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Drought prediction and characteristic analysis in semiarid Ceará, northeast Brazil

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Abstract For drought prediction and drought analysis in northeast Brazil, different methods and models have been developed and applied. For drought prediction both statistical and neural network models, using the patterns of atmospheric and oceanic conditions of the tropical Atlantic and Pacific, have been utilized. For the characteristic analysis several indices have been adjusted to the State of Ceará to analyse the characteristic duration, severity, and magnitude of historical droughts, i.e. to identify rainfall anomalies for diagnostic purposes. These indices are used as criteria for identification of drought conditions, e.g. by the relation between a regional humidity index and the actual evaluation of dry periods during the rainy season.

INTRODUCTION

Northeast Brazil is characterized by large interannual variations of rainfall. Annual precipitation ranges from 400 to 1200 mm, depending on the place and time. Throughout its long history, northeast Brazil has been plagued repeatedly by drought catastrophes. Famines are recorded since the early colonial era, and emigration to the other parts of Brazil began in the seventeenth century (Hastenrath, 1987). The so-called "Polígono das Secas" (Polygon of Droughts) covers an area of 940 000 km^2. The regional population in 1990 was 40 million (28% of Brazil's total population). Since agriculture is its major economic base, droughts have socio-economic repercussions for the whole region. Drought prediction, therefore, has remained a central concern and it plays an important role for a sustainable use of the limited water resources.

The vulnerability of agricultural production due to water deficit and the development of regional water distribution systems implies that drought analysis, the investigation of its dynamic meteorological causes, the development of a drought prediction model, and the analysis of drought characteristics by drought indices are extremely important.

The drought prediction and drought analysis in northeast Brazil is additionally important due to the following aspects: (a) there exist several irrigation projects along the great intermittent rivers; (b) the large-scale water supply systems from metropolitan areas depend on total runoff and actual reservoir storage; (c) the subsistence agricultural production is very vulnerable to precipitation deficit; and (d) the possibility of groundwater use is restricted (Freitas, 1997).

A comprehensive approach for studying regional drought problems, however, includes (Rossi *et al.*, 1992): (a) identification of meteorological causes and drought prediction; (b) evaluation of drought characteristics; (c) analysis of economic, environmental and social effects of drought; and (d) definition of appropriate measures for controlling drought effects. In this paper, emphasis is put on the first two aspects.

DROUGHT PREDICTION

It has been observed that there is no definitive periodicity in the incidence of droughts in northeast Brazil. Drought prediction plays, however, an important role by a drought assessment and response strategy plan. The identification of the meteorological causes and the development of a method to predict the droughts have been done by analysis of the global circulation system, especially the ENSO (El Niño-Southern Oscillation), and the patterns of atmospheric and oceanic conditions of the tropical Atlantic.

Two classes of methods have been used: statistical and neural network modelling. First regression analysis and conditional probability tables based on rainfall data from the Federal State of Ceará, as well as sea surface temperature, air pressure, wind stress etc. from both Pacific and Atlantic Ocean have been established as a basis for the modelling of the prediction. Dry, normal and wet years are classified by probabilities of exceedence.

Data set

The data used in this study consist of monthly rainfall data of the Federal State of Ceará, and an extensive data set describing the oceanic and atmospheric conditions of the Pacific and Atlantic Ocean. For the Pacific, Wright (1989) employed a method to take a number of potentially useful indices and to compile long-period series based on them, using comparisons between indices as an aid to identifying and removing inhomogeneities and filling data gaps. The following indices have been used:

(a) The SST (Sea Surface Temperature) index is a homogenized index defined by Wright as the mean SST anomaly over the region 6-2°N, 170-90°W; 2°N-6°S, 180-90°W; 6-10°S, 150-110°W. This index indicates the incidence of the El Niño (EN) phenomenon.

