contributes to the high ET in the rainy season and reduces the wet season storage.

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### 1. Introduction

[2] The reanalysis products produced by global forecast and analysis systems that assimilate observations have increasingly been used for validation, verification and initialization of regional models, as well as for diagnostic studies of atmospheric and hydrological processes [Betts *et al.*, 2003, 2005; Coe, 2000; Dai and Trenberth, 2002; Hagemann and Gates, 2003; Lenters *et al.*, 2000; Roads and Betts, 2000; Seneviratne *et al.*, 2004; Zeng, 1999]. The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, known as ERA40, is regarded as one of the best available reanalysis products. It is particu-

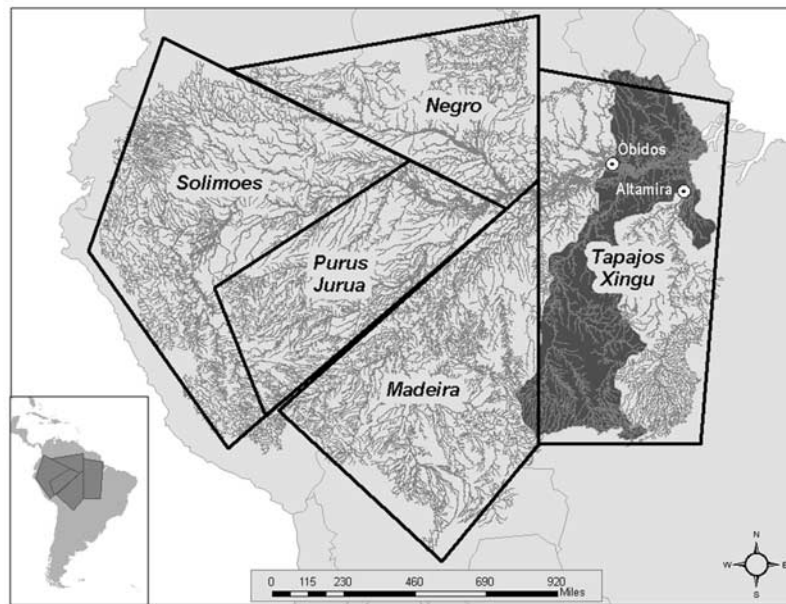
larly useful for studies in areas that lack an adequately dense observational data network, such as the Amazon River basin.

[3] However, Betts *et al.* [2005] find that errors in the atmospheric moisture analysis resulted in spurious decadal changes of ERA40 precipitation and runoff. The authors propose a correction that removes these large errors, but the interannual variability is poorly correlated with observations in the Amazon. Marengo [2005], using the National Centers for Environmental Prediction (NCEP) reanalysis, suggest that the nonclosure of the water cycle budget may mean that this reanalysis does not realistically represent these fields over the Amazon Basin.

[4] This paper further examines how well ERA40 hydro-meteorological variables agree with observations on seasonal, annual, and interannual scales; and diagnoses possible causes for the discrepancies between the reanalysis and observations. The role of soil moisture nudging in

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**Figure 1.** Drainage areas of the Amazon River and its main tributaries, and the locations of the Óbidos and Altamira river flow gauges. The dark gray shade represents the ungauged portion of the basin.

maintaining evapotranspiration through the dry season is also assessed.

## 2. Data and Methods

### 2.1. ECMWF Reanalysis (ERA40)

[5] ERA40 reanalysis data are available at a spatial resolution of  $2.5^\circ$  latitude by  $2.5^\circ$  longitude on the ECMWF website. The reanalysis project also generated basin-averaged data subsets designed to study the hydrometeorology of 31 river basins in the world. The Amazon River basin in ERA40 is divided into five subbasins with a total area of 5.71 million  $\text{km}^2$  (Figure 1). These subbasins are Rio Tapajós-Xingu, Madeira, Solimões, Negro, and the fifth basin includes several tributaries to the Amazon including the Juruá and Purus Rivers. These data are composed of twice-daily segments of the 0–12, 12–24, 24–36 h forecasts (FX). For this study the 0–12 FX data were used, because the time needed for precipitation spin-up/spin-down is small for the Amazon [Betts *et al.*, 2005]. For the entire Amazon Basin, the seasonal cycle of ET, P-R and the ERA40 soil moisture analysis increment were calculated by weighting each basin with its partial area.

[6] For the basin-wide comparison of ERA40 with observations, the gridded data were averaged over the catchment areas of the Óbidos and Altamira streamflow gauges. This excludes the Tapajós River basin, which is ungauged (see section 2.2). The hydrological years, from September to August of the following year, are used to compute annual means, and to examine the seasonal cycle between the period of 1980 and 2002, when both river discharge and precipitation data are available. For the evaluation of ERA40 ET against flux tower data, a special ERA40 output for single  $1.125^\circ \times 1.125^\circ$  grid points that overlap each flux tower were used.

