Observed and modelled historical hydroclimatic variability in South America: cases of the Amazon, São Francisco and Paraná–La Plata rivers

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Abstract The subject of this study is to analyse the hydroclimatic variability in three large river basins in South America: the Amazon, the São Francisco in Northeast Brazil and the Paraná–La Plata in subtropical southeastern South America. This study is based on long-term observations of river streamflow and rainfall in these river basins, as well as estimates of the water balance components. The focus is to identify interannual and decadal time-scale variability, as well as to investigate the variability of the atmospheric moisture transports in and out of the river basins typical of the present climate. Together with the observational analysis we use a 50-year simulation of decadal-scale variability from the Centro de Previsão de Tempo e Estudos Climaticos atmospheric global climate model (CPTEC AGCM). After identifying decadal time-scale variability, we link this variability to the observed variability on the Pacific and Atlantic oceans, and also identify these modes of variability in the CPTEC AGCM simulations.

Key words climate variability; semiarid regions; tropical climates; water balance

INTRODUCTION

In discussing the hydrology of South America, the emphasis of previous studies has been on the movement of water in the terrestrial system, considering precipitation and evapotranspiration as the forcing and streamflow and storage as the response. In this context, water that evaporates from the land surface is lost to the system if advected out of the prescribed region by atmospheric motion, but recycled in the system if it falls again as precipitation. On the other hand, the atmospheric approach that focuses on the water balance deals with the dynamics and thermodynamics of the atmosphere at larger scales. The moisture evaporates from land surfaces, thus acting not only as a source of water for later precipitation, but also changing the thermodynamic structure of the atmosphere through the alteration of the circulation and rainfall.

The components of the water budget vary considering different climate regions. The Amazon River drains an area of 6.2×10^6 km^2 and discharges an average of 6300 km^3 of water to the Atlantic Ocean annually. Average rainfall in the region is 2236 mm year^{-1}, oscillating between 1500 and 3300 mm throughout the basin. Close to the mouth of the Amazon River, on the coast of Pará, and in the eastern section of the basin, total annual average rainfall exceeds 3000 mm, with no dry season. In the central-north and south-southeast sections, rainfall is lower, in the region of 1500 mm. The peak of the rainy season occurs earlier (December–February) in southern
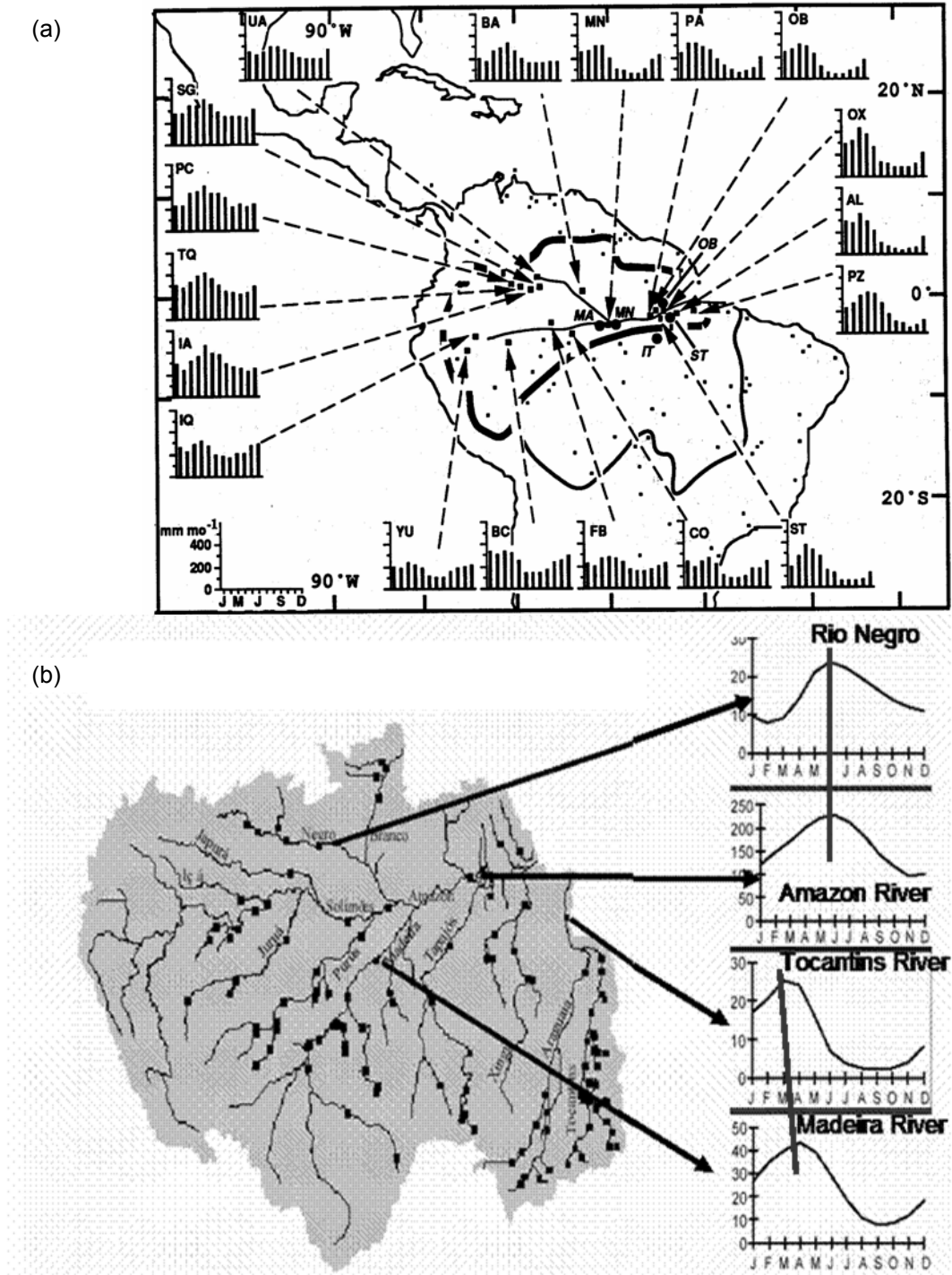
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(a)

(b)

Fig. 1 Annual cycle of rainfall and river discharges in the Amazon Basin.

