The Rainy Seasons of the 1990s in Northeast Brazil: Real-Time Forecasts and Verification

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ABSTRACT

Based on circulation diagnostics in the tropical Atlantic sector and the equatorial Pacific, empirical methods have been developed to forecast anomalies in the March–June rainy season of northeast Brazil from observations to the end of the preceding January. Techniques include stepwise multiple regression, neural networking, and linear discriminant analysis. The methods were developed from the dependent training period 1921–57, and their performance was validated on the independent record 1958–89, prior to real-time application. Real-time forecasts have been regularly issued during the 1990s. These forecasts were in close agreement with the observed rainfall, except for the extreme El Niño year of 1998. A possible cause of this failure is seen in the lack of comparably extreme Pacific warm events within the training period used for the development of the empirical methods.

1. Introduction

Tropical climate prediction is receiving increased attention, and there has been some progress (see reviews in Hastenrath 1985, 330–352; 1986; 1990a; 1995a; 1995b, 347–373; Barnston et al. 1994, 1999; Anderson et al. 1999). An early target of opportunity has been the classical problem of northeast Brazil droughts. In our work at the University of Wisconsin since the 1970s we have explored the annual cycle and interannual variability of circulation and climate in the tropical Atlantic sector. We found that the southernmost position of the Intertropical Convergence Zone (ITCZ) in the course of the annual cycle coincides with the short rainy season of Brazil's Nordeste centered around March–April; and that anomalous interhemispheric gradients of sea surface temperature (SST) in the Atlantic force anomalous fields of meridional wind component and latitudinal position of the ITCZ, with an anomalously far northerly ITCZ location causing drought in the Nordeste (Hastenrath and Lamb 1977; Hastenrath and Heller 1977). These findings subsequently stimulated papers by other groups (see review and references in Hastenrath 1995b, 302–309, 330–346).

Our diagnostic analyses formed the foundation for the development of methods for forecasting of anomalous rainy seasons in the Nordeste. As pertinent precursors we recognized the preseason rainfall in the Nordeste itself, the basinwide meridional wind component and interhemispheric SST gradient in the Atlantic, and, to a lesser extent, SST in the Pacific. We presented viable prediction methods by the mid-1980s (Hastenrath 1983, 1984; Hastenrath et al. 1984). Having thus demonstrated the feasibility of climate prediction for the Nordeste, we held out a challenge: input information through the end of January would be required by early February, so that the forecast could be issued early enough to be practically useful for the March–June rainy season. These were formidable logistical tasks. At the local level valiant efforts were made right away to collect the reports from a network of selected rain gauges in the Nordeste and to transmit them promptly (before the advent of fax and e-mail). Even more daunting was the demand on the larger scale, namely, the collection, quality control, processing, and distribution of meteorological ship observations over the tropical oceans. It took many years to build such capability.

In the meantime, we continued our research on Nordeste climate prediction, using 1921–57 as the dependent part of the record for method development and 1958–89 as the independent period to verify forecast performance (Hastenrath 1990b; Hastenrath and Greischar 1993a). By the beginning of 1992 the time was ripe: logistical capabilities at the international level had evolved to the point that sets of ship observations from the World Ocean became available with a delay of a

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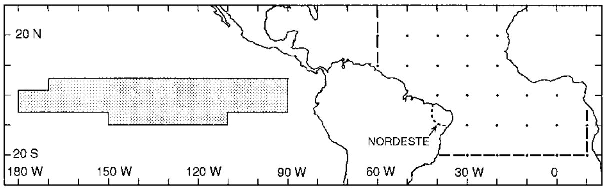

FIG. 1. Orientation map. The wind index V and SST index T2 were compiled for the entire Atlantic domain shown. Dashed lines demarcate the area for which the SST index T1 was constructed. Stippling in the equatorial Pacific marks the domain of the SST index PAC. Dotted line encloses the region of the 27 rain gauge stations used for the northern Nordeste.

few days and new electronic communications systems were in place. Promptly we began issuing climate forecasts operationally in real time. The decade has now come to a close, and the current paper offers an account of our empirically based climate predictions for the Nordeste with verification of performance.