### 2.2. Observational Data

[7] The ERA40 data do not have river routing information, so the runoff can be compared to observed streamflow only when it is integrated over the annual cycle for the entire upstream drainage area relative to the streamflow gauges. This is because the mean residence time of runoff can be up to five months in the Amazon River basin [Chapelon *et al.*, 2002; Marengo, 2005]. Two streamflow gauge stations, Óbidos ( $1.9^\circ\text{S}$ ,  $55.46^\circ\text{W}$ ) and Altamira ( $3.2^\circ\text{S}$ ,  $52.2^\circ\text{W}$ ), hereafter referred to as O+A, cover about 5.12 million  $\text{km}^2$  or 90% of the Amazon River basin. The Óbidos station monitors flow from most of the Amazon River basin including major tributaries such as the Solimões, Madeira, Purus-Juruá, and Negro Rivers. Altamira measures the flow from the Xingu River. The only major tributary not represented in these data is the Tapajós River to the south of the Amazon River main stem, roughly corresponding to the western half of the box labeled as Tapajós-Xingu in Figure 1.

[8] ERA40 precipitation was compared with two observational data sets. These are the Global Precipitation Climatology Project (GPCP-Version 2) [Adler *et al.*, 2003] and the Global Land Precipitation by the Climate Prediction Center (CPC) [Chen *et al.*, 2002], hereafter referred to as GPCP and CPC respectively. GPCP uses precipitation estimated from the Special Sensor Microwave/Imager data on polar-orbiting satellites to calibrate precipitation estimated from the infrared brightness temperatures measured by geostationary satellites. The satellite estimated precipitation is also calibrated by the rain gauge analysis [Adler *et al.*, 2003]. The gauge-only CPC method consists of defining the analysis value at a grid point by modifying a first-guess field with the weighted mean of the differences between the observed values and the first-guess values at station locations within a searching distance. A 10-year precipitation mean is used as the first guess, and the

**Table 1.** Locations, Experiment Periods, and Types of Surrounding Vegetation for the Flux Towers Used in This Analysis<sup>a</sup>

Flux Towers	Location	Years	Site Description
Floresta Nacional do Tapajós-km 83 ( <b>Tapajós</b> )	3°S, 55°W	2001 and 2002	Primary forest, selectively logged in Sep 2001.
Manaus-km 34 ( <b>Manaus</b> )	2.5°S, 60°W	2000 and 2002	primary forest
Reserva Biológica de Jaru ( <b>Jaru</b> )	10.1°S, 61.9°W	2001 and 2002	primary forest
Reserva Ducke Manaus ( <b>Ducke</b> )	2.5°S, 60°W	1984 and 1985	primary forest
Reserva Biológica de Cuieiras ( <b>Cuieiras</b> )	2.5°S, 60°W	1996	primary forest

<sup>a</sup>Names by which the towers are referred to in the text are in parenthesis.

searching distance is set to 300 km [Chen *et al.*, 2002]. Observed basin-mean rainfall is calculated for the O+A catchments using these two rainfall data sets.

[9] Direct measurement of ET is only available at a few sites in the Amazon, and these have relatively short time series. We use data from three Large-Scale Biosphere Atmosphere (LBA) Experiment flux towers and from one that precedes LBA. These are respectively the Floresta Nacional do Tapajós (km83), Manaus (km34), Reserva Biológica de Jaru, and Reserva Ducke-Manaus towers. We also used the ET values at the Reserva Biológica de Cuieiras, taken from Malhi *et al.* [2002]. Table 1 lists the location, period of experiment and vegetation type for each flux tower. The flux towers at Manaus, Cuieiras, and Ducke are located within the same grid point in ERA40. All flux towers are located in undisturbed primary forest, except for the Tapajós tower site, where selective logging occurred about one year after the tower installation.

[10] Runoff in ERA40 is primarily deep runoff or base flow, which increases rapidly once soil water in the 1 to 2.9 m soil layer exceeds some threshold greater than the field capacity. Surface runoff almost never occurs in ERA40 unless the soil is frozen. Infiltration of rainfall to the deep soil depends on the soil hydraulic properties, which are assumed uniform globally. Precipitation throughfall, which is determined by precipitation minus canopy interception loss, is computed in ERA40 based on the model proposed by Rutter *et al.* [1975]. The amount of water intercepted by vegetation varies with the leaf area index and the intensity of rainfall. A greater percentage of rainfall is intercepted by the forest canopy during an episode of light rain than during a storm with heavy rain. Interception loss in ERA40 is however not readily available to users, nor is it available from observations on the basin scale. So instead we evaluate the intensity of rain in this study.

[11] To estimate rain-rate, we use the TRMM merged passive microwave precipitation estimates/infrared precipitation product, specifically the 3B42V6 product [Adler *et al.*, 2000; Kummerow *et al.*, 2000]. These data were derived from the combined instrument rain calibration algorithm (3B42), which uses intercalibrated passive microwave estimates, microwave-adjusted infrared estimates from geostationary satellites, and adjustments to monthly gauge data. The TRMM rain-rate 3B42V6 product is available at a spatial resolution of 0.25° every 3 h in units of millimeters per hour. Rain-rates from these data were binned to 2.5° and 6-h resolutions to match those of ERA40. We then compare ERA40 and TRMM by calculating the cumulative probability density functions for the hourly rain-rates at each grid

for the entire domain of 80°W–40°W and 20°S–5°N and the period 1 January 1998 to 31 August 2002 when ERA40 and TRMM data overlap.