Amazonia, while northern and central Amazonia experience maximum rain in March–May (Fig. 1(a)). River discharge peaks earlier in southern Amazonia as compared to northern Amazonia (Fig. 1(b)). Since the late 1970s, large-scale water budget studies have been conducted for this region using a variety of observational data sets varying from radiosondes to global reanalyses (Fekete *et al*., 1999; Zeng 1999; Labraga *et al*., 2000; Roads *et al*., 2002; Marengo, 2004 and references quoted therein).

Located in the semiarid Northeast Brazil, one of the poorest regions of the world, the São Francisco River basin holds 10% of the Brazilian national population (about 12 million). It is one of the regions with the most extreme impacts of climate variability on the population (social, economic). Its importance is that the river generates hydroelectric power that serves northeast Brazil, and that can reach the populated and industrialized regions in Southeast Brazil. The São Francisco River produces approximately 10 400 MW, which is half of the hydropower generated by the Paraná–La Plata basin. The upper basin of the São Francisco River holds the most important regions of the valley, and also the highest demand of water due to intense agriculture. This region shows reduced seasonal climate predictability since regional characteristics (e.g. soil moisture memory) play a more important role in climate predictability as compared to remote sea-surface temperature (SST) forcing in tropical oceans (e.g. El Niño or tropical Atlantic meridional SST gradient for the middle and lower basins). Figure 2 shows the seasonal rainfall distribution in the basin, showing that the upper basin is first to experience its maximum of rainfall (related to features such as the South Atlantic Convergence Zone (SACZ) and cold fronts during November–March), while the lower basin experiences its rainy season later, as related to the Intertropical Convergence Zone (ITCZ) and its meridional movements (during March–May). Thy dry season occurs during the June–August season. The discharges at Sobradinho peak during January–March.

The La Plata River basin extends 3.6×10^6 km^2 in five South American countries. It is one of the largest rivers of the world, draining approximately one-fifth of the South American continent and conveying waters from central portions of the continent to the southwestern Atlantic Ocean. The Paraná–La Plata River system rivals the
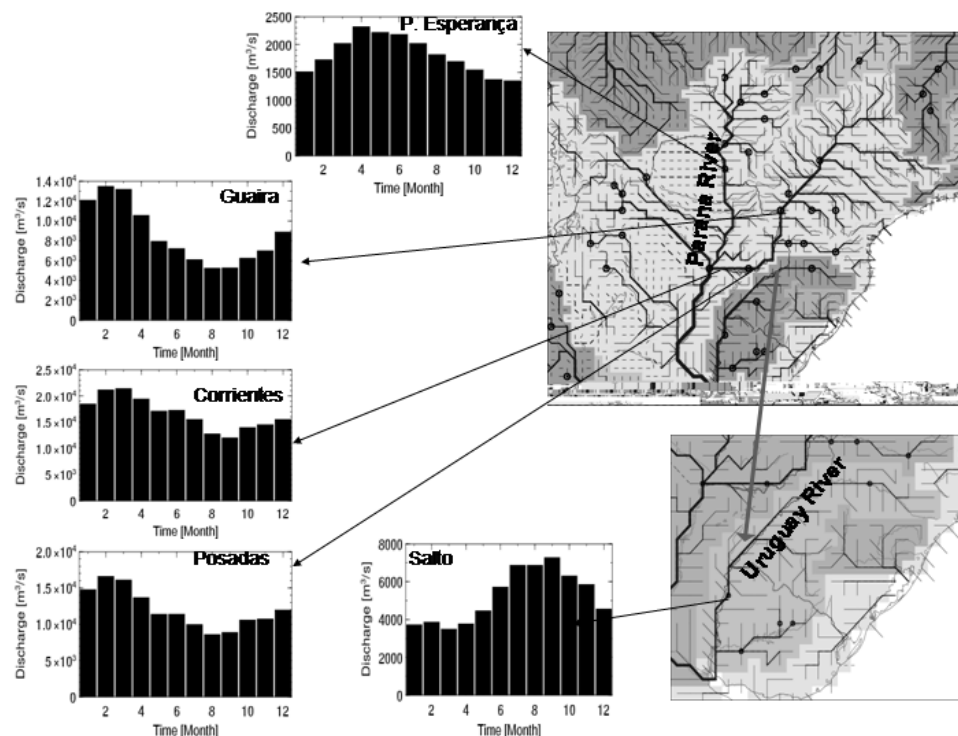

