Integrated atmospheric and hydrologic modelling for short-term and basin-scale forecasts in a tropical semi-arid context

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Abstract Precipitation in the Brazilian northeastern semi-arid region is characterized by a convective rainfall regime. Recently, numerical weather prediction models have been run with resolutions fine enough to potentially improve the quality of the simulated rainfall patterns within hydrographic basins and therefore contribute to more reliable flow forecasts. This paper presents a unidirectional coupling between BRAMS – Brazilian Regional Atmospheric Modelling System – and a lumped hydrological model in order to analyse the impact of precipitation uncertainties on runoff forecasts. The results show that forecasts produced one day in advance lead to reliable hydrographs, but for two to five days in advance, precipitation uncertainties impact the runoff forecast skill.

Key words runoff forecast; hydrological model; atmospheric model; semi-arid; uncertainty

INTRODUCTION

Evaluating the reliability of flow forecasts at the basin scale and driven by atmospheric predictions, involves detailed understanding of local and regional precipitation processes and their temporal and spatial patterns, of the sensitivity of the hydrological regime to the precipitation patterns, forecast models, both atmospheric and hydrological, and their parameterizations. In tropical regions, such as the Brazilian semi-arid region, weather forecasts are quite uncertain due to the convective characteristic of the rainfall systems. However, they are very important to water management, either for flash-flood forecasting or reservoir operation decision making. Rainfall forecasts by regional atmospheric models through downscaling of global atmospheric models, represent a promising possibility for improving weather forecasting at the basin scale. The refined grid of the regional atmospheric models could potentially better simulate the rainfall patterns over such basins and, thus, contribute to more reliable flow forecasts.

In recent years, the coupling of atmospheric and hydrological models has been investigated in both short- and long-term forecasts (e.g. Jasper *et al.*, 2002; Chang *et al.*, 2004). For semi-arid regions, seasonal forecasts were evaluated in order to quantify the influence of precipitation on runoff generation (Chiew *et al.*, 2003; Galvão *et al.*, 2005). However, one should be more cautious in using short-term forecasts for runoff generation.

This paper presents an evaluation of the potential use of coupled atmospheric and hydrological models for producing flow forecasts based on rainfall derived from numerical weather predictions. The rainfall data were input to a lumped hydrological model to produce the flow forecasts. The main objective of this investigation is the quantification of the uncertainties in the output of an atmospheric model relevant to hydrological prediction, and their impacts on the hydrological-model response.

HYDROMETEOROLOGICAL FORECASTS FOR NORTHEAST BRAZIL AND THEIR ASSOCIATED UNCERTAINTIES

Weather forecasts

Northeast Brazil is characterized by a large semi-arid area whose northern part receives most of the annual precipitation between February and April (Hastenrath & Heller, 1977). This rainy season is associated with the southward displacement of the Intertropical Convergence Zone – ITCZ. The ITCZ organizes convective clouds that are responsible for heavy rain events. Since the typical horizontal scale of these clouds is of a few kilometres, the runoff generation depends on the location of each cloud within a certain basin.

Weather forecasting for the tropical region is a challenging problem, since the atmospheric dynamics of this region is mainly driven by latent heat release in convective clouds. These clouds are a sub-grid process and are represented in a model through parameterizations. There are several parameterization schemes, based on a variety of closures. Different parameterizations give different rates of energy released to the atmosphere. Since rainfall precipitation is a by-product from these parameterizations, one can expect that the amount and location of the rain is dependent on the chosen parameterization scheme in an atmospheric model, or of the model itself. The mesh resolution of the atmospheric model also influences the amount of rainfall and this is another source of error to the hydrological model. A further point to be considered is that, although the accumulated precipitation of several days is reasonably well predicted, the forecast of short-term precipitation rates and precipitation peaks are a weak part of the process and the associated error in transferring these results to a hydrological model can be considerable.