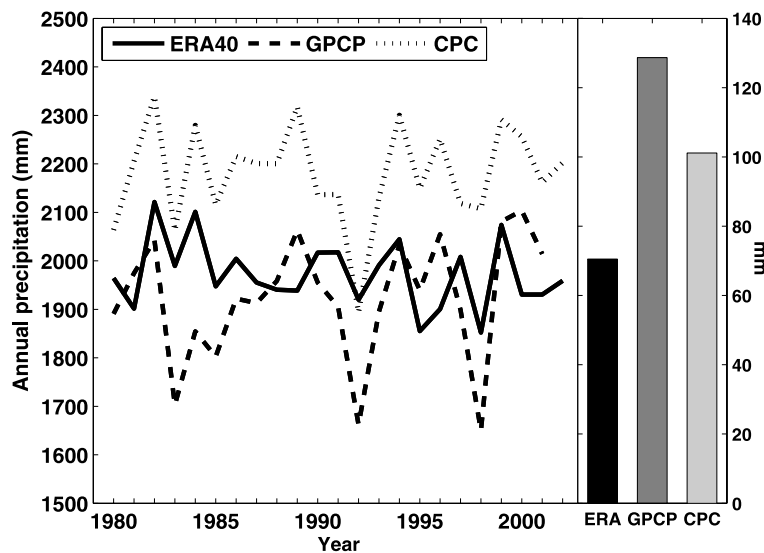
### 3. Results

#### 3.1. Precipitation

[12] Figure 2 shows the basin-mean annual precipitation in ERA40 compared with the GPCP and CPC data sets. Annual rainfall in ERA40 is on average 3% greater than that estimated by GPCP, but 10% less than that estimated by the CPC data set. Thus ERA40 falls within the uncertainty of the observations. Rainfall in the GPCP data set after 1986 is calibrated by rain gauges from the Global Precipitation Climatology Centre (GPCC) data [Adler *et al.*, 2003]. The ten-year mean annual rainfall of the GPCC data set is as much as 2 mm d<sup>-1</sup> lower than that of the CPC over tropical South America [Chen *et al.*, 2002], leading to a lower annual rainfall in the GPCP data. However, which rainfall data set more realistically represents the actual annual rainfall remains unclear. Additional constraints from other independently measured variables in the surface water budget will be discussed later in this paper to explore this question.

[13] Interannual variations of basin-averaged rainfall in the Amazon, shown as standard deviation bars on the right-hand-side in Figure 2, are generally within 7% of the annual mean for the period of this study, with the greatest deviations during El Niño-Southern Oscillation (ENSO) episodes. The years of 1983, 1992, and 1998 were strong El Niño years and were associated with the lowest observed precipitation, except for the CPC precipitation in 1998. The years 1989 and 1999 are among the highest annual precipitation totals in the series, consistent with strong La Niña episodes [Ropelewski and Halpert, 1987; Neelin *et al.*, 1998]. The interannual variations of the two observational data sets are more highly correlated than either of them is to the interannual time series of ERA40. The reanalysis tends to underestimate the interannual variability by overestimating precipitation for El Niño (e.g., 1992) and underestimating La Niña (e.g., 1989 and 1999) episodes, when compared to observations. 1992 was the only year when ERA40 produced more rain than both the GPCP and the CPC data sets.

[14] How well ERA40 captures the seasonal cycle of rainfall is evaluated in Figure 3. The phase of the ERA40 seasonal cycle agrees well with observations. The amplitude of the rainfall seasonal cycle is however underestimated compared to both GPCP and CPC, showing, respectively, a



**Figure 2.** Basin-averaged annual rainfall in ERA40, CPC, and GPCP data sets. The bars on the right represent annual standard deviation for ERA40, GPCP and CPC respectively.

low bias of 4% and 11% or 9 to 25 mm per month during the wet season (December to March). From the middle of the dry season (July) to the end of the transition season (November), the rainfall amounts in ERA40 agree with the CPC data, but they are as much as 22% (or 20 mm/month) higher than the GPCP data.

[15] The spatial distribution of rainfall is investigated in Figure 4 for December to February (DJF) and June to August (JJA), by subtracting the CPC precipitation from that of ERA40. During DJF, rainfall in ERA40 is on average lower than CPC (shaded areas in Figure 4) over most of the Purus-Juruá, Madeira, and Tapajós-Xingu subbasins. The low biases of rainfall in these basins are the main contributor to the underestimation of basin mean rainfall during the wet season (Figure 3). During the dry season, however, ERA40 rainfall is higher (lower) than that of the CPC by as much as 300 mm in parts of the Purus-Juruá and Madeira River (Negro and Solimões River). Figure 4 suggests that the subbasin rainfall may have larger percent errors than the Amazon basin average.

