Meteorological Early Warning Systems (EWS) for Drought Preparedness and Drought Management in Nigeria

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Abstract

The Nigerian Department of Meteorological Services (NDMS) is currently implementing a meteorological early warning system (EWS) as part of its effort to combat the effects of drought in Nigeria. Knowledge of the onset of drought and other hazardous meteorological conditions is important for drought preparedness and management. Presently, the basic users of EWS products are government, media, and the agricultural industry. The EWS forecasts are prepared using state-of-the-art equipment and models that were developed by NDMS staff or other researchers and scientists. These models include: (1) the Standardized Precipitation Index (SPI), (2) NDMS Prediction Schemes, and (3) Sea Surface Temperature (SST) Prediction Schemes. We used the SPI model to study incidences of drought in Nigeria, and conducted two studies to evaluate the skill of the NDMS and SST Prediction Scheme models. The results indicate that the north has the highest incidence of drought years, in comparison to the south. The skill of both the NDMS and SST Prediction Schemes is low, but these models were found to be appropriate for planning purposes. Some of the limitations we identified as being responsible for the lower skill level of these models include data quality, station density, delivery systems, and identification of the predictable components of climate. As a result, we are proposing, as part of our future needs, the development of a robust modeling technique to identify and predict band-limited cyclic components of climate that will be based on a nonlinear model of the earth/ocean/atmosphere system.

Introduction

"The Lord does whatever it pleases him in the heavens and on earth, He sends lightning with flooding, and brings whirlwinds from His storehouses." (Psalm 135: verses 6, 7).

Drought is a creeping phenomenon, characterized by extended periods with rainfall far below average, prolonged periods of dryness, high temperatures and evapotranspiration, very low humidity, and reduced streamflow and reservoir water levels (and in some cases completely dried-up water sources). It usually lasts 2-4 years, and if it is not well managed, it could precipitate another drought condition. It is for this reason that the need for drought planning and management in Nigeria cannot be overemphasized.

Extending northeast from the gulf of Guinea Coast in West Africa, Nigeria is located within latitudes 2^o–14^o N and longitudes 2^o 41°-14^o 42° E. It shares borders with Benin Republic to the west, Niger Republic to the north, Chad to the northeast, and Cameroon to the east. The country has an area of 923,766 km^2, with an average population density of 124/km^2; 180,000 km^2 are under cultivation and 9,000 km^2 are under irrigation (FGN 1997).

The total land area of Nigeria is delineated into 36 states (see Figure 1) that make up eight broad agro-ecological or land resource zones. The climate characteristics are summarized in Table 1. Climatologically and historically, it has been shown that major drought episodes associated with those of the Sudan-Sahelian drought occurred in Nigeria in locations north of latitude 11^o N in 1882-86, 1913-16, 1942-45, and 1971-73 (FGN 1998). These drought episodes caused massive famines. Indications from various studies show that with the present global warming, some hydrometeorological conditions could be reached that could trigger a major drought situation within this decade.

Each time drought occurs in Nigeria, the area that usually receives very severe impacts includes all areas north of 11^o N parallel (Kebbi, Sokoto, Katsina, Kano, Jigawa, Borno, Gombe, Adamawa and Niger states). The effects of the 1971-73 severe drought and the 1983-84 localized droughts on agricultural production prompted the federal government through its various relevant agencies to put in place institutional arrangements and schemes to minimize drought impacts.

With the present awareness of the effects of ongoing climate change and global warning, the importance of a meteorological early warning system becomes more apparent. It was from this background that the Nigerian Department of Meteorological Services (NDMS) put in place its EWS a few years ago. The development of the EWS therefore resulted in the setting up of various methods and services for the provision of weather forecasts, especially to warn the public of hazardous weather and hence minimize loss of life and property damage.

So far, the EWS project has benefited from an appreciable allocation of government funds, more so than any other meteorological project. About 50% of the total annual and 3-year rolling plan allocations to the department come under the EWS project. This funding has enabled the department to achieve 20-25% of the optimal level of implementation of other related projects. Also important is the fact that for drought projects, annual rainfall is one of the primary determinants for allocation of annual budgets and other funds, such as the “Ecological Fund,” to states, local governments, and national organizations and research institutions such as Ministries of Agriculture, Water Resources and Environment.