Regional atmospheric models are calibrated to yield good information about some variables, such as temperature, rainfall precipitation, wind, etc. Modelled rainfall, in particular, is not easy to compare directly with observations, given the space and time variability of rain. Therefore, a comparison with basin flow can be a more correct way to calibrate a model.

Runoff forecasts

Runoff generation processes are strongly dependent on the precipitation characteristics of a basin. The precipitation patterns of the Brazilian semi-arid region, combined with shallow soils, make runoff respond very quickly to precipitation events. The coupling between atmospheric and hydrological models in a short-term timescale forecast can be potentially very useful. However, runoff forecasts simulated by these coupled systems can have uncertainties related to the hydrological model itself (when it is not able to simulate discharge) and to the precipitation forecasts.

Precipitation errors are magnitude-, time- and space-dependent. Therefore, the generated discharges can be overestimated or underestimated, and they can also be anticipated or delayed, or they can even not be generated if a precipitation event is forecast outside the hydrographic basin. These impacts were reported by several authors (Yu *et al*., 1999; Jasper *et al*., 2002; Bartholmes & Todini, 2005). Nevertheless, it is still necessary to quantify and characterize the sole precipitation forecast influence in this system, especially on a daily basis, where one can expect less reliable forecasts.

ATMOSPHERIC AND HYDROLOGICAL MODELLING

The coupling between atmospheric and hydrological models was unidirectional. The daily rainfall data produced by the numerical weather prediction model were input to the hydrological model.

Numerical weather prediction model

Rainfall was forecast using the Brazilian version of the Regional Atmospheric Modelling System – RAMS (Pielke *et al*., 1992), known as BRAMS (http://www.-cptec.inpe.br/brams) – with two test grids of 20-km and 5-km resolution. Convection is parameterized according to Grell & Dévényi (2002). These forecasts have been produced on a daily basis through the *SegHidro Project* at the Federal University of Campina Grande, Brazil, since May 2005. The model is run for six days starting at 12:00 UTC. Initial and boundary conditions are from the CPTEC (Centre for Weather Forecast and Climate Studies, Brazil) global model, simulated with a 78-km horizontal resolution in Ecuador. At other latitudes, the east–west resolution is smaller as the model's resolution is measured in degrees that decrease poleward.

Hydrological modelling

The Tank Model (Sugawara, 1979) is a lumped model that considers the soil layer as tanks. The daily-basis model was adapted by Diniz *et al*. (1996) for semi-arid regions. Here, the model was calibrated to each event in order to minimize the influence of the hydrological model calibration errors in the coupled system, and to evaluate the precipitation uncertainties on the runoff generation. A trial-and-error calibration procedure was applied to adjust the simulated and observed hydrographs. Since the model is lumped, forecast precipitation data were spatially averaged over the basin.

CASE STUDY

Piancó is a medium-sized basin (4550 km^2) in northeastern Brazil. It is a typical drainage basin of this region, characterized by shallow soils, high evaporation rates and a scrub forest known as *Caatinga*. Annual mean rainfall is about 870 mm, concentrated in four months of the year. A set of three events were studied: (a) 16–23 March 2006; (b) 23 February–5 March 2006; and (c) 11–23 May 2006.

RESULTS

Precipitation forecast

Since the model is subject to a spin-up process, we neglected the first 12 hours of each simulation and considered the following five days for analysis. The forecast precipitation produced by the model using the grid resolutions of 5 km and 20 km presented no relevant difference between them. Therefore the following discussion refers to the 5-km resolution alone. Although the main features of most of the events were well represented, BRAMS overestimated small precipitation values (observed daily value <3 mm, e.g. Table 1 for event 1). BRAMS also predicted the rainfall peaks well. But for event 2 (Fig. 1(b)), besides the real peak the model forecast, two more peaks were forecast that did not occur. Figure 1 shows observed precipitation (Pobs), forecast precipitation one day in advance (P1), and forecast precipitation two days in advance (P2) (event 3 was omitted since it showed similar behaviour to that of event 1).