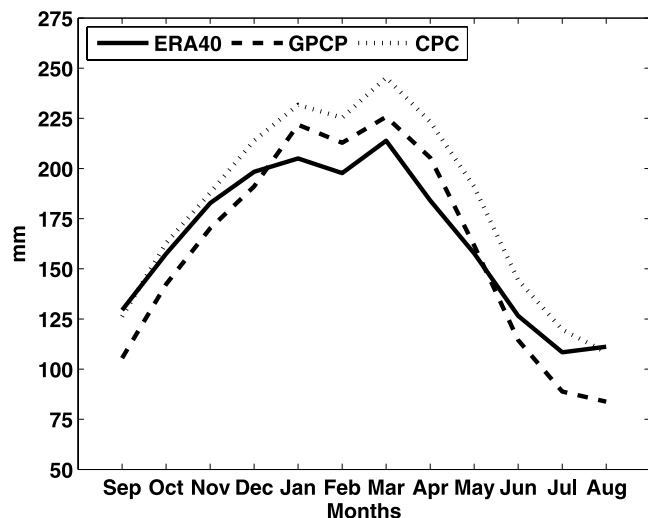
### 3.2. Runoff and Rainrate

[16] Figure 5 shows basin-averaged runoff compared to total river discharge at the streamflow gauges of Óbidos and Altamira, both near the mouth of the Amazon (Figure 1). The bars on the right-side of Figure 5 represent the standard deviations of ERA40 and observed annual runoff. ERA40 annual runoff underestimates river streamflow by 25% on average for the period of 1980–2002. ERA40 also shows a small decrease in runoff during the 1990s compared to the 1980s, while the streamflow observations show no clear trend. Some of this spurious interannual variability in runoff and precipitation in ERA40 is related to problems with the atmospheric moisture analysis [Betts *et al.*, 2005]. Clearly, however, the runoff fraction is underestimated in the re-analysis.

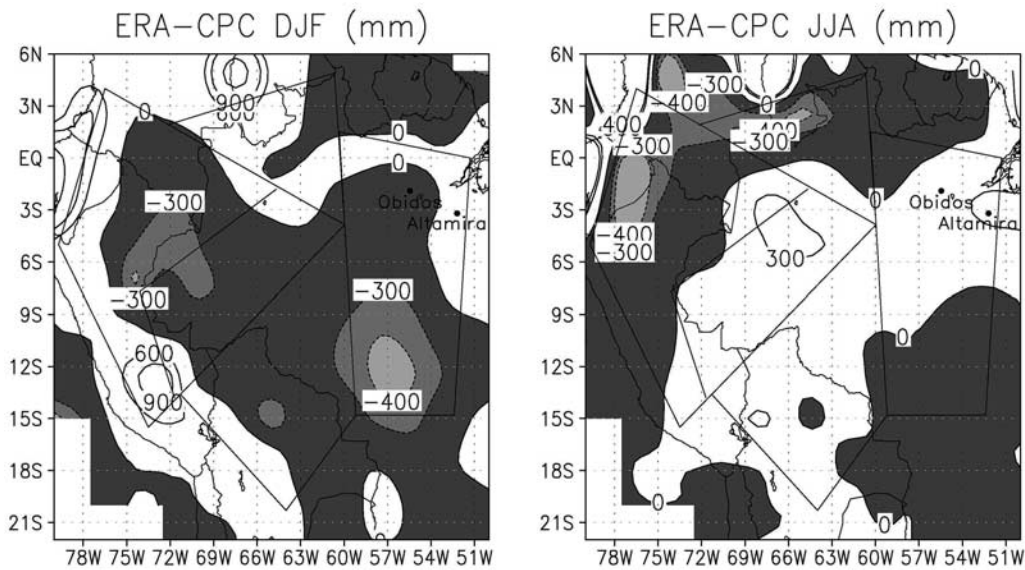
[17] To explore whether errors in the ERA40 runoff might be influenced by inadequate throughfall, we compare rainfall intensity between ERA40 and TRMM observations. In

densely vegetated areas, a significant amount of precipitation may stay on the leaves and evaporate. A single storm can saturate the canopy very quickly, whereas drizzle tends to produce a greater interception loss fraction for the same total rainfall. Therefore an adequate estimate of precipitation intensity, as well as a realistic model for the interception loss, is important to simulate throughfall.

[18] Figure 6 compares the cumulative probability density function for the 2.5° grid 6-hourly rainrate between ERA40 and TRMM. The values of rainrate are lower than those reported in literature [Anagnostou and Morales, 2002; Cutrim *et al.*, 2000] due to the lower spatial and longer temporal resolutions used in this analysis that are constrained by the ERA40 rainfall output. The results indicate a lower frequency of occurrence of lighter rain and higher occurrence of relatively heavier rain in ERA40 compared to



**Figure 3.** Mean annual cycle of ERA40, GPCP, and CPC precipitation for the period 1980–2002.



**Figure 4.** Differences between ERA40 and CPC for the mean seasonal total precipitation for the period 1980–2002 (Unit: mm). The left panel shows the wet season (DJF) and the right panel shows the dry season (JJA). The polygons represent the five Amazon subbasins in ERA40. The areas where ERA40 rainfall is lower than that of CPC (negative difference) are shaded.