(b) The DT index describes the air pressure gradient between Darwin and Tahiti, calculated monthly, and the mean over 3-month seasons. These data can be used as a Southern Oscillation (SO) index.

SST and DT indices were calculated and published since 1872 and 1851, respectively. However, due to the restricted availability of the rainfall data in northeast Brazil, data are used only from the year 1911 in this study.

For the equatorial Atlantic, monthly wind stress and sea surface temperature anomaly data were used. The data set covers a period from 1964 to 1989. These data relate to an area extending from 20°S to 30°N and from 60°W to the African coast. The data set for the period 1964-1979 were presented by Picaut *et al.* (1985), for the period 1980-1984 by Servain *et al.* (1987) and for the period 1985-1989 by Servain & Lukas (1990). This last period coincides with the first five years of the international Tropical-Ocean-Global-Atmosphere (TOGA) program.

Most of the raw data are measurements made on ships of opportunity. The rest is from fixed or drifting buoys. The data are transmitted over the Global Telecommunication System (GTS) and recorded in real time by the National Meteorological Center (NMC, Washington, DC). The average number of observations is over 6000 per month. The average monthly wind stress and sea surface temperature anomaly were computed for each 10° latitude by 10° longitude box (Servain & Lukas, 1990).

For the correlation analysis and development of the conditional probability tables the data of 30 rainfall stations have been used. These stations have been selected as the stations with the longest observation periods, starting in 1911, and representing a good regional distribution.

Statistical analysis

The objective of the statistical analysis was to analyse, on the basis of 30 rainfall stations of the Federal State of Ceará, the dependency between the incidence of the El Niño and the incidence of droughts in Ceará. The results of the correlation analysis reveal a modest relationship between rainfall and the SST and DT indices. These relationships alone are not strong enough for accurate drought prediction. However, they may be useful if they are expressed as probabilities of exceedence threshold levels. Therefore probability conditional tables have been produced for the selected precipitation stations. The 33% and 67% exceedence probability of the time series have been calculated to characterize the years as dry, normal or wet. The data of the ENSO-indices have been classified by warm (El Niño), normal and cold years.

As an example, Table 1 shows the conditional probability table of the rainfall of the months December until February (DJF) *vs* the SST-Index of the Pacific a half year before from June until August (JJA). It can be seen that if SST indicates a warm year (ENSO), in Ceará a dry period will appear with a probability of 66%. The results of the correlation analysis between the rainfall in northeast Brazil and global circulation indices like sea surface temperature (SST) anomaly patterns in the Pacific and Atlantic, wind stress, and air pressure gradient in the Pacific (Darwin-Tahiti) permits an estimation of future rainfall.

Table 1 Conditional probability table.

DJF	JJA (-1)		
	Cold SST	Normal SST	Warm SST
Wet period	31%	39%	12%
Normal period	35%	33%	22%
Dry period	34%	28%	66%

Neural network modelling

Recently, significant progress in the fields of pattern recognition and system theory has been made by use of artificial neural network modelling. Artificial neural networks have a flexible mathematical structure, and can identify nonlinear relationships and describe complex processes (Kosko, 1992).

In this study two different approaches for the drought prediction of northeast Brazil have been tested:

(a) modelling the time series of annual rainfall by the use of neural network for reference stations; and
(b) neural network modelling of the pattern recognition of the SST data of both Pacific and Atlantic.

For the 30 rainfall stations of Ceará a regional rainfall departure index according to Lamb *et al.* (1986) has been calculated for the rainy season and correlated with the SST of the Atlantic. Only the SST data of the regions with correlation higher than 0.3 (Fig. 1) have been used as input to the neural network model.

A prediction model for the rainy season is developed by neural network. Different topologies of networks and different combinations of the input data (annual and seasonal data from the tropical Atlantic and the Pacific Ocean) have been used. The proposed models offer a practical perspective of 6 months (rough prediction by use of Pacific data) and 3 months (more exact prediction by additional use of Atlantic data) for northeast Brazil.