Table 1 shows quantitative values of the area-averaged forecast precipitation for different initialization days. The relative deviation indicates (small values) whether the forecasts were close to the observed values. One can see that the predictability varies among the days; in some cases there are low relative deviations, even for forecasts five days in advance. Figure 2 shows the 1-day in advance forecast precipitation for 18 March 2006. It clearly shows the overestimation of small precipitation values outside the hydrographic basin. Inside the basin, however, although the distribution is not similar, the intensity of the event was captured.

Table 1 Precipitation forecasts for 16–23 March 2006.

Date in March 2006	16	17	18	19	20	21	22	23
	Precipitation (mm)							
Observed	0.1	1.2	17.6	16.5	9.4	19.8	0.5	6.6
1-day in advance	16.6	18.6	14.8	17.8	15.2	15.3	10.4	8.7
2-days in advance		16.0	19.0	16.6	12.3	16.4	13.4	9.2
3-days in advance			13.7	17.8	14.6	16.7	18.2	9.2
4-days in advance				13.5	17.2	14.4	17.3	11.1
5-days in advance					15.0	16.3	18.7	15.9
	Relative deviation							
1-day in advance	169.05	14.15	0.16	0.08	0.61	0.23	18.96	0.31
2-days in advance		12.03	0.09	0.01	0.31	0.17	24.68	0.39
3-days in advance			0.22	0.08	0.55	0.16	33.89	0.38
4-days in advance				0.18	0.82	0.27	32.06	0.68
5-days in advance					0.59	0.18	34.79	1.39

Relative deviation = abs(forecast – observed)/observed. The forecasts were initiated one day before the event begins (15 March 2006) for 6-days ahead; thus, there is no forecast for 16 March 2006 with 2-days in advance, and so on.

