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Evaluation of seasonal forecasting methods for water resource management in northeastern Brazil

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Abstract Rain in the semiarid and drought-prone northeast of Brazil is highly variable in space and time. Recently available forecasts of seasonal rainfall are at the regional or at the general circulation model (GCM) grid-square scales, and their usefulness for water management will depend on how far they can be disaggregated to give forecasts at the drainage-basin scale. In this paper seasonal rainfall forecasts produced by two methods—a statistical–empirical method and a GCM—are used to derive forecasts of flow volumes, using downscaling and resampling procedures. Performance measures show significant information loss where forecasts of seasonal rainfall are converted to runoff sequences intended for use in water resource management, although some gain is verified in a simulation of the operation of a reservoir using the forecasts.

INTRODUCTION

Rain in the semiarid northeast ("Nordeste") of Brazil is highly variable in space and time, generally falling between January and July, but concentrated in the four months February–May. In recent years, better understanding of atmospheric and oceanic behaviour has resulted in improved estimates of seasonal rainfall, benefiting from the fact that, for northeastern Brazil, it is a climatic phenomenon unusually well defined in its large-scale circulation setting (Hastenrath, 1991). However, these estimates are at the regional or at the GCM grid-square scales, and their usefulness—whether for water management, rainfed agriculture, domestic supply or irrigation—will depend on how far they can be disaggregated to give forecasts at the drainage-basin scale. A number of research groups are working on seasonal rainfall prediction for the northeast, using methods falling into two broad classes: (a) statistical–empirical, and (b) dynamic. The first group contains methods based on regression, discriminant analysis, and neural networks, among others. The second group includes models of atmospheric behaviour. This paper deals with one method from each group: namely, the forecasting method based on linear discriminant analysis used by the Hadley Centre for Climate Prediction and Research of the UK Meteorological Office, and the model of atmospheric circulation of the European Centre for Medium-Range Weather Forecasts (ECMWF) of the EU. These two models are denoted by LDA and GCM, respectively, in the following text. The evaluation of these forecasting methods for estimating rainfall, and their potential use for estimating runoff, selecting planting date optimized with respect to rainfall and reservoir operation are of great importance for the Brazilian northeast.

HYDROLOGICAL RECORDS

Hydrological records, particularly for discharge, are limited in the region. Rainfall records are available for 1911–1988 from a network of 66 stations situated in the north of northeastern Brazil, a region of about 500 000 km^2. Seasonal (February–May) rainfall anomalies averaged over this area constitute the "regional rainfall" series used in this paper. Piancó, a typical drainage basin in the region, was selected for study, where nine raingauges provided data for the "basin rainfall" over the period 1911–1988, two of them belonging to the regional rainfall network. Discharge was measured at the basin outlet (area 4550 km^2) from 1964–1988. Rainfall data for the GCM grid square which includes the basin (6.25–8.75°S, 36.25–38.75°W)—the "grid-square rainfall"—were available for 1911–1988 from 17 raingauges, a subset of the regional rainfall network.

Coremas Reservoir, located downstream of Piancó basin, was used to assess the value of the forecasts for water management. This reservoir has a total storage capacity of 1350×10^6 m^3, a contributing basin of 7947 km^2, and its surface is subject to high evaporation (2100 mm year^{-1}). It was designed to distribute water over a period of several years ("pluri-annual" operation) to meet demands for irrigation, domestic use, fisheries and power generation, which requires 40×10^6 m^3 month^{-1}.

METHODS

The Hadley Centre's LDA model (Ward & Folland, 1991) was calibrated using average values of eigenvectors of sea-surface temperature anomalies in the Pacific and Atlantic Oceans for months preceding the wet season, November–January, to produce forecasts of seasonal rainfall anomalies, February–May. The model was calibrated to forecast rainfall on both the regional and the drainage-basin scales. The forecasts are issued as probabilities associated with seasonal rainfall anomalies falling in five predefined categories.