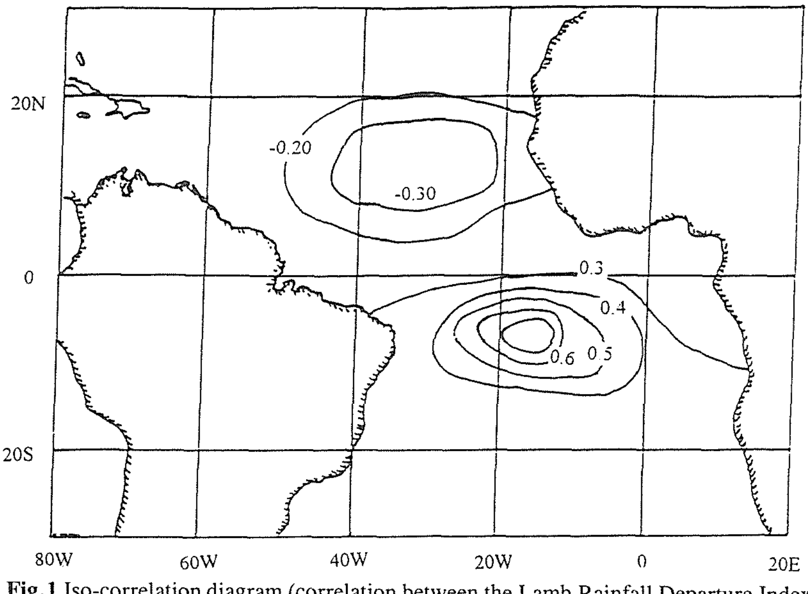

Fig. 1 Iso-correlation diagram (correlation between the Lamb Rainfall Departure Index for the Federal State of Ceará and the SST index of the equatorial Atlantic in February).

(a) Modelling the time series of the annual rainfall For selected reference stations neural networks have been used for the prediction of annual rainfall. The data from 1912 to 1978 were applied for training and learning of the model, and the data of the period from 1979 until 1985 were used for verification. The prediction of the rainfall was calculated stepwise for the next year.

For each station the quantiles 33% and 67% of the annual rainfall were calculated to classify dry, normal and wet years. A three-layer back propagation network was selected as the neural network type. As an example, the results of the station Umarí are given in Table 2.

Table 2 Prediction of rainfall (mm) at Station Umarí.

Year	Historical	Predicted	Relative error (%)
1979	670.9 (D)	567.3 (D)	−18.26
1980	815.5 (N)	1248.3 (W)	34.67
1981	683.4 (N)	757.6 (N)	9.79
1982	589.7 (D)	810.9 (N)	27.28
1983	483.1 (D)	647.0 (D)	25.33
1984	784.8 (N)	570.9 (D)	−37.47
1985	1702.7 (W)	1508.7 (W)	12.86

D = dry; N = normal; W = wet year.

(b) Modelling using SST and DT indices By this approach the artificial neural network was first applied to the SST and DT indices of the Pacific. To show the applicability, the results are presented for the station Cedro (Table 3). The historical rainfall data cover 73 years (1912-1984). The period from 1912 to 1973 was used for training and the period 1974-1984 for verification.

Table 3 Prediction of rainfall (mm) at Station Cedro.

Year	Historical	Predicted	Relative error (%)
1974	1679 (W)	1667 (W)	0.7
1975	1087 (W)	904 (W)	−17
1976	678 (N)	796 (N)	17
1977	1129 (W)	690 (N)	−39
1978	765 (N)	690 (N)	−9.8
1979	531 (N)	705 (N)	33
1980	814 (W)	671 (N)	−17
1981	542 (N)	600 (N)	11
1982	894 (W)	907 (W)	1.5
1983	332 (D)	126 (D)	−62
1984	1044 (W)	1220 (W)	17

D = dry; N = normal; W = wet year.