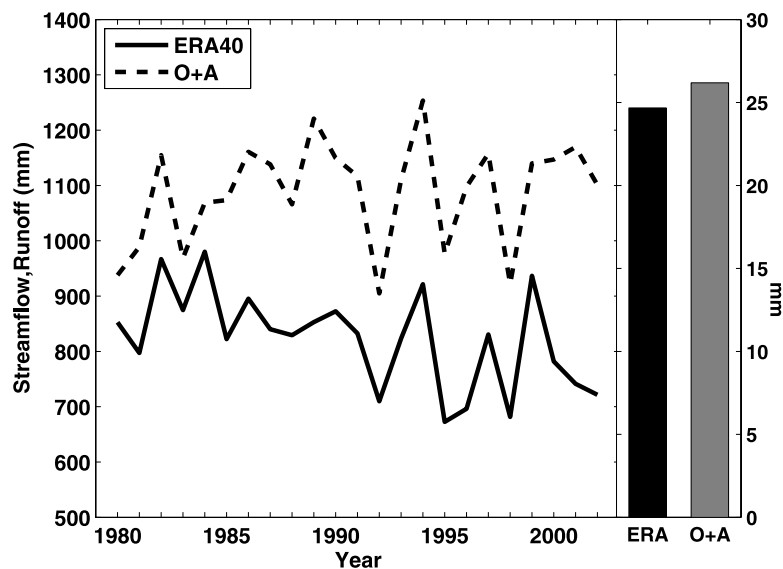
the TRMM data, consistent with the results of *Huffman et al.* [2007] that shows underestimation of light rain in TRMM. However, the 2.5° resolution of these ERA40 data is too coarse to resolve the actual rain-rate at the spatial scale of convective systems (~10 km to 100 km). An earlier study [*Betts et al.*, 2006], which compared ERA-40 evaporation with flux tower data over the boreal forest, suggested that ERA40 might have too much evaporation off wet canopies, but we cannot assess this with these rain-rate data.

### 3.3. Evapotranspiration

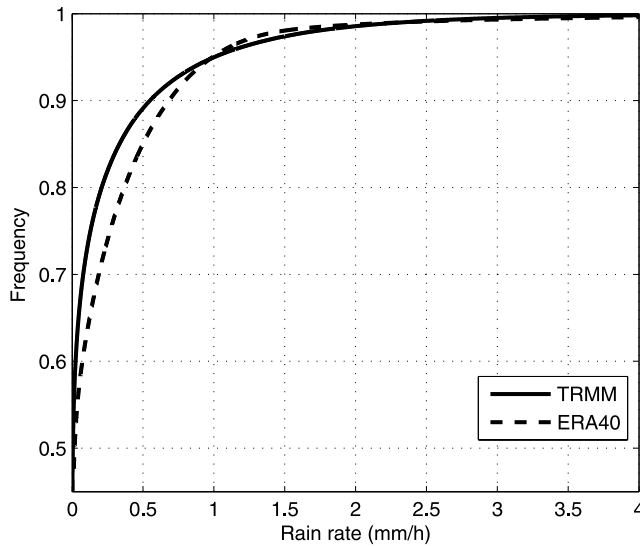
[19] Evapotranspiration (ET) is one of the most poorly observed variables in the atmospheric water budget. Rean-

alyses have been used as a surrogate for observed ET in previous studies of the hydrological cycle and wet season onset in the Amazon [*Eltahir and Bras*, 1994; *Li and Fu*, 2004; *Rao et al.*, 1996]. In this study, ERA40 ET is evaluated against the ET measured at the flux tower locations in the eastern, central, and southern Amazon.

[20] Figure 7 shows the annual mean ET for the periods and locations listed in Table 1. ET at these sites is measured by the eddy-covariance method, which is the most direct and accurate method available. The ET values are consistent with those previously estimated for the Amazon [*Eltahir and Bras*, 1994; *Matsuyama*, 1992; *Vorosmarty et al.*, 1996]. Although ET in ERA40 agrees with ET measured

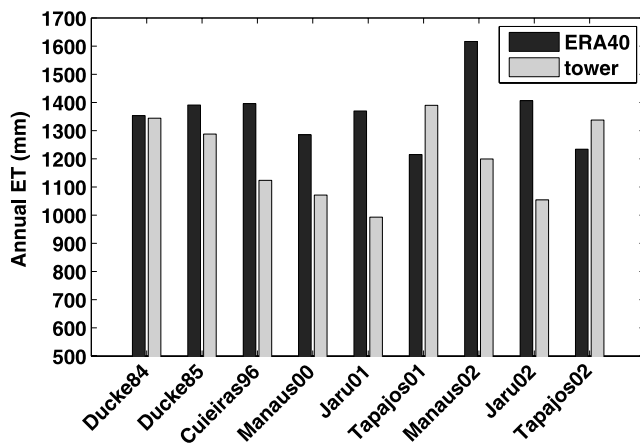


**Figure 5.** Annual streamflow measured at Óbidos and Altamira, and the corresponding mean runoff for the same drainage area in ERA40 (Unit: mm). The bars on the right-hand side indicate the standard deviations of annual runoff in ERA40 and the observed streamflow.