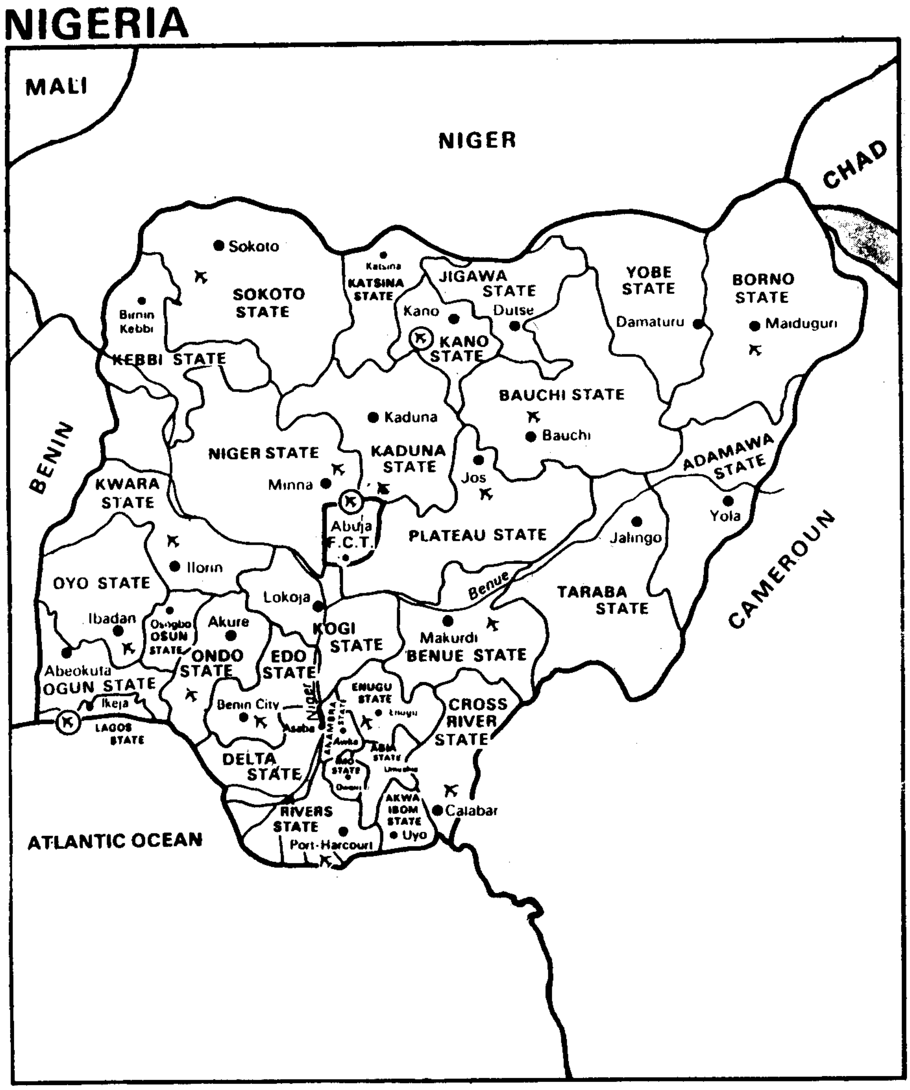

Figure 1. Map showing locations of the 36 states that make up Nigeria, and the adjoining countries.

Table 1. Agro-ecological zones of Nigeria (after FGN 1997).

Zone	Area %	Wet Seasons (s)			Mean Monthly Temperature(s) ^{o}C		
		Rainfall (mm p.a)	Kind	Length (Days)	Max	Normal	Minimum
Ultra Humid	2	2000+	Extended	300-360	32	28 –25	23
Very Humid	14	1200-2000	Bimodal	250-300	33	28-24	21
Humid	21	1100-1400	Bimodal	200-250	37	30-26	18
Sub Humid	26	1000-1300	Unimodal	150-200	37	30-23	14
Plateau	2	1400-1500	Unimodal	200	31	24-20	14
Mountain	4	1400-2000	Bimodal	200-300	36	29-14	5
Dry Sub Humid	27	600-1000	Unimodal	90-150	39	31-21	12
Semi Arid	4	400-600	Unimodal	90	40	32-33	13

In the process of implementing EWS, the acquisition of state-of-the-art equipment for strengthening the national meteorological network of observing stations became necessary. Presently NDMS has 50 synoptic (i.e., full-time) stations, 500 rainfall and agrometeorological stations, 20 automated weather stations, 3 weather surveillance radars, 1 total ozone station, 1 global atmospheric watch (GAW) station, and 10 global surface climate stations. In addition, we have 6 upper air and 6 marine stations that are evenly distributed over all climatic zones of the country.