2. Data and methods

Based on our diagnostic findings, the following preseason information provides meaningful predictors of Nordeste precipitation: preseason rainfall in the Nordeste itself, basinwide field of meridional surface wind component over the tropical Atlantic, SST in domains of the tropical North and South Atlantic, and SST in the equatorial Pacific (Fig. 1). Indices of these elements were compiled as described in Hastenrath and Greischar (1993a).

From a network of 27 rain gauges in the Nordeste (Fig. 1), indices of October–January (ONDJ) and of March–June (MAMJ) rainfall were constructed. These dimensionless indices are all-station averages of normalized departure, as detailed in Hastenrath and Greischar, (1993b).

From the Comprehensive Ocean–Atmosphere Dataset (COADS) (Woodruff et al. 1987) and using empirical orthogonal function (EOF) analysis, an index V of the January meridional wind field over the tropical Atlantic between 30°N and 30°S (Fig. 1) was created; a positive value is characterized by enhanced southerly flow, which is associated with dry conditions in the Nordeste.

From the SST dataset of Bottomley et al. (1990), we likewise constructed EOF-derived indices of SST in the tropical Atlantic (Fig. 1). Two files from this dataset are of interest here, as detailed in Hastenrath and Greischar (1993b): ‘‘File 29’’ consists of raw observations, and the index of the January SST field shall here be called ‘‘T1’’; while ‘‘File31’’ contains values corrected for presumed observational bias, and the index of the November–December–January SST conditions is here referred to as ‘‘T2.’’ The domains of the indices are defined in Fig. 1. A positive value of these indices is characterized by warm (cold) departures to the north (south) of the equator and is associated with Nordeste drought.

An index designated as ‘‘PAC’’ compiled from COADS represents the January SST conditions in the equatorial Pacific (Fig. 1); warm water anomalies tend to accompany dry conditions in the Nordeste.

To express the diagnostic relationships quantitatively and for prognosis, three standard statistical techniques were used (Hastenrath and Greischar 1993a), namely, stepwise multiple regression (R), neural networking (NN), and linear discriminant analysis (LDA). In general, NN may have an advantage over R where relationships are strongly nonlinear, and LDA may capture best the extremes. Diversity of input information competes with the desirable limitation in degrees of freedom. Accordingly, models limited to SST are in order as well as models using in addition other predictors. Of the various regression models two are considered here, and for consistency these are referred to by the same names used in the earlier publications (Greischar and Hastenrath 1995; 1996a,b; 1997a,b; 1998; 1999; Hastenrath and Greischar 1993a,b; 1994; 1995). The regression model R32 has as input the SST indexes T2 and PAC, while the regression model R25 as well as the neural network model NN use the rainfall index ONDJ, the wind index V, and the SST indices T1 and PAC. The linear discriminant analysis model LDA32 uses the same input as the regression model R32, and the linear discriminant model LDA25 uses the same as the regression model R25. Thus, the models R25, NN, and LDA25 have as input the preseason regional rainfall, Atlantic wind and SST fields, and equatorial Pacific SST, whereas in models R32 and LDA32 the input is limited to SST information. Observations to the end of the preceding January were used to predict the March–June rains. The years 1921–57 served as dependent portion of the record, or training period, to develop the method; and the period 1958–89 was used as independent portion of the record to validate the performance of the methods.

Four statistics are used to measure the forecast skill from stepwise multiple regression and neural networking (Nicholls 1984, 1985): the coefficient of temporal correlation (corr) between the forecast (RAIN′) and observed (RAIN), the root-mean-square error (rmse), the absolute error (abse), and the bias (bias). The last three statistics are compiled as follows:

$$\mathrm{rmse} = \left[\sum^{N} (\mathrm{RAIN}' - \mathrm{RAIN})^2/N\right]^{1/2},$$

$$\mathrm{abse} = \sum^{N} |\mathrm{RAIN}' - \mathrm{RAIN}|/N, \quad \text{and}$$

$$\mathrm{bias} = \sum^{N} (\mathrm{RAIN}' - \mathrm{RAIN})/N,$$

where the summation extends over the N forecast years. The four aforementioned measures of forecast performance from R and NN have previously (Hastenrath and Greischar 1993a) been presented for the period 1958–89 and are now also evaluated for the interval 1990–99.