Fig. 2 Annual cycle of river discharge in the Paraná–La Plata and Uruguay rivers.
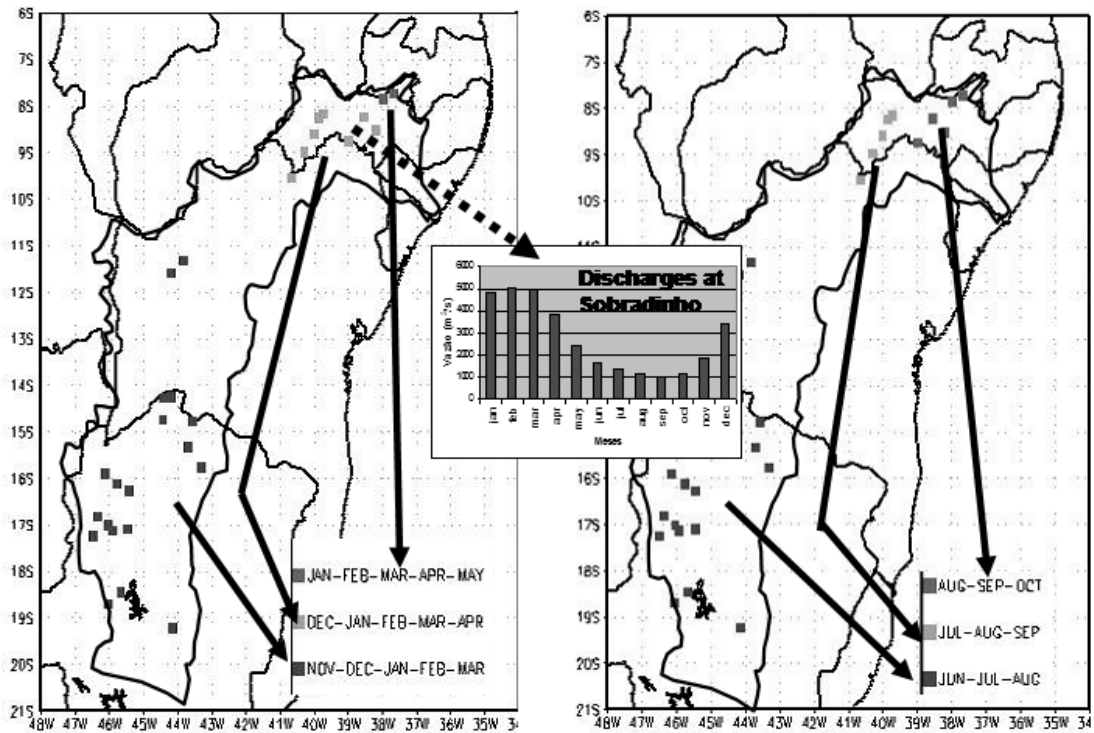
Fig. 3 Seasonal variability of rainfall in the São Francisco basin in (a) the wet season and (b) the dry season.

better-known Amazon River system in terms of its biological and habitat diversity, and far exceeds that system in its economic importance to southern and central South America. Its mean annual discharge is second only to the Amazon basin and fifth in the world, which in turn has implications for the generation of hydro-electric power. The hydroclimatology of the La Plata River is strongly affected by ocean conditions in both adjacent oceans and rainfall and river streamflow time series show several quasi-periodicities (interannual-ENSO, interdecadal), with a major shift in precipitation and the discharge of many rivers in the late 1970s. The potential for flooding occurs at any time of the year. The largest contribution during flood episodes comes from the Paraná River. Both the Paraná and the Uruguay rivers can at least triple the mean river discharge during flood events. The annual cycle of the Paraná and Uruguay river discharges varies as shown in Fig. 3.

The surface and upper-air observational network in the three basins is relatively poor and by itself cannot provide the comprehensive and complete information needed to measure the components of the energy and water balance estimates with less uncertainty. Some early studies using a few radiosondes in the Amazon and La Plata basins have produced some estimates of moisture flux convergence in and out of the basins, but not enough detail is known for the whole basin (Marengo, 2004 and references quoted therein). In most cases, to augment the scarce observations, we have to rely on imperfect models or products from data assimilation or gridded reanalyses and rainfall data sets, such as the global reanalyses produced by the National Center for Environmental Prediction (NCEP). Such reanalyses can highlight characteristics of the circulation and water balance and have provided useful estimates of some of the components of the

water budget whenever observed values were not available. However, there are no guarantees that this description will be superior to that obtained from objective analysis and radiosonde observations, especially over continental regions (Kalnay *et al*., 1996; Roads *et al*., 2002). The closure of the water budget and a quantification of the uncertainties in the water and energy balance components are the main objectives of the GEWEX–Global Energy and Water Cycle Experiment programme and its regional components, the Large–scale Biosphere Atmosphere experiment (LBA) (Amazonia) and La Plata Basin (LPB).

Previous modelling studies have focused on the water budget of the Amazon and La Plata basins, or on some of its components (e.g. Vorosmarty *et al*., 1989; Marengo *et al*., 1994; Lau *et al*., 1996; Nijssen *et al*., 2001; Roads *et al*., 2002; Cavalcanti *et al*., 2003), either for present climate and for experiments on Amazonian deforestation and using different global climate models (GCMs). Nijssen *et al*. (2001) focused on the prediction of global river discharge using macroscale hydrological models and, for the case of the Amazon and La Plata rivers, they showed some improvement in the depiction of the annual cycle after calibration of model parameters. The introduction of river routing schemes coupled with a climate model's source runoff provides the basis for closing the hydrological cycle (Marengo *et al*., 1994) and a better simulation of the runoff annual cycle. The evapotranspiration estimated from the NCEP reanalyses is between 10 and 20% greater than some observed values from flux towers in southern and central Amazonia from the LBA experiment (Marengo, 2004).

The results of an intercomparison of 29 global climate models from the in Atmospheric Model Intercomparison Project (AMIP) (Lau *et al*., 1996) show that, while the model ensemble mean runoffs are consistent with the climatological observed river discharge for the Amazon and La Plata rivers, the intermodel variability is substantial. The models yield even more divergent results over other world river basins. These results suggest that some GCMs may have moderate capability of capturing some aspects of the climatological variation of runoff. Lau *et al*. (1996) did not include the São Francisco River basin in their analyses.