The synoptic stations are equipped with basic conventional operational instruments and equipment. Automated weather stations are established alongside the conventional ones, with a view to upgrading our level of data acquisition. In addition, high-tech instruments employing both computer- and satellite-based technology such as Meteorological Data Distribution (MDD), Primary Data User System (PDUS), and Analysis, Forecasting, Data Processing and Operational System (AFDOS) have been acquired and installed. However, our major constraints or limitations include data quality and station density. Most of our synoptic stations are located in urban centers and at airports. These locations are known to generate local heat that is capable of influencing measured data. The lack of sufficient stations to adequately cover the length and breadth of the country has led to the use of extrapolation techniques in order to prepare certain EWS products.

However, despite our constraints, we have begun intensive monitoring and forecasting of weather and climate systems in Nigeria with the newly acquired equipment. So far, we have been able to contribute to national socioeconomic development and sustainable management of natural resources and the environment in Nigeria. The following are some of the information products obtained from the use of EWS models:

1. Short-, medium-, and long-range weather forecasts.
2. Prediction of onset and cessation of the rainy season.
3. Prediction of wet and dry spells.
4. Seasonal climate forecast.
5. Fog forecasting.

6. Seasonal agrometeorological forecasts.
7. Dust haze forecasting.
8. Outlook for onset of drought (SPI).
9. Soil moisture monitoring (FAO method).
10. Storm surges and coastal erosion forecasting, etc.

Currently, telecommunication between the stations is achieved by use of single side band (SSB) radio, high-frequency radio, and satellite-linked communication instruments. International linkage is achieved through the Global Telecommunications System (GTS), a component of which is presently partially installed at the Meteorological Forecast Office, Muritala Muhammed Airport, Ikeja, Lagos. Very Small Aperture Terminal (VSAT) technology has been acquired to enable the Department to link with products of World Area Forecast System (WAFS) centers of ICAO and WMO. In addition, the Digi-cora upper air equipment is being upgraded to link with the WMO's Global Positioning System (GPS) for the acquisition of upper air data, especially the upper air winds. Other telecommunication equipment recently acquired to further facilitate data collection and dissemination includes:

- MESSIR-VISION: Meteorological weather forecasts workstation for improving the accuracy of weather forecasts with sufficiently long lead-times.
- MESSIR-COMM: An automatic message system used as an interface engine between the Meteorological Service and the World Meteorological Organization GTS.
- MESSIR-SADIS: Satellite-based workstation for providing real-time aeronautical weather forecasting information, particularly to pilots.

The most important primary user of EWS products is the Nigerian government, but there are other users, including sectors such as the media, farmers, schools, and the public (see Table 2). In terms of measuring user reactions to and comments on EWS products, we found that the general public is becoming more aware of our services, judging by the comments, complaints, and criticism either received directly or reported in the media. We now receive more requests for press interviews on current weather and its effects on human activities and agricultural production. Moreover, there is an increased awareness of weather forecasts by the public, judging by complaints received by media houses when the weather forecasts are not aired.

The objective of this chapter is to present an overview of the EWS project that includes an evaluation of the EWS models and their effectiveness for drought preparedness and management in Nigeria. We will present information on our current progress as well as future goals aimed at sustaining or improving our current level of combating drought.

Table 2. Primary users of EWS products and how the products are used.