Secondly, data from the Atlantic were used additionally. They gave the best results for the actual prediction, as shown in Table 4 for the station Santana do Cariri, classified as wet (W), normal (N) and dry (D), and compared with the observed data. The years 1964-1974 were used for the training of a three-layer back propagation network, and the years 1975-1980 for the verification.

The application to all 30 stations gives a regional distribution of rainfall prediction classified by wet, normal and dry. As a consequence of these results, an early warning could be given to farmers 6 months before the rainy season starts.

Table 4 Prediction of rainfall (mm) at Station Santana do Cariri.

Year	Historical	Predicted	Relative error (%)
1975	1168 (W)	1104 (W)	−5.48
1976	874 (N)	968 (N)	10.75
1977	862 (N)	756 (N)	−12.29
1978	1020 (W)	1141 (W)	11.86
1979	883 (N)	473 (D)	−46.43
1980	822 (D)	821 (D)	−0.12

D = dry; N = normal; W = wet year.

DROUGHT CHARACTERISTIC ANALYSIS

Drought indices

For the purpose of assessing the degree of droughts and their management, several rainfall drought indices based on 30 stations of the State Ceará were calculated for the period January-June (rainy season): the Rainfall Anomaly Index (RAI), the Bhalme & Mooley Drought Index (BMDI), the Herbst Severity Index (HSI) and the Lamb Rainfall Departure Index (LRDI). It was tried to use indices that allow spatial and temporal comparison of droughts. The historical droughts were analysed by the characteristics duration, severity and magnitude. These indices are used as criteria for identification of drought conditions, e.g. by the relation between a regional humidity index and the actual evaluation of dry periods during the rainy season.

The Rainfall Anomaly Index (RAI) was derived by Rooy (1965) and it can be expressed as follows:

$$\text{RAI} = 3\left[(p-\bar{p})/(\bar{m}-\bar{p})\right] \tag{1}$$

for positive anomalies and:

$$\text{RAI} = -3\left[(p-\bar{p})/(\bar{x}-\bar{p})\right] \tag{2}$$

for negative anomalies, where p is the actual rainfall, $\bar{p}$ is the long term average rainfall, $\bar{m}$ is the mean of the ten highest values of p in the time series, and $\bar{x}$ is the mean of the

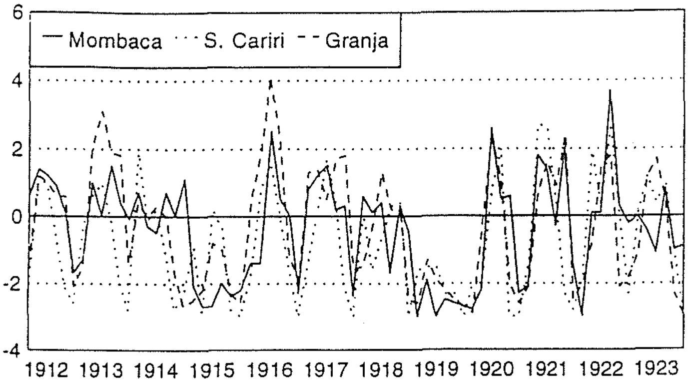

Fig. 2 Rainfall Anomaly Index (RAI) for three stations in Federal State of Ceará.

ten lowest values of p. The application of these indices for three stations in Ceará is illustrated by Fig. 2.