The GCM (Becker, 1997) is the ECMWF model (IFS T63L31 cy13r4), and seasonal ensemble simulations have been made available under the European Union research programme "Prediction of climate variations on seasonal to inter-annual time scales" (PROVOST). Each ensemble is 120 days long, consists of nine members and gives hindcasts of cumulative rainfall at ten-day intervals, over the period 1979–1993, for grid squares of 2.5 × 2.5 degrees of latitude and longitude. Relevant for forecasting rainfall anomalies of the Nordeste was the ensemble over the period March–June. Downscaling was necessary to obtain predictions at the drainage-basin scale and was effected by a linear regression relating grid-square and basin rainfall series. Frequency analysis on the nine members of the ensemble produced probabilistic forecasts in the same format of those of LDA.

Using the rainfall forecasts and their probabilities, a resampling procedure was applied to historical series of rainfall and runoff for the Piancó basin, thus obtaining probabilistic estimates of future runoff volumes; the method is described by Croley (1996). This approach basically consists of building a structured set of coupled events of seasonal rainfall and runoff anomalies from the historical record that gives relative frequencies of seasonal rainfall satisfying the probabilities of the climate forecast. The probability distribution of the structured set of seasonal runoff can be determined by considering the relative frequencies of the events.

The main calibration and verification periods for all models employed in this study (except for the GCM, which requires no calibration) were taken as 1911–1978 and 1979–1988 respectively. Due to limitations in the availability of rainfall and runoff data, the forecasts produced by both models for periods after 1988 could not be evaluated in this stage of the research.

The ranked probability score (*RPS*) was used as a measure of forecast accuracy. The *RPS*, used for probabilistic forecasts of categories, such as those described above, penalizes forecasts increasingly as more probability is assigned to event categories further removed from the actual outcome (Wilks, 1995). The score for a perfect forecast is $RPS = 0$; the worst possible score is $RPS = J - 1$, where J is the number of categories in which the forecast space is divided. In our case, $J = 5$ and the worst score is $RPS = 4$. The *skill score* refers to the relative accuracy of a set of forecasts, with respect to some set of *reference* forecasts (taken in this paper to be long-term average values of the predictand). It is interpreted as a percentage improvement over the reference forecasts. The skill score for *RPS* is

$$S_{\mathrm{ref}} = 100(1 - RPS/RPS_{\mathrm{ref}})$$

If the forecasts being evaluated are inferior to the reference forecasts ($RPS > RPS_{\mathrm{ref}}$), $S_{\mathrm{ref}} < 0\%$; if the forecast is perfect, $RPS = 0$, and the skill score attains its maximum value of 100%; otherwise, if $RPS = RPS_{\mathrm{ref}}$, then $S_{\mathrm{ref}} = 0\%$, indicating no improvement over the reference forecasts (Wilks, 1995).

A standard deterministic dynamic programming (DP) scheme (Loucks *et al.*, 1981) was used to evaluate the impact of the runoff forecast on the monthly operation of the Coremas Reservoir. The median of the seasonal runoff probabilistic forecasts, extrapolated in the proportion of the contributing area of the reservoir in relation to the area of Piancó basin, was used as input to the DP model. Disaggregation in time for the forecast seasonal total to the monthly values was effected simply by dividing the forecast runoff in proportion to the long-term monthly mean runoff. The long-term monthly mean runoff was used as input for the other months of the year. The operating horizon was taken as one year, starting in the first month of the season being forecast, i.e. March when using GCM and February in the case of LDA forecasts. The average relative shortage over the operating year was taken as the objective function to be minimized: this relative shortage was defined as the proportion between the shortage and the desired demand during a certain month. Its average over the period of operation, using the releases prescribed by the DP scheme, produces the average relative shortage index (*ASI*) which is a measure of performance of the operation. The reference measure ASI_{ref} is obtained when long-term monthly means are used to give the seasonal inflow volumes used as input to the DP.