	User	How Products Are Used
1	Government	Determine policies on resources (human and revenue) allocation
2	Farmers, unions, cooperative societies, forestry, wildlife and environmental practitioners	Adapted and used in a package with other information by extension workers for effective application (e.g., translating into local languages when passing agronomic and other information packages to farmers)
3	Schools, colleges, universities, research institutes	Most primary data and indices used for research and training
4	Public engineering construction	Adapted and used in a package with other information to design structures
5	Media (print, radio, electronics, etc.), NGOs, CBOs, etc.	Adapted and used in a package with other information for public awareness and education programs

Monitoring Drought Using the SPI over Nigeria

Materials and Methods

The SPI is used to study the relationships between drought duration, frequency, and time scale, as described by Agnew (1999). For the most part, the daily, monthly, and annual rainfall values for the period 1960-90 were used for this study, but the SPI was also determined for other years beyond 1990 when data was available. A general homogenization procedure based on running averages was used to extrapolate data that was lost for most southern stations during the civil disturbances period of 1966-70. The whole data sets were obtained from NDMS, and they belonged to the existing 40 synoptic stations.

The SPI for each station was determined using the equation below:

$$\text{SPI} = (X_{ik} - X_i) / \sigma_i$$

where σ_i = standardized deviation for the ith station, X_{ik} = rainfall for the ith station and kth observation, and X_i = mean rainfall for the ith station. All negative SPI values are taken to indicate the occurrence of drought, while all positive values show no drought.

To determine drought intensity, SPI values of equal to or less than -0.50 were used. The frequency of occurrence of drought years within each decade was determined on a station-by-station basis by simple statistical means, and the result was then summed over the 40-year period.

Results and Discussion

Results of the SPI analyses indicate that all the climatic zones within Nigeria had experienced drought at one time or another during the study period (Table 3). However, the extreme northern zone of Nigeria has the highest number of occurrences of drought years during the study period.

In this zone, the number of drought years ranged between 12 and 18. This result did not come as a surprise because of the awareness that the north is more prone to drier conditions than the south.

The frequency of drought occurrence per decade-year varies greatly between decades and among stations, but ranged between 1 and 8. The third decade-year (1980-89) has the most severe and highest number of drought occurrences for the period studied. On climatic zone analysis, the dry, semiarid north zone, which lies within latitude 10^o N and 12^o N, had the highest frequency of drought incidences, while the middle-belt zone had the lowest frequency. The southwest and southeast zones have almost the same number of drought years, ranging between 5 and 14 years.

It is noteworthy that the most severe drought years (1973, 1983, and 1987) coincided with the global droughts widely believed to be the result of El Niño’s effect.

Prediction of the Dates of Onset and Cessation of Rainy Season and Monthly and Annual Amounts of Rainfall Using Surface Data

Materials and Methods

The NDMS prediction schemes developed for this work use surface data from the 40 synoptic stations in Nigeria. In these schemes, the predictors are the equivalent and saturated equivalent potential temperatures:

$$\theta_e = \Theta \exp (Lq/C_pT_v)$$
$$\theta_{es} = \Theta \exp (Lq_s/C_pT)$$

where Θ = potential temperature, Θ_e = equivalent potential temperature, Θ_{es} = saturated equivalent potential temperature, L = latent heat of condensation, q = specific humidity, C_p = specific heat for dry air at constant pressure, and T_v = virtual temperature of the air.

The predictants are the dates of onset and cessation of the rainy season and monthly and annual amounts of rainfall. The schemes make use of only surface data (pressure, temperature, and relative humidity) on a daily basis for about 30 years for their development and about 10 years for testing and validation.

The calculation of equivalent and saturated equivalent potential temperatures involved a prior calculation of saturation vapor pressure from the Clausius-Clapeyron equation. The saturation vapour pressure is given as:

$$E_s = E_{so} \exp \{M_vL(T-T_o)/(R^*T_oT)\}$$

where e_{so} = 6.11 hpa, T_o = 273.06, R* = universal gas constant, p = pressure, k = R/CP, and R is the specific gas constant for dry air = 287 $Jkg^{-1}k^{-1}$.

Table 3. Number of occurrences of drought years.