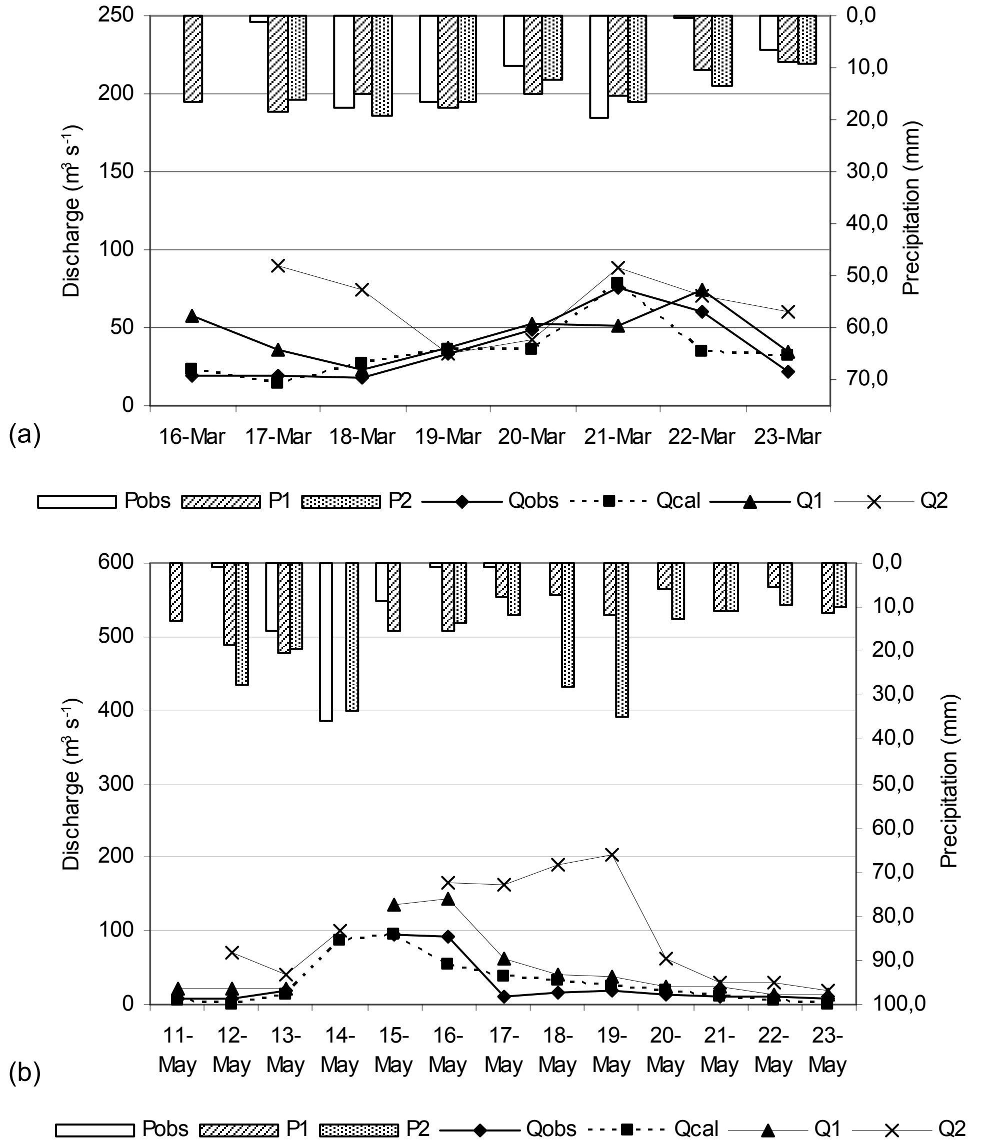

Fig. 1 Discharge and area-averaged precipitation: (a) Event 1: 16–23 March 2006; (b) Event 2: 11–23 May 2006. Pobs: observed precipitation; P1: one day in advance precipitation forecast; P2: two days in advance precipitation forecast; Qobs: observed runoff; Qcal: calibrated runoff; Q1, Q2: one and two days in advance runoff forecasts. The discontinuities in hydrographs Q1 and Q2 for event 2 were caused by a failure of one day in the rainfall forecast.

Runoff forecast

Runoff simulations were run for each of the five days of precipitation forecasts. The hydrographs were updated daily using observed precipitation data. For example, in Event 1 (16–23 March 2006) for the precipitation forecast beginning on 17 March, the 16th was filled with the observed precipitation. Forecasts one day in advance (Table 2) formed a single curve (Fig. 1, Q1). The same reasoning applies for two days in advance.

For Event 1 (Fig. 1(a)), all forecasts coherently represent the shape of the hydrograph. For forecasts one day in advance (Q1) even its magnitude was well