RESULTS AND DISCUSSION

The following problems were encountered when assessing to what extent LDA and GCM models could contribute to water resource management in northeastern Brazil:

(a) limited hydrological records, particularly of runoff; which limited the test period to 10 years only;
(b) downscaling of grid-square rainfall forecasts to the Piancó basin scale;
(c) the small number of "integrations" in the ensemble calculated in GCM usage;
(d) conversion of rainfall forecasts to runoff; and
(e) evaluation of runoff forecasts in terms of reservoir management.

Bearing in mind these difficulties, *RPS* and skill measures obtained when the LDA and GCM models were used to forecast seasonal rainfall and runoff were as shown in Table 1. These results were also interpreted in terms of planting dates and irrigation demands; this interpretation is not presented in this paper due to space limitations.

Although the period 1979–1988 is short, it is particularly valuable as a validation period because it includes both one of the driest periods on record—coinciding with the El Niño event of 1983—and one of the wettest years, 1985.

This paper will not compare the performance of the two methods for forecasting seasonal rainfall, but discusses the usefulness of the two approaches in the practical context of water resource management. In any case, rigorous comparison between them is ruled out by differences in the scope of series produced by the two models, and in the periods of the year that they cover. However, as they are representative of the two main classes of models used for seasonal forecasting and give forecasts with a precision similar to that of other models in the two classes, the results presented here give a broad indication of the value of forecasts obtained from their use, and give an idea of what might be done in other regions with broadly similar climatic characteristics.

The accumulated dilution of the value of forecasts resulting from conversion of rainfall forecasts to runoff sequences useful for water resource management at the basin scale (e.g. reservoir operation) is evident from Table 1. Comparison of the *RPS* for regional rainfall with that of basin rainfall predicted by LDA shows that the value of forecasts diminishes as the model is calibrated using a smaller scale; and it also

Table 1 Performance measures for evaluating the forecasts: ranked probability score (*RPS*) and its reference (RPS_{ref}) averaged over 1979–1988, skill score and coefficient of correlation (*R*).

Method	Predictand	*RPS*	RPS_{ref}	Skill (%)	*R**
LDA	Regional rainfall	0.60	1.02	41	
	Basin rainfall	0.68	0.84	19	
	Basin runoff	0.79	0.80	1	0.79
	Basin runoff†	0.70	0.81	13	0.65
GCM	Grid-square rainfall	0.67	0.78	14	
	Basin rainfall	0.83	0.80	–4	
	Basin rainfall‡	0.59	0.82	28	
	Basin runoff	0.97	0.80	–22	0.91
	Basin runoff‡	0.75	0.82	9	0.93

* computed using the median as the forecast;
† using 1964–1988;
‡ except for 1979.

diminishes as information is transferred to another variable at the same scale, as in the case of runoff volumes derived from rainfall. In the case of downscaling, when GCM is used, the scale transformation is effected not by direct calibration with records collected at the smaller scale, but use of a simplified transfer function; this also causes a dilution of information.

To compound these difficulties, model performance was assessed using only 10 years of data, and this also must be taken into account. In 1979, for example, the observed seasonal rainfall from March to June in the basin was very different from that in the grid square. In the basin, 1979 was relatively wet, with total rainfall between 40 and 60% of long-term seasonal rainfall; at the grid-square scale, the corresponding percentages were only 20–40%. The GCM forecast of total rainfall for the grid square was relatively good (rainfall predicted by all nine members was below 20% of the long-term mean); however the linearity of the downscaling procedure giving basin-scale rainfall, and the resampling procedure necessary to convert rainfall forecasts into runoff volumes, resulted in an incorrect "very dry" forecast. As the test period is so short, the high *RPS* of 1979 (3.00) greatly influenced the mean *RPS* over the 10 years. The fragility of these values when derived from such a short series can also be seen when they are compared (as was possible for the LDA model) with results obtained for the longer period 1964–1988, using the entire flow record for the Piancó basin. As Table 1 shows, the skill changes significantly, although it is still low. Therefore, besides the need for caution in their interpretation, the performance measures confirm the hypothesis of significant information loss where forecasts of seasonal rainfall are converted to runoff sequences intended for use in water resource management.