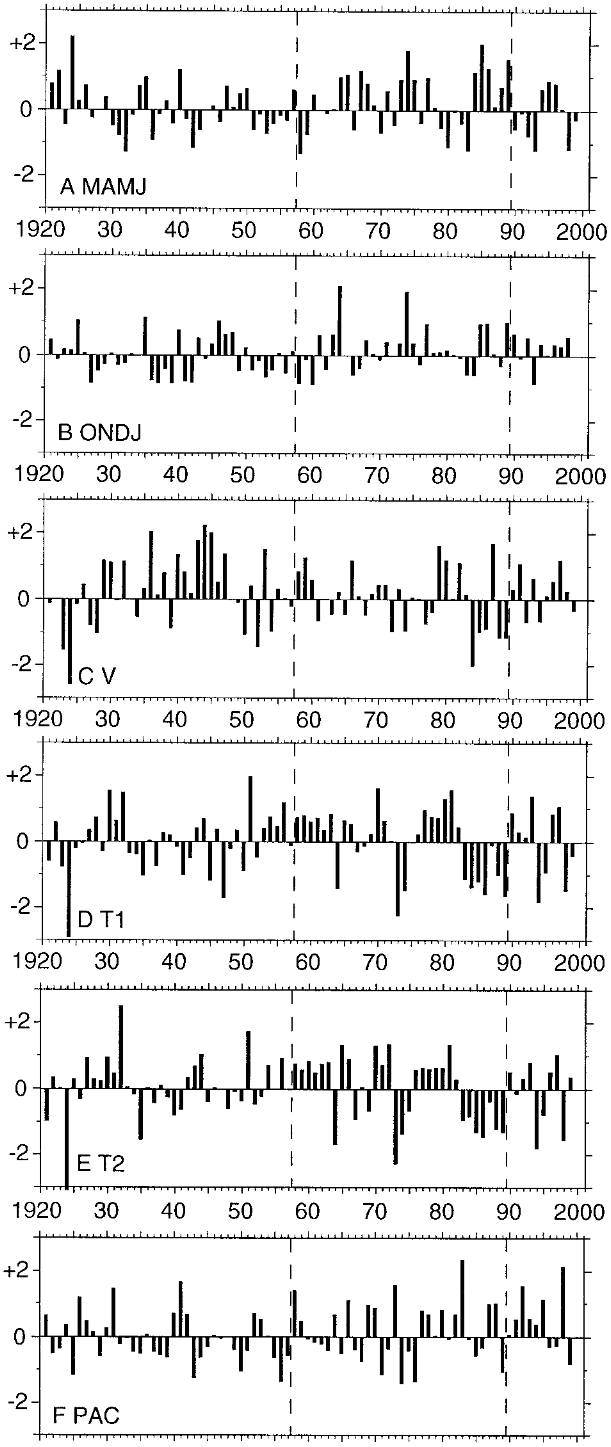

FIG. 2. Time series of elements used in method development and prediction. Vertical dashed lines separate the periods of 1) training (1921–57), 2) verification (1958–89), and 3) real-time forecasts (1990–99). (a) Index of Mar–Jun rainfall in Nordeste MAMJ; (b) index of Oct–Jan rainfall ONDJ; (c) index of Jan meridional wind component over the tropical Atlantic V; (d) index of Jan SST in tropical Atlantic T1; (e) index of Nov–Dec–Jan SST in tropical Atlantic T2; (f) index of Jan SST anomaly in equatorial Pacific PAC. All dimensionless except °C for PAC.

In the LDA, the Nordeste rainfall index MAMJ of the period 1923–57 was divided into five intervals: Q1, very dry; Q2, dry; Q3, normal; Q4, wet; and Q5, very wet. These categories or quints are defined by the boundaries −0.57, −0.29, +0.05, and +0.66. The performance was evaluated by hit rate (Ward and Folland 1991).

The models have also been transferred to pertinent research institutions in Brazil, namely, Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME) in Fortaleza, Ceará, and Instituto Nacional de Pesquisas Espaciais (INPE) in Cachoeira Paulista, Saõ Paulo, to parallel our activities at the University of Wisconsin. Real-time forecasts for the Nordeste have also been issued regularly by the Hadley Centre of the U.K. Met. Office and occasionally by other groups (e.g., Folland et al. 1993; Ward et al. 1994; Coleman and Davey 1998; CPC 1993a,b; Graham 1994).