S/No.	Stations	1960-69	1970-79	1980-89	1990-99	Total
1	Maiduguri	1	3	7	5	16
2	Sokoto	1	5	8	3	17
3	Katsina	2	3	5	8	18
4	Nguru	-	2	7	3	12
5	Gusau	-	3	3	3	9
6	Kano	1	2	5	1	9
7	Potiskum	1	2	4	1	8
8	Yelwa	-	1	3	2	6
9	Kaduna	2	3	3	5	13
10	Bauchi	-	4	6	2	12
11	Yola	2	2	1	3	8
12	Minna	-	1	4	-	5
13	Bida	1	3	2	4	10
14	Lokoja	-	2	3	1	6
15	Ibadan	3	4	3	2	12
16	Ikeja	1	5	4	2	12
17	Benin	1	2	5	1	9
18	Enugu	2	3	5	2	12
19	Calabar	1	2	1	1	5
20	Lagos	-	3	5	1	9
21	Ondo	4	5	3	2	14

The dates of onset of the rainy season are estimated from the date when the anomalies of equivalent potential temperature are positive for at least 15 days. This is considered as the beginning of abundant moisture supply. The mean number of days between this date and the mean onset date for each station is added to this date of positive equivalent potential temperature anomaly to obtain the onset date for the station for the year.

The dates of cessation are estimated from the date of maximum difference between the anomalies of the equivalent and the saturated equivalent potential temperatures. This maximum difference between equivalent and saturated equivalent potential temperature is considered the “maximum moisture deficit” of an unsaturated atmosphere. The mean number of days between this date and the mean cessation date is added to this date of maximum difference between equivalent, and saturated equivalent potential temperatures to obtain the cessation date for the station for the year (Omotosho 1999).

The annual rainfall is predicted from two approaches. The first is from the graph of annual rainfall against the sum of the anomalies of the equivalent potential temperature plotted with about 30 years of data. The sum of the anomalies of equivalent potential temperature is considered as accumulated excess moisture. The second is from the graph of annual rainfall against the sum of the differences between the equivalent and the saturated potential temperatures, plotted with about 30 years of data. The annual rainfall prediction is made after the summation of each of these two predictors used independently within 3 or 4 months preceding the date of onset of rains for the station for the year.

The same approach is applied for the prediction of monthly rainfall. However, a slight difference is that the summation of the predictors is made for the two months preceding the month for which the rainfall prediction is to be made.

Results and Discussion

The model gave a good prediction of the onset Julian day of the rainy season for stations north of 8^o N but gave late dates for stations south of 8^o N. Generally, the prediction was very good in only 66% of the stations analyzed.

The residual between predicted and observed cessation Julian day appears minimal and is not statistically significant. The model gave a good prediction of the length of the rainy season in both northern and southern stations but was inconsistent in its level of accuracy across the studied stations.

Predictions of the annual rainfall amounts were lower than those observed in more than 90% of the stations under study (Figure 2). The departures from observed are, however, random and cannot be thought of as a constant error term that could be inherent in the model. The prediction models' performance could be an indication of an absence of a certain factor or factors that directly influence rainfall.

The monthly rainfall prediction was limited to only 11 northern stations because of their proneness to drought conditions. With the exception of a few stations, the general sense of the prediction closely approximates the observed values.