On the other hand, another performance measure—the correlation between observed and forecast runoff volumes, when the latter are taken as the median values of the frequency distribution obtained by resampling—is relatively high, both when LDA and GCM are used (Table 1). This shows (see Fig. 1 for the case where runoff forecasts were derived using the GCM model) that, although runoff forecasts are inaccurate in absolute terms, they follow the general trends in observed runoff

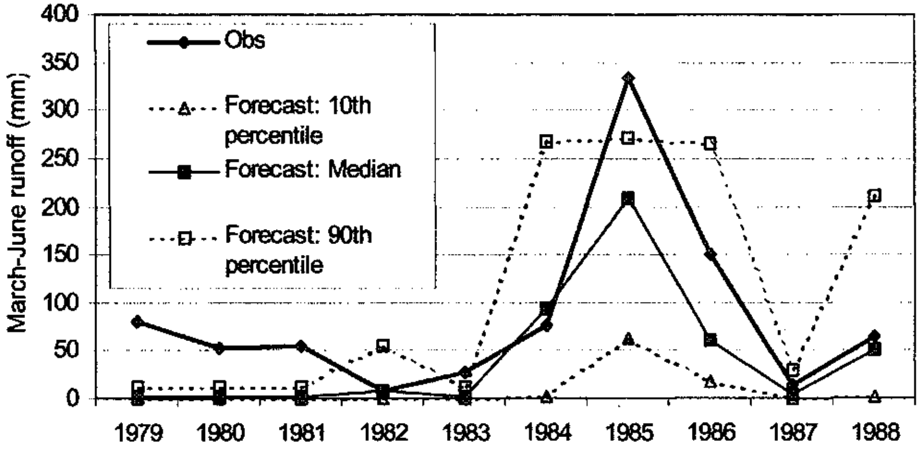

Fig. 1 Seasonal runoff as estimated through resampling using forecasts by GCM after downscaling for Piancó basin.

sequences, identifying years that are wetter or drier than average. This result points the way for future research.

Runoff between February and May is 94% of the total annual runoff from the Piancó basin; that between March and June is 86%. Therefore, if it were possible accurately to forecast runoff during these periods, difficulties of reservoir operation would largely disappear. In the verification period, the Coremas Reservoir gave problems due to water scarcity in the years 1983–1984 and, if runoff forecasting is to be useful, one would have expected that reservoir operation would have been modified to remove the problems encountered in this period. However, simulating its use with forecast runoff volumes did not improve the situation, giving the result that the reservoir would be almost empty during two months at the beginning of 1984. This was despite the improvement showed by the shortage index when forecasts were used (Table 2).

Table 2 Performance of Coremas Reservoir operation when using seasonal forecasts: average relative shortage index (*ASI*) and its reference (ASI_{ref}) for 1979–1988.

Runoff forecast method	*ASI*	ASI_{ref}
LDA	0.40	0.62
GCM	0.44	0.48

One of the possible reasons for the small gain when using the runoff forecasts to improve operation of the Coremas Reservoir lies, perhaps, in the fact that it is pluri-annual, designed to store water for use over several years, so that single-season forecasts are of lesser value. If this is the case, methods giving forecasts over a longer period (e.g. Kane, 1997), but with less skill, may be useful, perhaps to indicate trends two or three years ahead. A combination of these two types of information is potentially useful for pluri-annual reservoirs like those of northeastern Brazil. Another explanation for the limited gain could have been the use of an optimization procedure—deterministic dynamic programming—which does not take account of the probabilistic nature of runoff volumes, using only a representative value, in this case the median runoff. Research is in progress to test this hypothesis, using both forecasts with longer time horizon and stochastic methods of reservoir operation.

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