**Figure 6.** Cumulative distribution function of hourly rainrate for the 2.5° grids for ERA40 and TRMM data. Unit: mm/h.

in the 1980s, it appears to have 15%–30% high bias compared to later observations in central and southern Amazon. Does this result suggest a possible overestimation of ET by ERA40? It is important to note that the sum of the surface latent and sensible fluxes measured by the eddy-covariance method can be 10% to 30% lower than surface net radiative flux [Finnigan *et al.*, 2003; von Randow *et al.*, 2004]. For example, Foken *et al.* [2006] estimated that the lack of energy closure implies a possible ET underestimation of about 15%. However, Malhi *et al.* [2002] showed that energy balance closure of for the Cuieiras site was within 5% for timescales longer than 4 h, suggesting a high confidence in flux measurements for that site. ET in ERA40 agrees with observations within the observational uncertainty of 15% at Ducke and Tapajós in the equatorial central and eastern Amazon. However, at Jaru, Cuieiras, and Manaus in the southern and central Amazon, the ERA40 reanalysis



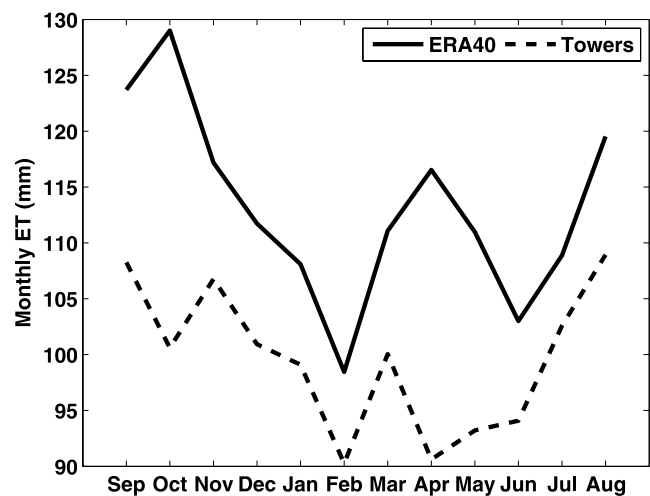
**Figure 7.** Comparison between the annual ET at ERA40 grid points, co-located with flux tower measurements, showing the locations (see Table 1) and the year(s) of the field experiments. Unit: mm.

overestimates ET beyond the data uncertainty. The seasonal cycle of the ET shown in Figure 8 suggests a systematically higher ERA40 ET in all seasons compared to the observations. However, the limited sample size and large variability of the ET measurements prevent us from determining whether the differences are significant or not.

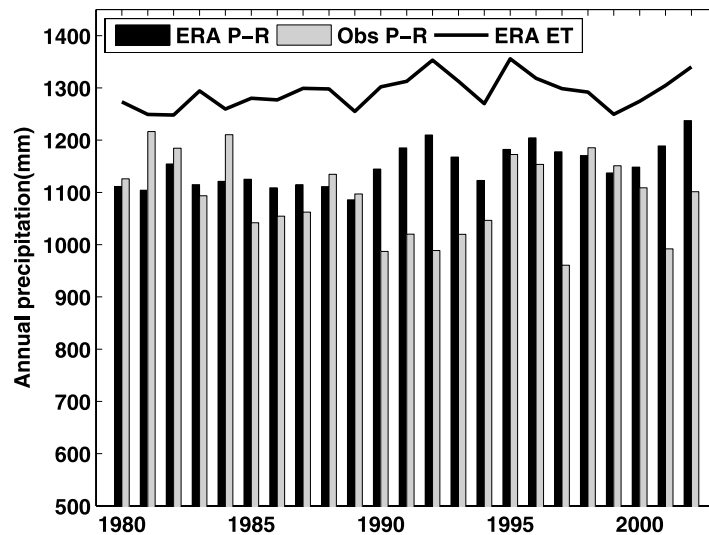
[21] In ERA40, increments of soil moisture (and first-layer soil temperature) are added based on the differences between simulated and observed screen-level humidity and temperature [Douville *et al.*, 2000]. These increments effectively nudge the soil moisture to maintain a model ET that gives a more realistic screen-level diurnal cycle of humidity and temperature. In the dry season, the addition of soil water is substantial.

[22] The difference between annual basin-mean P and R (denoted as P-R) would closely balance ET in the absence of soil moisture nudging. Figure 9 compares (P-R) with the actual ET in ERA40, and with the observed (P-R) derived from the CPC precipitation data and the streamflow gauge data. The difference between the actual ET and P-R in ERA40 indicates how much water has been added as soil moisture increments on the annual timescale. The annual P-R in ERA40 agrees overall with that observed, although ERA40 underestimates both rainfall and runoff compared to the CPC data and streamflow measurements. The actual ERA40 ET is about 10% higher than the ERA40 P-R over the study period, similar to the average 10% high bias when compared to the flux tower measurements (Figure 7). The overestimation of annual ET relative to both the ERA40 and observed P-R, and to the flux tower ET, suggests that the soil moisture nudging may be one of the causes. In particular, while nudging leads to a good agreement with the ET measurements at the Ducke and Tapajós towers, it overestimates ET in other sites especially in the southern Amazon (Figure 7).