OBJECTIVES AND MODELLING STRATEGY

Model water budget calculations for the Amazon, Paraná–La Plata and São Francisco river basins are assessed from a 50-year nine-member ensemble climate simulation from the CPTEC AGCM. Comparisons are made with estimates of water budget components derived from gridded data sets and estimates of areal precipitation and runoff for the 1950–2001 period. The main goal is to provide a regional view of the climatological water budget simulated by the model for three large basins in South America, and to show the ability of the model to reproduce the components of the water budget and their variability.

Model description, experiment design and data used for validation

The characteristics and performance of the CPTEC AGCM are well described in Cavalcanti *et al*. (2002) and Marengo *et al*. (2003). This model is a modified version of

the spectral COLA AGCM, which was adapted from the National Centers for Environmental Prediction (NCEP) AGCM. A land surface module (Simple Biosphere Model, SSIB) that considers the vegetation influence in a sophisticated manner (Xue *et al.*, 1991) was introduced by COLA. The CPTEC AGCM now has two options for convective precipitation: the Kuo scheme (Kuo, 1974) and the Relaxed Arakawa-Schubert (RAS) scheme (Moorthi & Suarez, 1992). The dynamical and physical processes in the COLA model are described in Kinter *et al.* (1997). Climatological zonal mean ozone and atmospheric CO_2 amount (345 ppm) are fixed, and the CPTEC AGCM does not include aerosols (volcanic) and changes in solar variability.

The model resolution in this simulation is T62L28, which represents triangular truncation of 62 waves in the horizontal coordinate and 28 levels in the vertical sigma coordinate (21 in the troposphere and seven in the stratosphere). A detailed analysis of the simulated climatology and the skill of the CPTEC AGCM is documented in Cavalcanti *et al.* (2002) and Marengo *et al.* (2003). These two papers analysed 10-year nine-member climatology for the period 1982–1991. This model is able to simulate the main features of the global climate and the results are consistent with analyses of other AGCMs. The seasonal cycle is reproduced well in all analysed variables and systematic errors occur at the same regions in different seasons. The Southern Hemisphere Convergence Zones are reasonably well simulated, although the model overestimates precipitation in the southern portions and underestimates in the northern portions of these systems.

At regional levels, the CPTEC AGCM simulates well the annual cycle of precipitation for several continental and oceanic regions in the tropics and mid latitudes. Interannual variability of rainfall during the peak rainy season is realistically simulated in Northeast Brazil, Amazonia and southern Argentina–Uruguay, where the model shows good skill.

Experiment design

The climate simulation is performed for a 50-year nine members ensemble run. In an ensemble mode, the model was initialized with nine different initial conditions derived from nine consecutive days of ECMWF daily analyses, from 17 to 26 January 1950. Spectral data of temperature, zonal and meridional wind components and relative humidity are transformed to spectral coefficients of virtual temperature, divergence, vorticity, specific humidity and logarithm of pressure, which are the initial conditions for each day. Surface pressure is calculated from the geopotential height, temperature and topography. Monthly observed SST fields from the Climate Prediction Center/NCEP monthly Optimum Interpolated SST dataset (Reynolds & Smith, 1994) are applied as boundary conditions, from January 1950 to December 2001. The results are analysed from January 1951 to December 2001, considering the seasonal averages for each variable. Ensemble means are used to compare the model results to observational datasets. Water balance components are calculated to obtain the model water budget. The variables analysed in spatial fields are precipitation, evaporation (derived from latent heat), vertically integrated moisture convergence and runoff.

Data used for model evaluation

Global and regional precipitation fields are derived from the gridded data from the CRU 0.5°–0.5° lat–long (Climate Research Unit, New *et al.*, 2000). Mean rainfall is calculated for the Amazon, Paraná–La Plata and São Francisco river basins with a weighted average applied to the gridded data. The CRU data set included interpolation techniques to fill gaps in the gauge coverage, and in this data set the rainfall station data were interpolated as a function of latitude, longitude and elevation using thin-plate splines. The accuracy of the interpolation was assessed (New *et al.*, 2000) using cross-validation and by comparisons with other climatologies.

River data were provided by the Brazilian ANEEL—National Agency for Water and Energy. Streamflow of the Amazon River is measured at the gauging site of Obidos station (01°55′S; 55°28′W). The discharge measured at Obidos does not represent the real conditions of water that reaches the mouth of the Amazon, since it does not include the waters of the Xingú and Tocantins rivers (Marengo *et al.*, 1994; Roads *et al.*, 2002). Therefore, these values were corrected (Marengo, 2004): the mean discharge at Obidos is 175 000 m^3 s^{-1} (or 2.5 mm day^{-1}) and the corrected values at the mouth of the Amazon reach 210 000 m^3 s^{-1} (or 2.9 mm day^{-1}). This corrected value has been used by Zeng (1999), Roads *et al.* (2002) and Marengo (2004). These data are available since 1971. The annual cycle of discharge at Obidos is characterized by a maximum in May–July (Marengo, 2004; Zeng, 1999), while the maximum discharge of rivers with basins that extend across northern-central Amazonia is detected in April–June and that for rivers with basins that extend over southern Amazonia is in March–May. This is consistent with the annual cycle of rainfall, where rainfall in northern-central Amazonia peaks in March–May and that in southern Amazonia peaks in December–February.

