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Short- and long-term flow forecasting in the Rio Grande watershed (Brazil)

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Abstract

As part of a research project to improve flow forecasts for the operation and planning of Brazilian hydroelectric reservoirs, a large-scale distributed hydrological model has been used with quantitative precipitation forecasts and an empirical data assimilation procedure. This article summarizes some results obtained for the Rio Grande watershed (145 000 km^2), one of the Hydrologic Ensemble Prediction Experiment (HEPEX) test beds. For the short-term horizon (up to 12 days), results show that this methodology can clearly improve real-time operation of reservoirs. However, longer-term flow forecasts (time horizon up to 6 months) still require improvement in forecasts from climate models. Copyright © 2008 Royal Meteorological Society

Keywords: **distributed hydrologic model; model updating; flow forecast**

1. Introduction

Real-time operation and management of reservoirs would be improved if future reservoir inflows could be estimated. A combination of observed precipitation and quantitative precipitation forecasts (QPFs) can be used as input to a rainfall-runoff hydrologic model to forecast reservoir inputs for both short and long time horizons (Bell and Moore, 1998; Collischonn *et al*., 2005). The quality of flow forecasts can be improved by using a procedure for model updating based on assimilation of observed data (O'Connell and Clarke, 1981; Bell and Moore, 1998; Romanowicz *et al*., 2006). Besides their use for flood control (Wood and O'Connell, 1985; Moore *et al*., 2005), streamflow forecasts may also strongly benefit hydropower production (Maurer and Lettenmaier, 2004; Bravo, 2006).

In Brazil, hydropower accounts for up to 79% of the total electrical energy installed capacity (ANEEL, 2005). An interconnected national transmission network allows the integrated management of the energy production in hydroelectric dams and other sources by the national system operator (ONS). The decision-making process involves the use of optimization models, which are strongly dependent on forecasts of energy load and water availability. At present, flow forecasts are determined from statistical models based on time series of precipitation and streamflow (Guilhon, 2002; Maceira and Damazio, 2005).

As part of a research project to improve short- and long-term flow forecasts used for the operation and planning of Brazilian hydropower systems, a large-scale distributed hydrological model has been used together with QPFs and a data assimilation procedure. This article summarizes results obtained for short- and long-term flow forecasting in the Rio Grande watershed, one of the test beds of the Hydrologic Ensemble Prediction Experiment (HEPEX).

2. Methodology

2.1. Quantitative precipitation forecast

For short-term flow forecasts, QPFs were obtained for a time horizon from 1 to 10 days, with a horizontal resolution of about 40 km, from the regional ETA model which is run operationally by the Brazilian Center for Weather Prediction (CPTEC) (Chou, 1996; Chou *et al*., 2000). These daily forecasts were produced at weekly intervals and issued every Wednesday from January 1996 to November 2001. QPFs given by the ETA model over South America have been shown to be useful for short period weather forecasts (Bustamante *et al*., 1999; Chou and Justi da Silva, 1999), extended forecasts (Chou *et al*., 2000, 2002) and seasonal forecasts (Chou *et al*., 2005).

For longer-term flow forecasts, QPFs were produced by the CPTEC using the Atmospheric Global Circulation Model (AGCM), which is based on model code used by the USA's Center for Ocean-Land-Atmosphere Studies (COLA) with adaptations (Cavalcanti *et al*., 2002; Marengo *et al*., 2005). Persisting SST anomalies and five initial conditions were used to produce QPF scenarios for up to 6 months in advance. Daily forecasts for the period July 1997 to March 2003, with a spatial resolution of approximately 200 km and 28 layers in the vertical were available. A statistical technique based on a transformation of the probability distribution (Wood *et al*., 2002; Hay and Clark, 2003) was used to correct systematic errors in rainfall forecast, considering the probability distributions of observed rainfall and of model climatology for the period 1951–2001.

2.2. The distributed hydrological model

The hydrological model used was the MGB-IPH large-scale model, which consists of modules for calculating the soil water budget, evapotranspiration, flow propagation inside a cell, and flow routing through the drainage network (Allasia *et al*., 2006; Collischonn *et al*., 2007). The drainage basin is divided into square grid cells connected by channels, with each consisting of three reservoirs for groundwater, surface, and sub-surface water. The multi-objective MOCOM-UA optimization algorithm (Yapo *et al*., 1998) is used with three objective functions: volume bias (ΔV), the Nash-Sutcliffe model efficiency for streamflow (NS) and for the logarithms of streamflow (NSlog).

For real-time forecasting, it is important to have the hydrological model operating in adaptive mode (Moore *et al*., 2005), so that the model output is based on previous model inputs as well as on previous observed outputs, which are used to update the model prior to forecast issue. In this study, the updating method described in Paz *et al*. (2007) and Collischonn *et al*. (2005) was used. This method uses observed streamflow data up to the time of forecast issue to update model state variables (streamflow values along the drainage network, and water content in the groundwater reservoir of each cell).