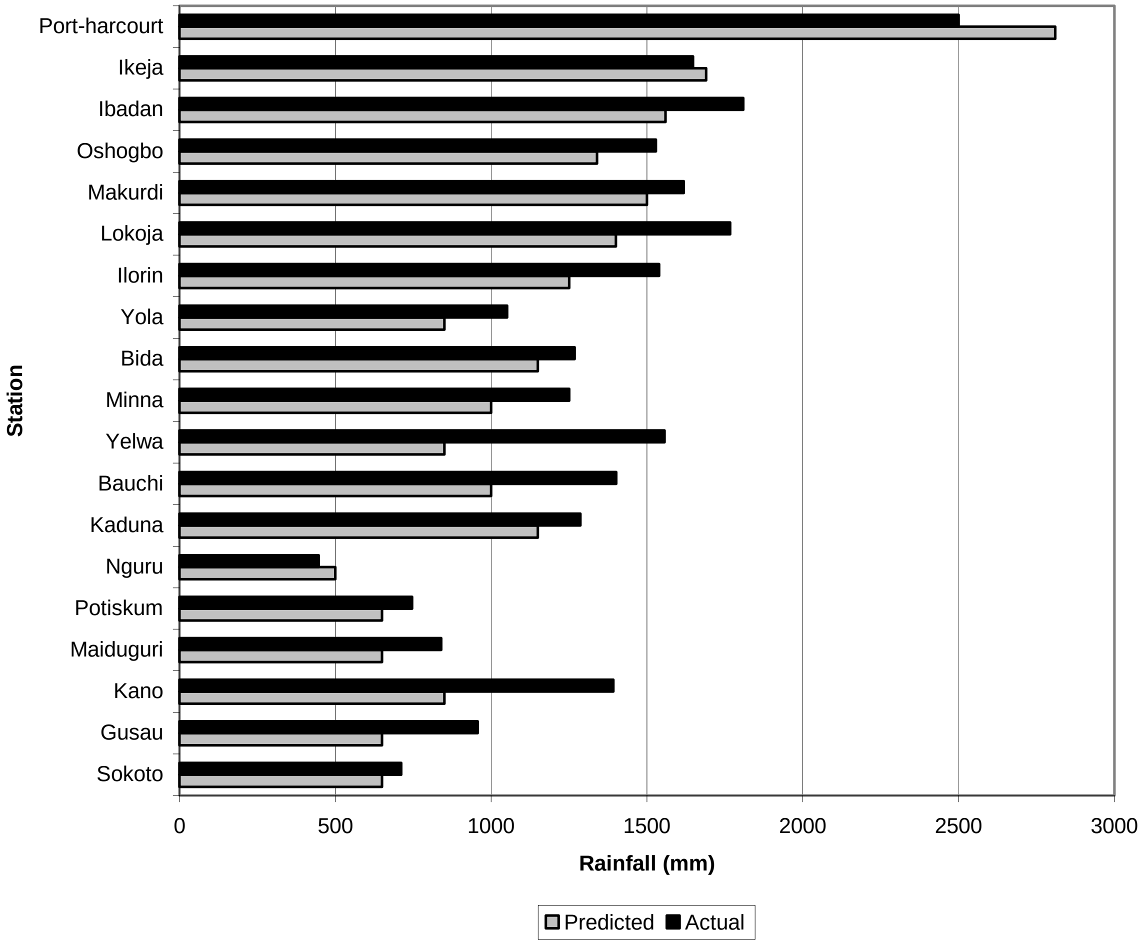

Figure 2. Observed versus predicted 1999 annual rainfall in some selected Nigerian stations.

Prediction and Evaluation of Seasonal Rainfall Based on Sea Surface Temperature for the Period 1998-2000 in Nigeria

Materials and Methods

Standardized anomaly series of rainfall were derived from monthly data obtained from NDMS. Thirty stations evenly distributed across Nigeria with complete historical data for the period 1961-99 were considered. SST data for the corresponding period were obtained from the U.K. Met. Office (through the African Center of Meteorological Applications for Development, ACMAD), and the Equatorial Atlantic (EQATL), East and Central Pacific (N1N03), and North Atlantic (NATL) regimes were considered.

To determine correlations between SST anomalies (SSTA), the regions, and the stations, the stations were divided into three zones, and standardized rainfall anomalies were calculated for each zone. Two-month running averages were calculated. The regression model:

Y= Constant + A(SSTA)

was employed after obtaining correlations between SSTA in the regions and each of the 30 stations. Thereafter, the zonal data were substituted in the model and matched with SSTA in the various sea domains. Empirical orthogonal functions (EOF) analysis was also applied. The above methods were used for 1998 and 2000 data sets, while another method, the ENSO composite/rainfall percentile method, was adopted in 1999. The second method gave an indication of whether rainfall will be below normal ($P<45$), normal ($45<P<55$), or above normal ($P>55$).

Results and Discussion

Generally, results for individual stations show good positive correlations between rainfall for stations in the southwest, up to latitude 10^o N, and equatorial Atlantic SSTA. The best forecast skill was obtained with April-May and May-June SSTA, giving a lead time of 1-2 months. Stations to the southeast up to latitude 10^o N had weak correlations with all predictions. Those to the north of latitude 10^o N showed some moderate correlations with July-August-September SSTA in Nino 3 and March-April EOF (see Table 4).

Although the efforts made so far to predict seasonal rainfall for the country using the SST have had some success, the limitation of the scheme is its inability to predict the onset, cessation, and amount of rainfall for the benefit of the farmers. However, the scheme in its present form is ideal for national planning. Since the ENSO composite/percentile method can be used as early as October of the preceding year, one can say that the SST prediction scheme is still very useful for the country’s seasonal outlook.