Mean discharge of the São Francisco River basin is measured at the Sobradinho gauging station (40.83°W, 9.42°S), with data available since January 1931. This location was chosen because the streamflow is unaffected by upstream regulation. To the north of this site, there is some water use for power generation. The mean discharge is approximately 2800 m^3 s^{-1}, peaking in February–April and exhibiting an interannual variability as high as 15 000 m^3 s^{-1} or as low as 622 m^3 s^{-1}. Upstream, the annual cycle of discharges shows maxima in December–February and this difference is associated with the annual cycle of rainfall: the maximum rainfall in this section of the basin is detected in December–January, due to frontal activity and the presence of the SACZ, while in the medium and lower basins the maximum rainfall is detected later, in March–April, due to changes in the position of the ITCZ and the SST gradient between the tropical Atlantic both sides of the Equator.

The Paraná River originates at the confluence of the Grande and Paranaiba rivers, and flows from north to south, except on the boundary between Paraguay and Argentina, and then flows to the south again until the delta of the river knows also as the La Plata River. It has three main sections: the upper basin (Alto Paraná) which covers from its origins to the confluence with the Paraguay River at Corrientes, the middle Paraná between Corrientes and approximately 32°S, and the Lower Paraná, between 32°S and the delta of the river (or Río de la Plata). The main discharge of the Paraná–La Plata was about 19 300 m^3 s^{-1} in 1951–1970 and 26 000 m^3 s^{-1} in 1980–1999, an increase of 35%.

For all three river basins, the NCEP/NCAR reanalyses (Kalnay *et al*., 1996) are used to estimate vertically integrated moisture convergence (*C*), evaporation (*E*) and runoff (*R*). Estimates of precipitation (*P*) are also derived from the CRU gridded data set from each basin, and observed runoff is derived from the measurements at Obidos for the Amazon basin, Sobradinho for the São Francisco River and Corrientes for the Paraná River.

RESULTS AND DISCUSSION

Model *vs* observed rainfall and runoff

Before we discuss the quality of the rain simulated by the CPTEC AGCM, it should be mentioned that Marengo *et al* (2003) indicated that the model is very good (see ROC scores in Fig. 4) at simulating annual and interannual variability of rainfall, even though rainfall is systematically underestimated by the model. The relatively low scores in the Paraná–La Plata may be due to the fact that the basin mixes two rainfall regimes: the model shows relatively high skill in the middle and lower part of the basin and relatively low skill in the upper basin. A similar explanation can be given for the São Francisco, where low skill in the upper basin is mixed with relatively higher skill in the middle and lower basins.

The time series of modelled and observed rainfall in the three basins are shown in Fig. 5. The figure shows underestimation of rainfall in the Amazon basin and, to some degree, in the Paraná–La Plata, while the model overestimates rainfall in the São Francisco basin. The model simulates well the annual cycle of rainfall. This over-estimation is due to the "artificial" overestimation of rainfall along the SACZ in the upper basin.

As a consequence of this rainfall simulation, a problem of underestimation of river discharge is shown in both the Amazon and Paraná rivers, and the problem is worst in
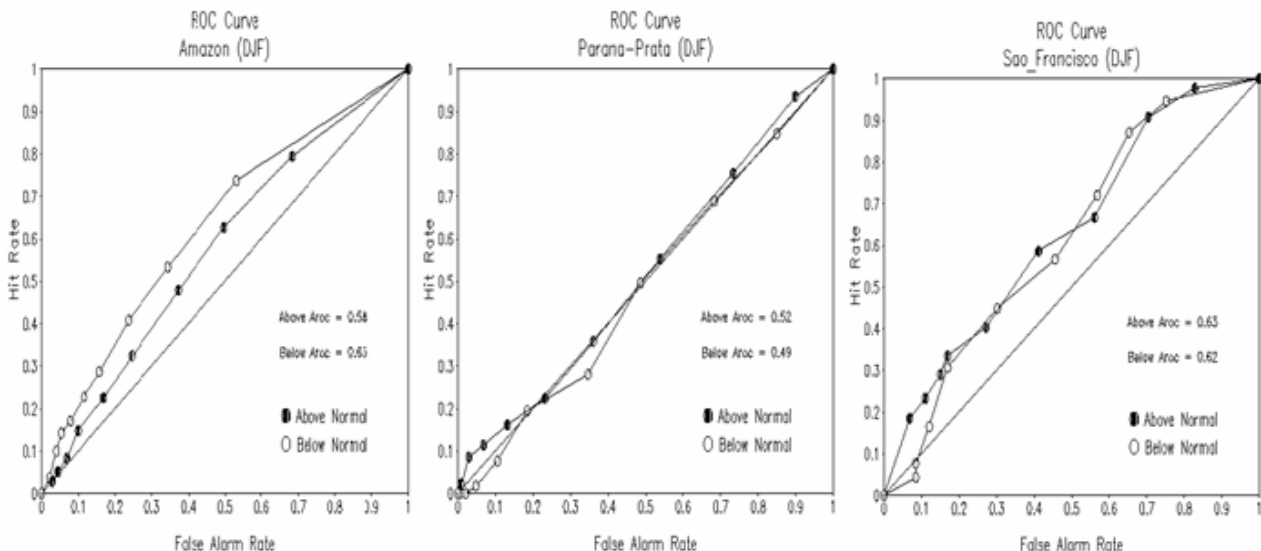