2.3. The flow forecast

Given QPFs from the ETA model, flow forecasts for the short-term horizon were calculated on a weekly basis, beginning every Wednesday, according to the following procedure: (1) the hydrologic model runs in simulation mode using observed rainfall up to the instant at which rainfall forecasts are issued, (2) the data assimilation procedure is used to update model state variables, (3) forecasts of flow are calculated for the next 10 days, using the QPFs from the ETA model, interpolated to the grid-points of the hydrologic model, (4) flow forecasts for a further 2 days are calculated, assuming that there is no further rainfall. The 'perfect precipitation' scenario (assuming that future catch by the raingauge network were known in advance) was also used to assess flow forecasting efficiency unaffected by errors or uncertainties in rainfall forecast (Duckstein *et al*., 1985; Goswani *et al*., 2005).

Long-term flow forecasting uses rainfall forecasts from the CPTEC AGCM model interpolated to the model grid-points and beginning on the first day of each month, extending to the following 6 months. Up to the day immediately before forecasts begin, the hydrologic model is run using observed rainfall data. Each member of the rainfall ensemble forecast produces a different flow scenario, thus resulting in a 5-member ensemble of flows.

3. Rio Grande watershed

The Rio Grande drains an area of about 145 000 km^2 of the Brazilian States of Minas Gerais and São Paulo (Figure 1). This river is the main tributary of the River Paraná in its upper basin, and is used extensively for hydropower generation. The main hydropower installations are Marimbondo, Água Vermelha, Furnas and Estreito, each of which has an installed capacity greater than 1000 MW. In total, the Rio Grande watershed has an installed capacity of about 7722 MW, which corresponds to approximately 11.7% of the Brazilian total. Mean annual rainfall over the basin is approximately 1400 mm and is highly concentrated during the 6 months from November to April. Flow forecasts are required for both reservoir operation and local flood control purposes.

4. Results

Parameters of the hydrological model were calibrated for each sub-catchment. In all cases except one, the values of the NS and NSlog coefficients were about 0.9 in both calibration and validation periods. Values of volume bias were also acceptable, with values less than 0.05% during calibration, and less than 7% at validation. The following sections present

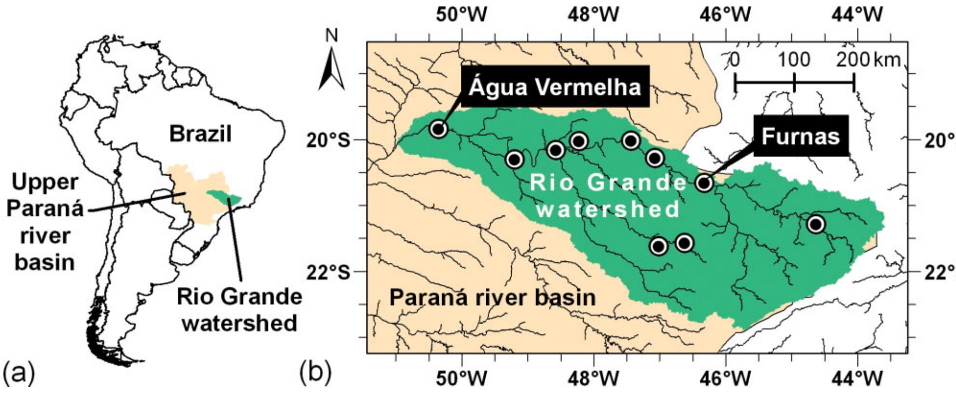

Figure 1. (a) location of Rio Grande watershed, and (b) outlets of the Furnas and Água Vermelha watersheds.

some particular results of short- and long-term flow forecasts respectively, at the outlets of Água Vermelha (139 000 km^2) and Furnas (52 000 km^2) catchments.

4.1. Short-term forecasts

For short-term flow forecasting, several configurations of the empirical data assimilation procedure were tested, varying the parameter values of such procedure (Paz *et al*., 2007). In general, the results showed that updating of channel flows was not important for daily forecasts in the Rio Grande watershed, due to the relatively rapid response of the basin, and to the fact that flow is observed at daily intervals. However, the update of water storage in the groundwater reservoir of each cell significantly improved the quality of flow forecasts. Figure 2 shows results at the outlet of the Água Vermelha watershed, using QPFs produced by the ETA model (Figure 2(a)) and assuming that rainfall to be recorded in the future by the raingauge network were known in advance (Figure 2(b)). In each graph, the coloured traces are consecutive forecasts issued on each Wednesday, for a time horizon up to 12 days; animations showing the sequence of forecasts at successive emission dates are given as **supplementary material** to this article, in the file prevShort.avi. These results were obtained using the best set of updating parameters among those tested, as given in Paz *et al*. (2007). The results are relatively good in the sense that they capture reasonably well the rising and falling hydrograph limbs, which would lead to useful improvements in operational management of the hydroelectric system.

Two performance measures are typically used by the ONS: the mean relative error (MRE) for the fourth time-step ahead, and the MRE considering the average of forecast values issued for time-steps 4–10. Compared with the results of the statistical model currently used by ONS (Guilhon, 2007), the methodology used in this article reduced by 10% the error at the fourth time-step, and by 20% the error for the performance between time-steps 4–10 days into the future.