Regional drought analysis

As an example of the regional drought analysis, the application of the drought index devised by Bhalme & Mooley (1980) is demonstrated. For the calculation of this index the monthly rainfall totals for the 30 reference stations in Ceará were used. The periods of observation range from 47 to 77 years. For the index computation only the rainfall totals for the months January to June were applied. These are the months during which most of the stations receive over 80% of the annual totals. Figure 3 shows the results

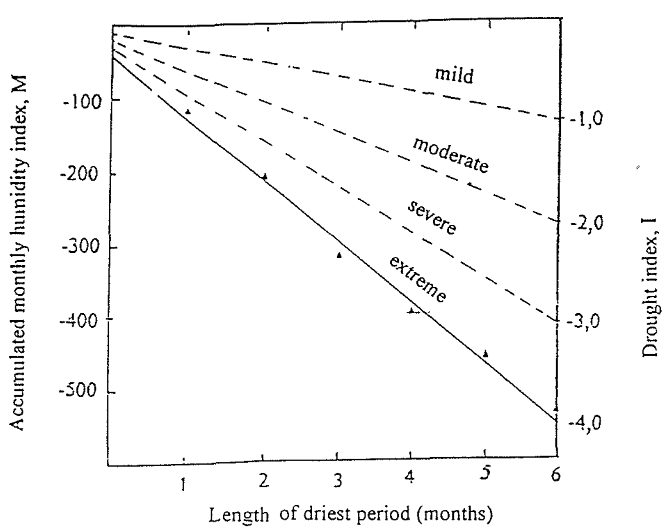

Fig. 3 Regional drought analysis for the Federal State of Ceará by using the Bhalme & Mooley Drought Index.

and classification of droughts for the whole State of Ceará. The position of the actual humidity index indicates the evaluation of the drought intensity, e.g. a moderate or severe period during the rainy season.

RESULTS

The results of this study show that the droughts of northeast Brazil can be partially predicted by conditional probabilities of the rainfall related to the SST index of the Pacific. The use of the Atlantic data improved the rainfall prediction by the application of the neural network modelling.

These results can be used for a drought monitoring system, for deciding the appropriate measures to alleviate the effects of an actual drought, like appropriate tools for the reservoir management and for impact analysis of the droughts on agricultural production in northeast Brazil.

REFERENCES

Bhalme, H. N. & Mooley, D. A. (1980) Large-scale drought/floods and monsoon circulation. *Mon. Weath. Rev.* **108**, 1197.

Freitas, M. A. S. (1997) Regional drought analysis by statistic methods and neuro-fuzzy-systems with application to northeast Brazil (in German). Mitteilungen Inst. f. Wasserwirtschaft, Univ. Hannover, Germany (in press).

Hastenrath, S. (1987) The droughts of northeast Brazil and their prediction. In: *Planning for Drought, Toward a Reduction of Societal Vulnerability* (ed. by D. A. Wilhite & W. E. Easterling). Westview Press, Boulder, Colorado, USA.

Kosko, B. (1992) *Neural Networks and Fuzzy Systems, A Dynamical Systems Approach to Machine Intelligence*. Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA.

Lamb, P. J., Peppler R. A. & Hastenrath, S. (1986) Interannual variability in the Atlantic. *Nature* **322**, 238-240.

Picaut, J., Servain, J., Lecomte, P., Lukas M. & Rougier, G. (1985) *Climatic Atlas of the Tropical Atlantic Wind Stress and Sea Surface Temperature 1964-1979.* Université de Bretagne Occidentale - University of Hawaii.

Rooy, M. P. van (1965) A rainfall anomaly index independent of time and space. *Notos* **14**, 43.

Rossi, G., Benedini, M., Tsakiris, G. & Giakoumakis, S. (1992) On regional drought estimation and analysis. *Wat. Resour. Manage.* **6**, 249-277.

Servain, J., Seva, M., Lukas, S. & Rougier, G. (1987) Climatic atlas of the tropical wind stress and sea surface temperature: 1980-1984. *Ocean-Air Interactions* **1**, 109-182.

Servain, J. & Lukas, S. (1990) *Climatic Atlas of the Tropical Atlantic Wind Stress and Sea Surface Temperature 1985-1989: Oceans Tropicaux Atmosphere Globale.* ORSTOM.

Wright, P. B. (1989) Homogenized long-period Southern Oscillations indices. *Int. J. Climatol.* **9**, 33-54.