Fig. 4 Relative operational characteristic (ROC) scores for rainfall in the Amazon, Paraná–La Plata and São Francisco basins (Marengo *et al*., 2003).
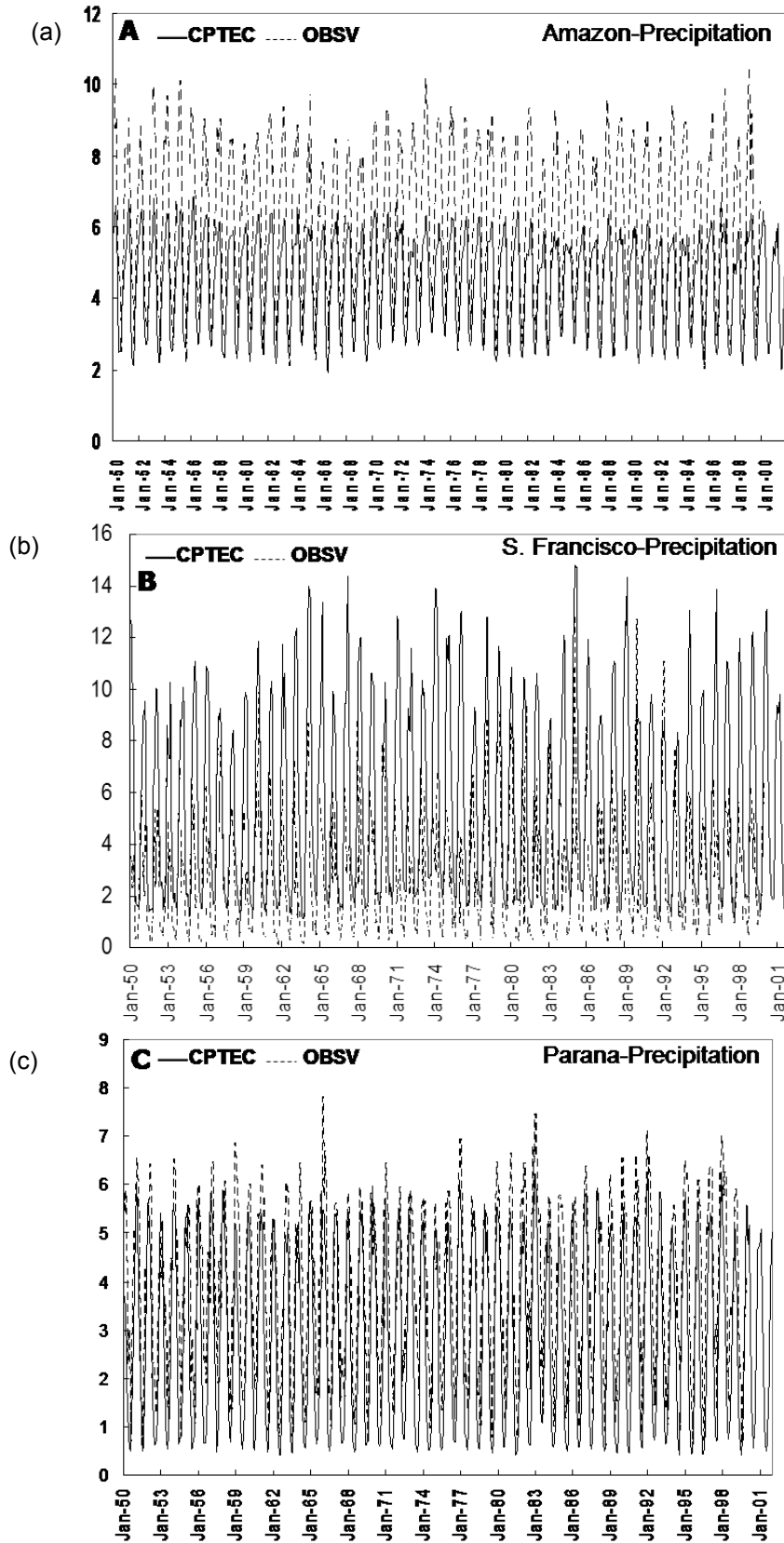
Fig. 5 Time series of observed (thick broken line) and modelled (solid line) rainfall for the (a) Amazon, (b) São Francisco and (c) Paraná–La Plata rivers. Observations are from the CRU. Units are in mm day^{-1}.
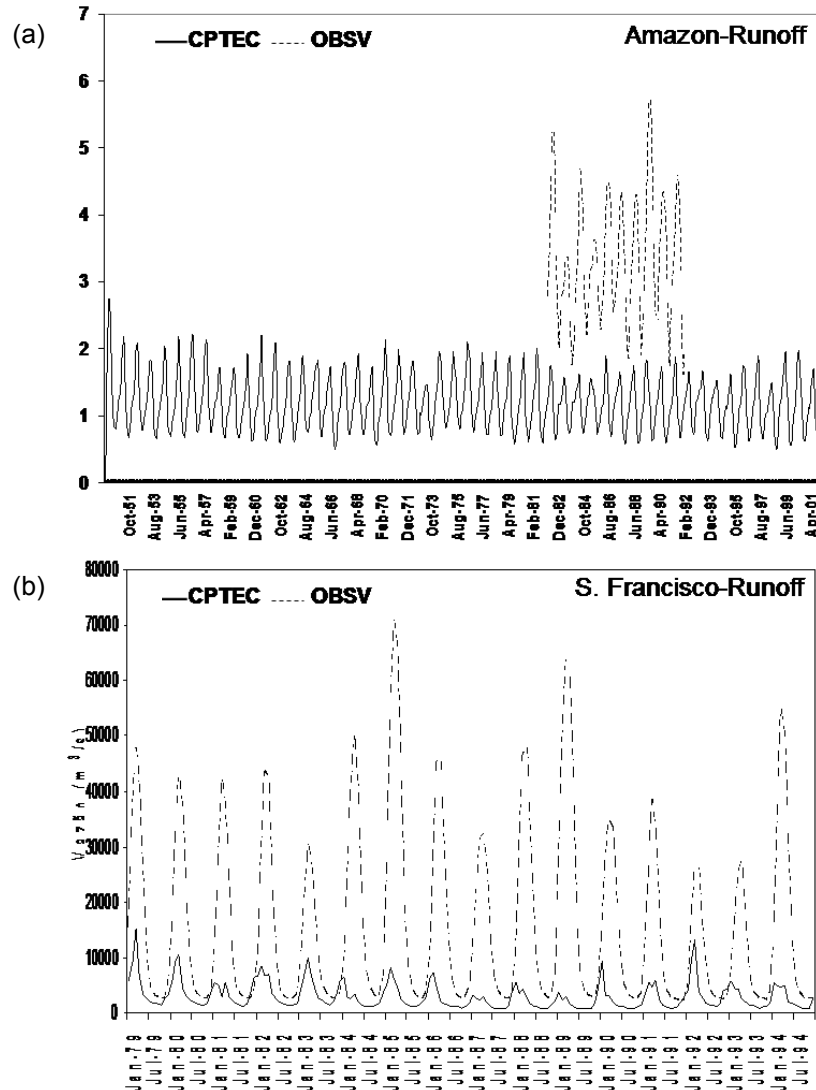
Fig. 6 Time series of observed (broken line) and modelled (solid line) river discharges in (a) the Amazon River—observations (in mm day^{-1}) from Obidos; and (b) the São Francisco River—observations (in m^3 s^{-1}) from Sobradinho.