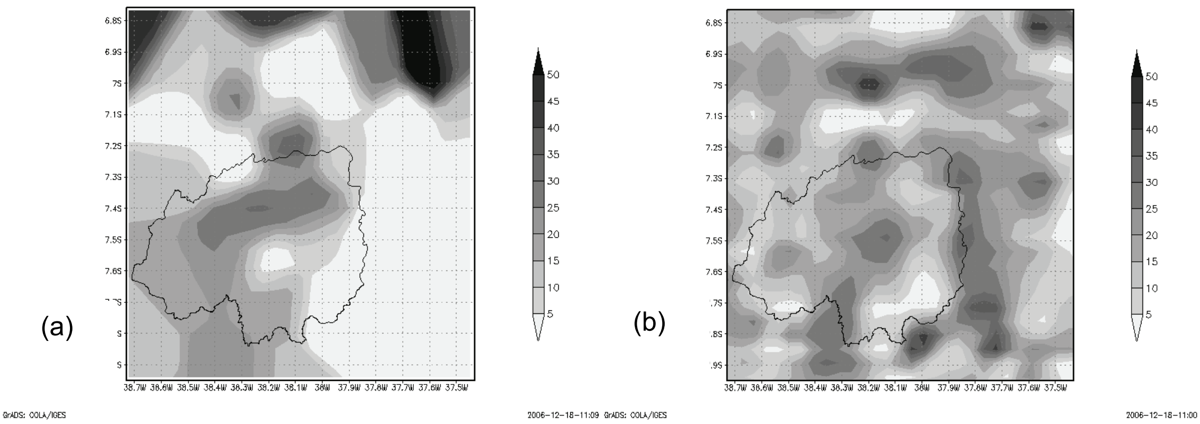

Fig. 2 Precipitation (mm) forecasts for 18 March 2006: (a) observed; (b) one day in advance.

Table 2 Runoff forecasts for 16–23 March 2006.

Date in March	16	17	18	19	20	21	22	23
	Runoff (m^3 s^{-1})							
Qobs	18.8	19.0	18.3	33.4	48.7	75.3	59.8	22.1
Qcal	23.6	14.7	26.4	35.8	35.6	78.7	35.1	31.6
1-day in advance	57.1	35.7	23.1	37.3	52.1	51.9	74.5	34.2
2-days in advance		90.2	74.7	32.8	41.9	88.6	70.5	60.9
3-days in advance			103.5	115.3	39.2	82.0	129.0	60.7
4-days in advance				111.9	145.5	62.7	118.3	119.5
5-days in advance					128.9	165.6	110.9	139.7
	Relative deviation							
1-day in advance	2.03	0.88	0.26	0.12	0.07	0.31	0.25	0.55
2-days in advance		3.74	3.08	0.02	0.14	0.18	0.18	1.76
3-days in advance			4.65	2.45	0.20	0.09	1.16	1.75
4-days in advance				2.35	1.99	0.17	0.98	4.42
5-days in advance					1.65	1.20	0.86	5.33

Qobs: observed runoff (m^3 s^{-1}); Qcal: calibrated runoff (m^3 s^{-1});
Relative deviation = abs(forecast –observed)/observed.

simulated. For the other forecasts, an overestimation of runoff was observed (as shown for Q2). For Event 2 (Fig. 1(b)), the runoff forecast one day in advance also correctly represented the shape of the hydrograph (Q1). In both cases, it seems that for a short advance the hydrological model filtered the precipitation overestimation presented in the first two days of the simulation. In Event 2, for the forecast two days in advance (Q2), it seems that precipitation uncertainty begins to impact the runoff forecast; this also occurs to the other forecasts (three to five days in advance). The behaviour of Event 3 is similar to that of Event 2.

Table 2 shows quantitative values of runoff for all forecasts of event 1, as well as the observed and the calibrated runoff. The relative deviation for runoff forecasts two days in advance is worth noting, since both the timing and magnitude of the hydrograph recession were well represented. The runoff forecast was only affected in the first two days, when the forecast precipitation was overestimated.

CONCLUSIONS

This paper reports an experience of unidirectional coupling of atmospheric and hydrological models in the Brazilian semi-arid context. A set of short-term weather forecast data was employed to analyse the influence of precipitation forecast uncertainties on runoff estimates. The numerical weather prediction model was run with two different grid resolutions (20 km and 5 km). The results showed low sensitivity to grid resolution, since BRAMS's nested grids are fully coupled, producing similar estimates when averaged over the basin. Therefore, only the 5-km grid results were analysed. The operational precipitation forecasts used in this study suggest a potential for using daily weather forecasts, for reservoir operation or flash-flood estimation purposes in the semi-arid Brazilian Northeast, one day in advance. The hydrological model is capable of filtering small errors in this case. For two to five days in advance, the precipitation forecast uncertainties begin to increasingly impact the runoff forecast. Part of that is caused by BRAMS bias in forecasting small precipitation values. Even so, these bias uncertainties presented more, or, less defined patterns for the three events tested. This suggests that heuristic correction procedures can eventually be used to reduce the predictive uncertainty.

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