Recent Progress: Remote Sensing/Geographic Information System (GIS)

One objective of the Nigerian Department of Meteorological Services’ Information Technology Unit is the operational application of remote sensing to create information products. In view of the perceived advantages of remote sensing applications, the NDMS has acquired and is installing the following information technology equipment:

- personal computers, one of which is the server, an HP Vectra 6/233 MT series 6 with 128MB, a 6GB hard disk, 4 MB RAM, 1 HP T400es tape drive (external), and 1 HP Sure Store CD writer (internal);
- an HP Vectra 5/200 MHz computer with an HP Design Jet 750 Plus plotter and a Digitizer Calcomp Drawing Board III (12”x18”);
- a PC/SAT-HRPT weather satellite system; and
- Image Analyst, Erdas Image Pro, Spatial Analyst, ArcView, and MS Office 2000 software.

Table 4. Skill and evaluation of seasonal rainfall forecast based on sea surface temperature (SST).

Year	Zone	Skill (%)	Forecast	Observed
1998	North	40	BN to N	N
	SW	20	N	N
	SE	40	N to ABN	ABN
1999	North	30	N	ABN
	SW	30	BN to N	N
	SE	40	AB	AB
2000	North	40	N	
	SW	20	BN to N	
	SE	40	N to ABN	

The use of this system, when operational, is expected to lead to an improvement in drought and environmental monitoring in the country. Remote sensing will be applied to monitor weather elements, measure components of the hydrologic cycle, and estimate crop yields. The system will produce regular products to support weather forecasting and hydrologic resources. Agricultural monitoring will also be supported by the system. These products will be produced on a regular basis and distributed to users.

Future Program on Long-Range Forecasting of Nino 3 and Associated Predictability of Nigerian Temperature and Rainfall

Objectives

We propose to use a robust modeling technique to identify and predict band limited cyclic components in a limited set of monthly SST and Nigerian rainfall and air temperature data. These data are available on the U.S. National Oceanic and Atmospheric Administration (NOAA) website and from NDMS. The correlation between SST and Nigerian temperature and rainfall will be determined for approximately 40 stations. For the Nigerian climatological stations, teleconnections between SST and monthly temperature and rainfall would indicate the usefulness of the former as a predictor.

The project products will include:

1. a written report summarizing the methodology,
2. predictability performance for the 3-year period (1999-2001), and
3. prediction for the period 2001-2003.

Methods and Procedure

If daily data for climatic variables such as air temperature and rainfall are averaged over a calendar month and the results plotted over many years, the plots will show interesting tendencies. Generally, temperature data will show a somewhat regular yearly cyclic pattern, while the rainfall data will be much more irregular in form, with a weaker cyclic pattern. When these seasonal cyclic patterns are estimated and removed from the data, all variables will show a random characteristic over the years, with no pattern immediately discernible. It is the purpose of this project to identify whatever cyclic patterns exist in the SST and Nigerian temperature and rainfall data.

Trends in cycles of climatic variables are difficult to understand, let alone predict. If the model to be developed can relate these trends to underlying physical processes in the atmosphere and ocean, then the understanding of this process will allow us to identify the predictable components of climate. A purely statistical model that excludes a priori knowledge of the physics of the problem is of limited value in identifying the predictable components of climate change. The model to be developed relies on an underlying physical climatic model, based on a nonlinear model of the earth/ocean/atmosphere system.

Although a portion of the spectrum of climatic data is band limited and quasi-cyclic, the problem of signal extraction and prediction in the presence of noise remains formidable. The problem is the nature of the noise. To extract a cyclic signal in the presence of these nonlinear noise components, a robust norm criteria will be adopted. Analysis of this type has been successfully applied in fields as disparate as seismic data analysis (Claerbout and Muir 1973) and medicine (Frome and Yakatan 1980).

As an example of the application of this type of robust prediction, we show both the observed and prediction set for Kano rainfall, based on data through December 1999. The prediction can be compared with the actual data from January 1999 to December 1999 (Figure 3). For the current year, 2000, the rainfall prediction calls for reduced, but not significantly different from normal, rainfall for Kano.