the Amazon River, with underestimation by more than 50%. The overestimation of discharges in the São Francisco River reaches more than 200% (Fig. 6). Since the CPTEC AGCM does not have a routing scheme, there is an out-of-phase relationship between the observed and modelled peak of discharge, with the simulated discharge peaks occurring 2–3 months before the observed peaks. The model also underestimates the observed discharge at Corrientes for the Paraná River (not shown), and exhibits a similar problem with the simulation of the annual cycle as in the other to rivers.

Water balance

Table 1 shows that, over the Amazon basin, regional precipitation exceeds evaporation and the basin acts as a sink of moisture ($P > E$). Estimates of the water balance for the

Table 1 Components of an "observed" climatological water budget for the three basins: Amazon basin (1970-99, from Marengo, 2004); Paraná and São Francisco basin (1970-2002). Units are in mm day^{-1}. P is derived from the CRU data set, R from observed discharges at Obidos, Sobradinho and Corrientes), and E is derived from the NCEP reanalyses.

Component	Amazon	Paraná	São Francisco
P	5.8	3.1	2.6
E	4.3	2.8	2.5
R	2.9	0.6	0.8

Amazon region do not show a closure of the budget, with an average imbalance of almost 50%, suggesting that some of the moisture that converges in the Amazon region is not accounted for. Large uncertainties are detected in the evaporation and moisture convergence fields derived from the reanalyses, and in the case of evaporation it can be as large as 10–20% as compared with the few field observations from across the basin. For the Paraná and São Francisco basins, $P > E$, but rainfall is almost half of that of the Amazon Basin. These results agree with the spatio-temporal variations of the water budget components in the Amazon region as investigated by Marengo (2004). Using a combination of hydrometeorological observations (P, R) and moisture fluxes and evaporation derived from the NCEP/NCAR reanalyses (C, E), for the period 1970–1999, he shows that there is a seasonality and interannual variability of the water balance that varies across the basin.

The annual cycle of the water balance components in the three basins is shown in Fig. 7, with the observed plots (NCEP + observations) on the right and the simulated plots on the left (CPTEC AGCM). An underestimation of rainfall, discharge and evaporation is observed for the Amazon River, as well as overestimation of rainfall and runoff in the São Francisco basin. The annual cycle is well simulated for P and E, and R shows some out-of-phase relationship between observed and modelled peaks. Possible problems are the representation of convective processes and radiation in tropical regions. The parameterization of evaporation over the ocean also needs a revision.