4.2. Long-term forecast

Some results of the long-term ensemble flow forecast at the outlet of Furnas catchment are shown in Figure 3. The 6 graphs in this figure correspond to consecutive forecasts, each of them issued on the first day of a month (indicated by the arrow) and extending for the following 6 months. In each graph,

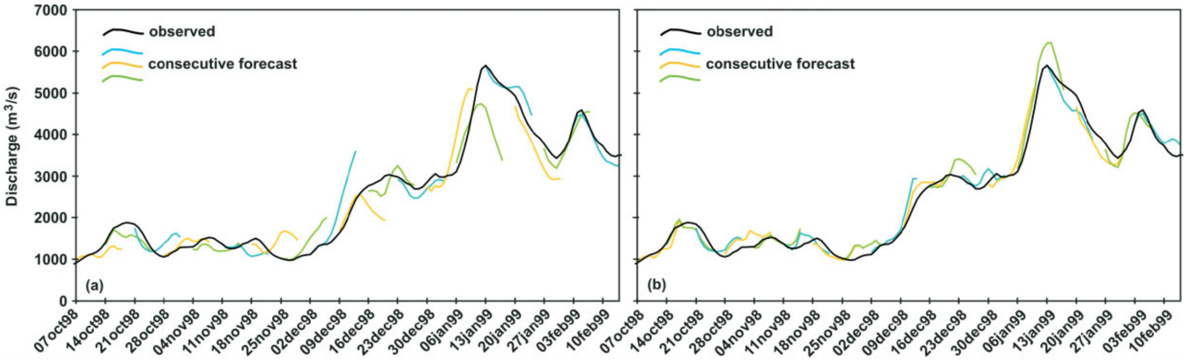

Figure 2. (a) Short-term flow forecasts at the outlet of Água Vermelha catchment using QPFs from the ETA model, and (b) assuming that future catch by the raingauge network were known in advance.

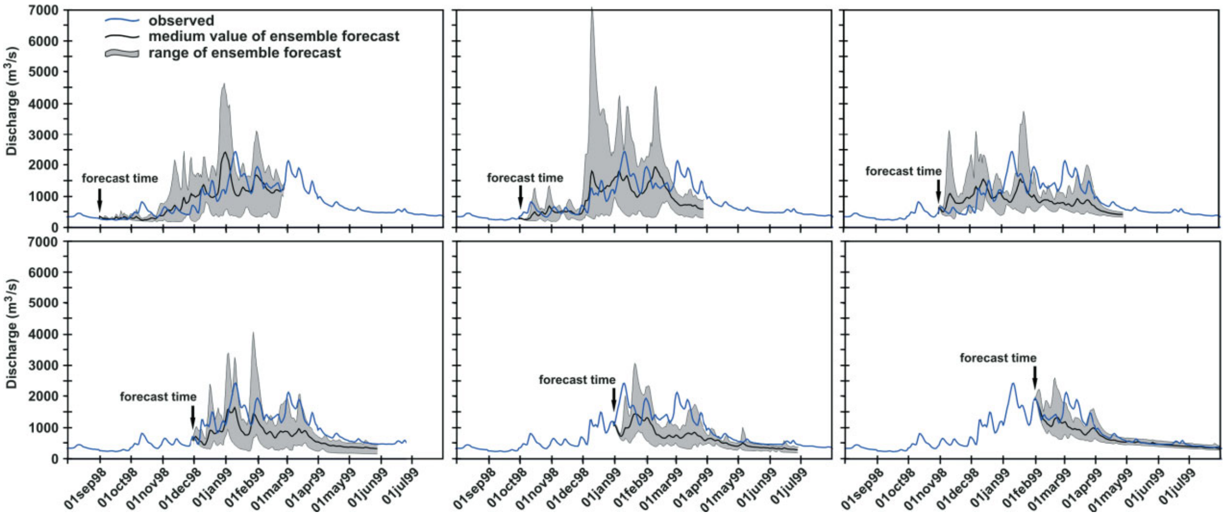

Figure 3. Long-term ensemble flow forecast at the outlet of Furnas sub-basin.

the grey band represents the interval between the highest and lowest flow forecasts obtained from the ensemble of rainfall forecasts, while the black line is the mean of the forecasts obtained from the ensemble. The band shows a relatively wide dispersion of flow forecasts, but in general it includes the observed flow sequence (blue line). The mean value of the ensemble of forecasts can be considered satisfactory when compared with observed flows. Animations showing the sequence of forecasts at successive emission dates are given as **supplementary material** to this article, in the file prevLong.avi.

5. Conclusions

The results obtained for the Rio Grande watershed suggest that flow forecasting through the coupling of atmospheric and hydrologic models shows potential for improving operation and planning of Brazilian hydropower systems. For short-term horizons of up to 12 days, this method reduced errors by 10–20% in flow forecast relative to the present statistical forecasting technique used by ONS. Considering long-term forecasts of 1–6 months in advance, acceptable results were obtained in terms of predicting the general tendency of seasonal flows. Given the long lead-time in this case, forecast performance is much more dependent on the climate model than on the hydrologic model. Thus, improvements in the forecast skill of the climate model are still required.

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