[23] Figure 10 shows the mean annual cycle of ERA40 P-R and ET for the period 1980–2002 along with the mean annual cycle of the soil moisture increments for the same period (but excluding the years 1989 to 1994 for which the 06 and 18UTC forecast are missing from this basin archive).



**Figure 8.** Mean seasonal cycle of ET for ERA40 and flux tower measurements, derived from data shown in Figure 7.



**Figure 9.** ERA40 ET compared with the time series of the annual mean P-R in ERA40 and that derived from the CPC and river flow gauges for the period of 1980 to 2002.

The surplus of P-R over ET, which is available to recharge the soil moisture storage during the wet season (November to February), is about 45 mm. This is only about 28% of the 162 mm needed to maintain a realistic ET during the dry season, as indicated by the deficit of P-R relative to ET during the period from April to September. Hence extra water has to be added to the soil in the dry season. The annual budget of P-R relative to ET shows a deficit of about 123 mm, which is mostly compensated by the soil moisture nudging (113 mm per year).

[24] Observations, on the other hand, suggest that the soil moisture recharge during the wet season is sufficient to maintain dry season ET, even when the dry season rainfall is reduced to more than 50% of its normal value [Juarez *et al.*, 2007]. Thus insufficient recharge of the soil moisture storage during the wet season is probably the main cause of the insufficient soil moisture supply during the dry season, and the subsequently large soil moisture nudging in the reanalysis. It is also possible that the model interception may have a high bias [Betts *et al.*, 2006], which contributes to the high ET in the rainy season, and reduces the wet season storage. Another issue is that the soil water reservoir in ERA40 is only 2.89 m deep, and most of the roots are located in the first meter. In contrast, von Randow *et al.* [2004] show that the forest drawdown of soil water in the dry season is almost as large for the 2–3.4 m layer as for the 0–2 m layer. Thus a shallow rooting layer may contribute to a lower seasonal soil moisture storage capacity in ERA40.

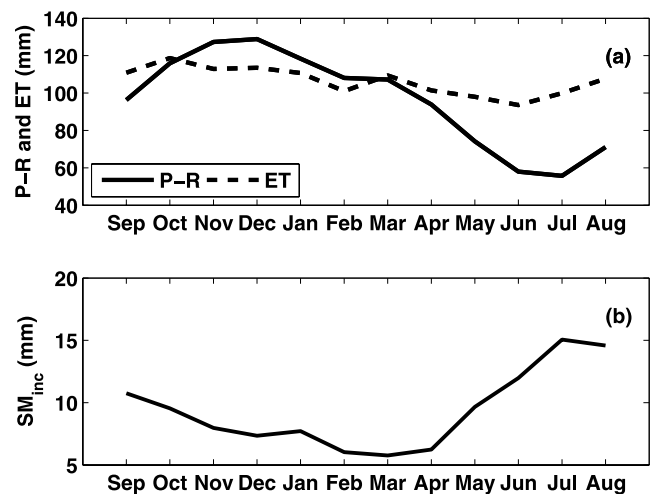
**3.4. Annual Mean Water Budget**

[25] Due to the lack of basin-scale ET observations and the discrepancies between different rainfall data sets, the research community was previously unable to balance the water budget for the Amazon River basin [Marengo, 2005]. To address this problem, we explore an alternative way to infer basin-scale ET, and determine how well we can balance the water budget for the Amazon River basin using available information. Currently, ET measured by the eddy covariance method at flux towers is considered the most

reliable estimate of ET, but these ET measurements are only available at a few sites in the Amazon River basin. ERA40 represents the large-scale patterns of the atmosphere for the whole basin, but may have a bias in its ET values. Using the data sets in Figure 7, we averaged annual ET at the flux tower sites ( $ET_{obs,towers}$ ) and at the corresponding ERA40 grid boxes ( $ET_{ERA40,towers}$ ) and used this ratio to calibrate the basin mean ET of ERA40 ( $ET_{ERA40,basin}$ ) to give a simple climatological estimate of annual basin ET, corrected to these flux tower observations ( $ET_{obs,basin}$ ). That is,

$$ET_{obs,basin} = ET_{obs,towers} \frac{ET_{ERA40,basin}}{ET_{ERA40,towers}} \quad (1)$$

[26] Clearly, the time series of in situ ET observations are too short to estimate climatological annual ET. However, Juarez *et al.* [2007] have shown that the seasonal and interannual changes of ET at a given location are less than



**Figure 10.** Mean seasonal cycle of (a) P-R and ET and (b) the soil moisture increment  $SM_{inc}$  in ERA40.

**Table 2.** Area Mean Surface Water Budget Variables for ERA40 and Observations<sup>a</sup>

Precipitation, mm	Runoff/ Streamflow, mm	P-R, mm	ET <sub>basin</sub> , mm	ET <sub>tower</sub> , mm
CPC 2179	O+A 1087	1092	ET <sub>obs,basin</sub> 1134	ET <sub>obs,towers</sub> 1200
GPCP 1925	O+A 1087	838		
ERA40 1973	ERA40 828	1145	ET <sub>ERA40,basin</sub> 1289	ET <sub>ERA40,towers</sub> 1363

<sup>a</sup>The observed ET is the annual mean, averaged over the eight tower data sets shown in Figure 7.