In terms of predictability, it is observed that regions where the remote forcing (e.g. SST anomalies in tropical oceans) is stronger exhibit relatively higher predictability (e.g. Northeast Brazil, northern Amazonia, southern Brazil) as compared to regions where the predictability is lower (west central Brazil, South American monsoon). This lower predictability seems to be related to local forcings, such as soil moisture or land surface processes. Koster *et al.* (2002) showed that, for the upper Paraná and São Francisco basins, the fraction of precipitation variance explained by SST anomalies is lower than that explained by the land–atmosphere feedback. In these regions, the precipitation variance induced by a chaotic atmospheric dynamic linked to land–atmosphere feedback is higher. In comparison, over the Amazon basin and northeast Brazil, the fraction of precipitation induced by tropical SST variations is higher, partly explaining the relatively better predictability of the water balance components, mainly precipitation and runoff. This better predictability refers to seasonal climate prediction.
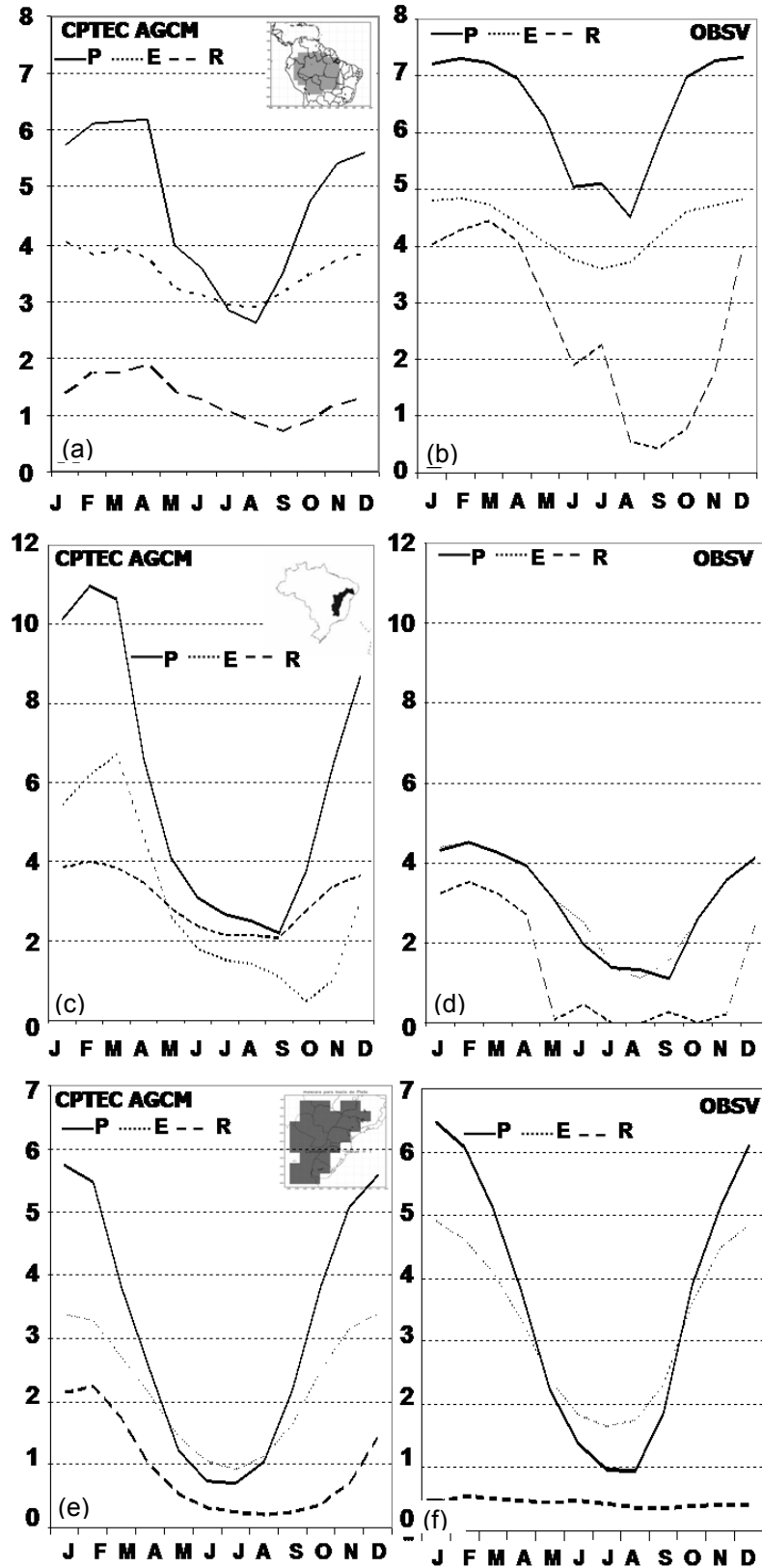
Fig. 7 Annual cycle of the simulated (left) and observed (right) components of the climatologic water balance in the (a, b) Amazon, (c, d) São Francisco and (e, f) La Plata basins. Units are in mm day^{-1}. Runoff is observed at Obidos, Sobradinho and Corrientes, *P* is observed from the CRU and *E* is derived from the NCEP reanalyses.

SUMMARY AND CONCLUSIONS

The components of the water budget of the Amazon, Paraná–La Plata and São Francisco river basins are simulated by the CPTEC AGCM, and then compared with the observed water balance components derived from the NCEP reanalyses and observations. The model is able to reproduce the precipitation seasonal cycle. There are also large differences over Amazonia and the São Francisco River basin, where the model tends to underestimate and overestimates precipitation, respectively. The model overestimates precipitation over the Andes and over Northeast Brazil, and under-estimates precipitation over many areas in the interior of the continent including the Amazon basin.

Although the ROC scores shows relatively lower predictability in the La Plata and higher predictability in the São Francisco basin, in general the upper basins of these two rivers fall in a region of lower predictability, that seems to be dominated by regional land surface forcing as compared to remote tropical SST forcing. The runoff follows the same tendency as the precipitation, with the annual cycle showing an out-of-phase relationship between the simulated and observed peaks, due to the fact that the model does not have a routing component.

The deficiency of the model in simulating the amount of precipitation can be partially related to the convection scheme. Comparing the CPTEC AGCM with other model simulations of rainfall in the Amazon basin shows similar underestimations, and suggests that, at least in part, precipitation differences can also be related to the convection scheme.

The analysis of time series of rainfall and discharges in Amazonia shows that the ENSO signal is well reproduced by the model in magnitude and variability. Over the tropics, the model simulates a clear eastward-propagating anomaly in tropical convection and rainfall when anomalously warm tropical Pacific events associated with El Niño occur.

The imposed monthly observed SSTs prevent the interaction of fluxes between the ocean and the atmosphere, while it occurs between land and atmosphere. The COLA version of a coupled ocean–atmosphere GCM which is being implemented at CPTEC should overcome this lack of interaction, improving the energy budget. Imbalances in the energy budget were also related to the radiation scheme and cloud-cover calculation, which also calls for improvements in the parameterization schemes. These improvements must occur before the CPTEC coupled model can be implemented.

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