3. Diagnostic background

Figure 2 depicts the time series of the elements used in the climate prediction. In line with the remarks in section 2, Fig. 2b ONDJ runs broadly parallel, and Figs. 2c (V), 2d (T1), 2e (T2), and 2f (PAC) opposite to Fig. 2a (MAMJ). Three time intervals are distinguished: 1) 1921–57, 2) 1958–89, and 3) 1990–99. As explained in section 2, interval 1 is the dependent portion of the record, or training period, used to develop the methods, while interval 2 is the independent portion of the record from which the performance of the methods was validated, prior to their application in real time in the 1990s. Interval 3 is the interval for which performance is examined in the current paper.

Figure 3 illustrates the long-term evolution of relationships between the various predictors and the predictand. In accordance with Fig. 2, correlations of the predictand MAMJ are overall positive with (Fig. 3a) ONDJ, and negative with (Fig. 3b) V, (Fig. 3c) T1, (Fig. 3d) T2, and (Fig. 3e) PAC. Mostly correlations appear stronger in the later portion of the record. This may be due to intrinsically closer relationships or improved quality of observations.

4. The forecasts and verification

Forecasts were produced right after receipt of the last item of necessary input observations and then promptly faxed to Brazil. They were issued on 21 February 1992, and in subsequent years on 4 March, and 11, 8, 7, 18, 5, 19, and 7 February. The forecasts were also regularly reported in forecast bulletins and workshop proceedings (Hastenrath and Greischar 1993b, 1994, 1995; Greischar and Hastenrath 1995; 1996a,b; 1997a,b; 1998; 1999). In addition to these eight years of real-time forecasts, we also completed the calculations for 1990 and 1991, the two years following the 1958–89 verification period

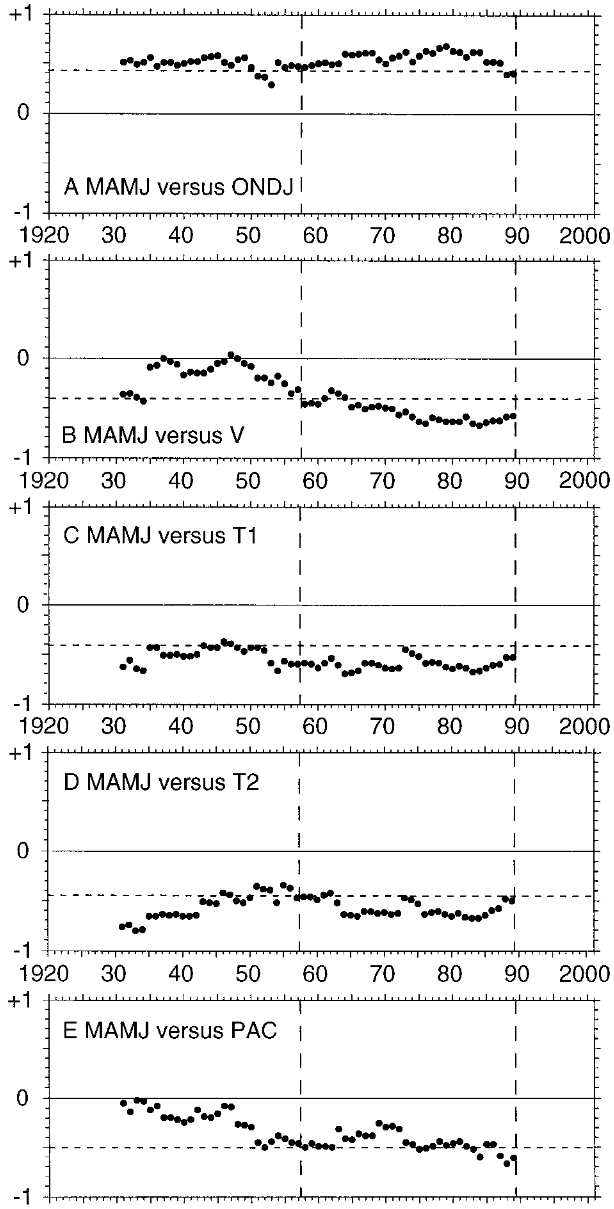

FIG. 3. 21-yr sliding correlations between Mar–Jun rainfall in Nordeste (MAMJ) and indicated elements. Vertical dashed lines separate periods as in Fig. 2. (a) ONDJ, (b) V, (c) T1, (d) T2, and (e) PAC. Dashed lines indicate approximately the 5% significance level.

and preceding the era of timely availability of input observations.