Justification

Multiple-year rainfall and temperature foresight capability is critical in developing a viable long-range early warning system. Drought and crop yields are functions of many variables, but are particularly dependent on certain key climatic factors. Drought or rainfall projections, however, have always been subject to uncertainty because of the difficulty in predicting specific climatic behavior. This project seeks to remedy this uncertainty by developing a climatic foresight model that can estimate trends of the associated climatic variables in a monthly time-step for upwards of 2-3 years into the future.

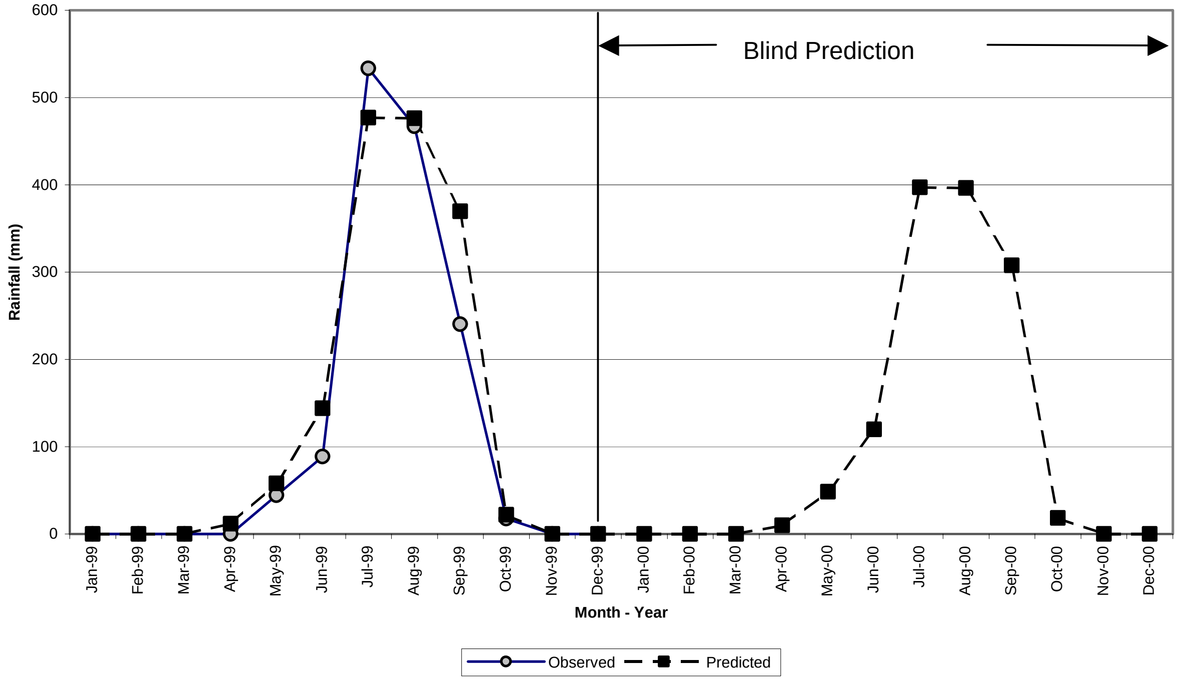

Figure 3. Observed versus predicted rainfall for Kano, Nigeria.

Conclusion

The users of EWS products include governmental organizations, media, agricultural industry, and the general public. There is evidence that these users believe that EWS products are relevant and useful in their work. For this reason, we are encouraged to continue finding the optimal level of implementing and improving EWS products in Nigeria.

Through this study we have now identified areas that are most prone to drought in Nigeria. These areas, located between latitude 10^{o} and 12^{o} N, experienced drought incidents in more than 15 of the last 40 years. The monitoring and prediction of drought in these areas is therefore necessary for preparedness and drought management.

Although predictions of onset, distribution, and cessation of the rainy season based on the NDMS prediction schemes described earlier were lower than observed in most cases, these predictions nevertheless proved useful as a planning tool. When used in combination with predictions based on SST, it is possible to increase the skill and usefulness of the predictions. We currently have and are acquiring equipment necessary for the smooth running of additional EWS models and operations. However, the major constraints we face are data quality and problems of station density.

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