12%. Their analysis was based on in situ measurements of ET obtained during the past two decades across different parts of the Amazon rain forest areas with very different rainfall climatologies. Thus the annual ET estimate based on in situ data in equation (1) is probably a reasonable approximation of the climatological annual ET for the last two decades covered by our ERA40 reanalysis, although it is likely to have the same low bias of order 10% as the flux tower measurements.

[27] In Table 2, the estimated ET<sub>obs,basin</sub> is evaluated against observed P-R. Note that the uncertainty of the GPCP data may be of order 10% [Fekete *et al.*, 2004]. The uncertainty in the CPC data can be 6% for annual precipitation over land [Chen *et al.*, 2002]. Uncertainty in streamflow measurements can also be 6–7% based on comparison with estimates derived using satellite radar topography [LeFavour and Alsdorf, 2005]. The fourth column of Table 1 shows that annual ET<sub>obs,basin</sub>, estimated to be 1134 mm, matches more closely (within ~4%) the annual P-R estimated from CPC precipitation data and streamflow measurements. In contrast, P-R estimated using GPCP rainfall data, is 298 mm (26%) lower than ET<sub>obs,basin</sub>. Using the CPC rainfall data gives a closer balance for the basin-scale surface water budget than using the GPCP data. ET<sub>obs,basin</sub> provides an independent constraint on the biases of the different rainfall data sets. It also suggests that our approach of scaling flux tower ET probably provides a reasonable annual ET for the Amazon River basin for the period when flux tower measurements were available, although it is still possible that both precipitation and observed ET have a low bias of order 10%.

#### 4. Conclusions

[28] The surface water budget variables from ERA40 over the Amazon River basin were examined on seasonal, annual and interannual scales using the available observational data to clarify the strengths and limitations of the reanalysis. The ERA40 annual precipitation is about 10% lower than that of CPC rain gauge based data set due to the underestimation of wet season rainfall, but agrees well with the GPCP rainfall data. However, the surface water budget analysis using independently observed streamflow and ET data suggests that GPCP underestimates rainfall. The CPC rainfall data provides a more nearly balanced surface water budget. Interannual variations of the annual rainfall, particularly the larger variations related to ENSO episodes are

qualitatively represented by the reanalysis, although their amplitude is underestimated. On the subbasin scale, ERA40 underestimates rainfall compared to the CPC data over most of the Purus-Juruá, Madeira, Solimões and Tapajós-Xingu River basins during the wet season (DJF), with some areas showing an underestimation greater than 300 mm (~30%). During the dry season (JJA), rainfall is overestimated by as much 300 mm (~40%) in parts of the Purus-Juruá and Madeira River subbasins and underestimated by approximately the same amount in parts of the Negro and Solimões River subbasins, despite good agreement in the basin-mean precipitation.

[29] The total annual runoff in ERA40 is on average 25% lower than that suggested by river flow measured at Óbidos and Altamira near the mouth of the Amazon River. ERA40 shows similar rain-rate intensities when compared with the rain-rate of spatially and temporally rescaled TRMM data. However, even the native resolution of ERA40 is greater than the spatial scale of convective systems, so modeled rain-rates are less than those observed. There is a possibility that the model interception may have a high bias, which contributes to the high ET in the rainy season, and reduces the wet season storage.

[30] ET in ERA40, averaged over grid points collocated with flux tower measurements, agrees with that measured within the observational uncertainty. Individually however, in five out of nine years, ET in ERA40 is larger than that observed by more than 20%, suggesting that the ERA40 ET may have a high bias, despite the probable low bias of the eddy covariance method of order 10%. This high bias of ERA40 is seen over the entire seasonal cycle.

[31] The observed difference between precipitation and runoff (denoted as P-R) agrees more closely with the P-R of ERA40 than with the ET of ERA40, which is augmented by soil moisture nudging. On the seasonal scale, soil moisture nudging is largest during the dry season, when it is needed to produce a more realistic ET. This addition of soil water appears to compensate for the low soil moisture recharge during the previous wet season. Insufficient recharge may be caused in part by the underestimation of rainfall during the wet season. However, the relatively shallow rooting layers in the reanalysis model do not represent the deep soil water reservoir characteristic of the Amazon forest.

[32] We propose a method to scale up in situ ET fluxes to basin scales using the ERA40 estimated basin-averaged annual ET. This scaled ET agrees with the observed difference between precipitation and runoff, P-R, to within 4% if we use the CPC rainfall data. This approach allows us to balance the surface water budget averaged over the Amazon River basin within observational uncertainty.

[33] Reanalyses provided by global forecast and analysis systems are often used as surrogates for studying atmospheric and surface hydrological cycle processes. However, certain applications should be viewed with caution, especially those involving long-term changes of runoff, detailed spatial distribution of rainfall and the closure of the water budget.

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