Figure 4 presents dotplots of the MAMJ rainfall index over the aforementioned intervals 1921–57, 1958–89, and 1990–99, for the regression models R32 and R25 and neural network NN, with open circles representing observed values, and solid dots the regressed (trained for NN) and predicted values. Forecast performance is further evaluated in Table 1 for R32, R25, and NN and in Table 2 for LDA, in both tables for the 1958–89 verification period (B) of the method development (Hastenrath and Greischar 1993a) and the 1990s. Tabulation is presented separately for the entire period (C) 1990–99, and the years (CC) 1990–97 plus 1999 (i.e., excluding the year 1998). These separate evaluations are meant to provide a quantitative framework for compar-

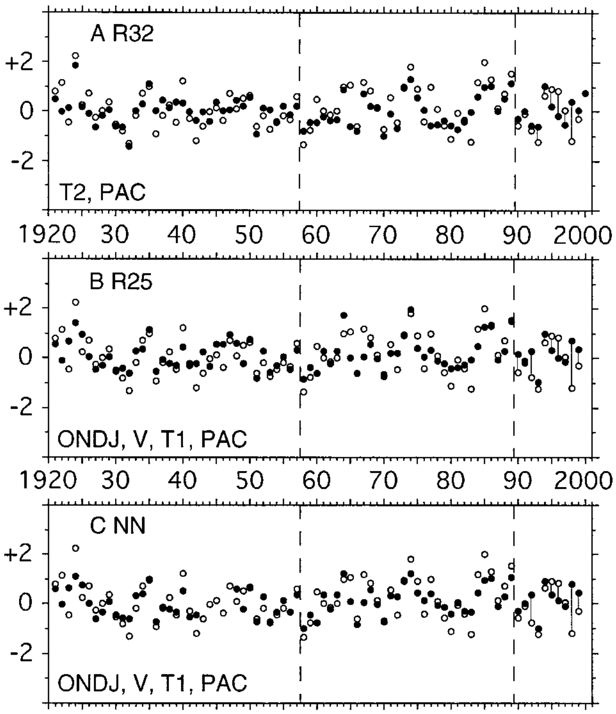

FIG. 4. Time series plots of Mar–Jun rainfall index from (a) regression model R32, (b) regression model R25, and (c) neural network model NN. Solid dots denote regressed (trained for model NN) values for the years up to 1957, and forecast values from 1958 onward. Vertical dashed lines separate periods as in Fig. 2. Open circles indicate observed MAMJ values. For years from 1990 onward, vertical solid lines join the symbols of predicted and observed values.

TABLE 1. Performance comparison of forecasts from information through January for Mar–Jun. For model R32 inputs are T31 and PAC, and for models R25 and NN inputs are ONDJ, V, ST29, and PAC. Symbols are as follows: var = explained variance = square of correlation coefficient between predicted and observed rainfall, in hundredths (asterisk indicates significance at the 1% level of the corresponding correlation coefficient = square root of var); rmse = root-mean-square error; abse = absolute error; bias = bias.

	Var	Rmse	Abse	Bias
Model (B) 1958–89				
R32	58*	64	49	−28
R25	61*	55	44	−6
NN	66*	55	45	+13
Model (C) 1990–99				
R32	17	72	58	+12
R25	8	85	68	+34
NN	9	86	66	+39
Model (CC) 1990–97, 1999				
R32	42	54	46	−4
R25	30	62	54	+17
NN	32	62	52	+21

TABLE 2. Linear discriminant analysis.

Period	Hit rate
Model LDA32	
(B) 1958–89	0.38
(C) 1990–99	0.40
(CC) 1990–97 plus 1999	0.44
Model LDA25	
(B) 1958–89	0.34
(C) 1990–99	0.20
(CC) 1990–97 plus 1999	0.22

ison and should not detract from the fact the 1998 forecast failed.

Figure 4 bears out for models R32, R25, and NN and for most years of the 1990s close agreement of the predicted with the observed rainfall. A very large contrast is, however, apparent for the year 1998 and a lesser difference for 1992. Although the years of real-time forecasts are few and significance testing is precluded, the measures of forecast performance were computed and tabulated in Table 1. Over the entire interval (C) 1990–99 rmse, abse, and bias are larger and explained variance is much smaller than for the model verification period (B) 1958–89. For the years (CC) 1990–97 and 1999 (excluding the year 1998), R32 shows a performance comparable to that for the model verification period (B) 1958–89, with weaker results for R25 and NN. Table 2 presents the performance of LDA, where the model LDA32 has the same input as the regression model R32, and model LDA25 the same input as the regression model R25. The model LDA32 based solely on Atlantic and Pacific SST in November–December–January shows for the periods (C) 1990–99 and (CC) 1990–97 plus 1999 performance at least as strong as for the method verification period (B) 1958–89; by contrast, for model LDA25, containing preseason Atlantic atmospheric information in addition to Atlantic and Pacific SST in January, the performance in the 1990s is poor.

In appraising the performance into the 1990s, the long-term evolution of relationship with indicative indices is of interest. The correlation plots in Fig. 3 demonstrate that these have remained overall stable and strong. More relevant for the causes of the poor forecast in 1998 (and to a lesser extent 1992) are the time series plots of predictors in Fig. 2. Thus it is seen from Fig. 2e that the training period (A) 1921–57 contained no Pacific warm anomalies even remotely comparable to the extreme 1998 El Niño year, and even the less warm 1992 finds only two corollaries in the training period. This specific deficit of information in the training period constrains the validity of the empirical method. Plausibly, situations not captured in the training period are not well handled in the real-time forecasting. It is further noteworthy in Tables 1 and 2 that R32 performed better than R25 and NN, and LDA32 performed better than LDA25. It can be conjectured that the limitation to only two predictors in R32 and LDA32 allows the role of PAC to emerge more strongly.

Our earlier diagnostic research (Curtis and Hastenrath 1995; Hastenrath 2000) has shown how atmospheric circulation anomalies over the Atlantic in January associated with Pacific warm events lead in the subsequent months to the buildup of an anomalous interhemispheric SST gradient in the Atlantic and thus to the surface wind and ITCZ configuration conducive to Nordeste drought. The mechanisms through which Pacific warm events affect the Atlantic are thus in large part understood (Curtis and Hastenrath 1995; Hastenrath 2000), but the lack of extreme El Niño in the training period used for the method development makes application in such situations less suitable.

5. The 2000 rainy season

While this paper was in the editorial process, it became time for the forecast of the 2000 rainy season. SST information was obtained by early February 2000, enabling the forecast from model R32 plotted in Fig. 4. The wind data for the tropical Atlantic were also received as usual. By contrast, the collection and transmission of rain gauge measurements should be a matter of concern. Ever since the era of difficult communication predating fax and e-mail, the rain gauge reports have been reliably obtained. However, for July 1999 onward, reports have arrived only for a few stations and months. This precluded application of models R25 and NN. Even more critically, without the proper rain gauge reports, there can be no verification of forecast performance. The present admirably advanced communication technology is no remedy.

6. Concluding remarks

The climate dynamics of the tropical Atlantic and northeast Brazil have been a subject of our research at the University of Wisconsin for one-quarter century. We successively elucidated the annual cycle of surface circulation and climate and the circulation mechanisms of Nordeste droughts, and on this diagnostic basis we developed viable empirical methods for climate prediction. Then, from the mid-1980s onward, timely compilations of input observations became a major communal challenge. Since the early 1990s we have been able to issue seasonal forecasts in real time. Predictions agreed well with observations, except for the extreme 1998 El Niño year. This failure may be related to the lack of pertinent information in the long training period, which contained no comparably extreme Pacific warm event. As other groups engaged in tropical climate prediction reach a decade-long record of real-time forecasts, it would be desirable to see the publication of sustained forecast performance.

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