Estimating Crop Yields from Simulated Daily Weather Data

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ABSTRACT

A weather generating model called WMAKER was developed at Utah State University to simulate daily climatological values using monthly average values and standard deviations of precipitation, temperature, number of rainy days and potential evapotranspiration. The data generated by the WMAKER Model were used to simulate yield probability values for corn under rainfed and irrigated agriculture for stations of Quixeramobim and Brasilia (Brazil) and San Andres and La Union (El Salvador), using the PLANTGRO and CERES-Maize models. The yield probability values were then calculated using actual daily climatic data. It was concluded that the results obtained with actual data were in close agreement with those calculated by the WMAKER Model.

The IBSNAT project will soon have yield models available for 10 crops. With adequate documentation, training programs and a monthly data base, these models can become powerful tools for increasing agricultural production, particularly in the developing countries.

INTRODUCTION

Various crop growth and development models or crop yield models have been developed for use with daily climatic data. Models designed for use with daily weather values include the Hanks (1974) PLANTIGRO model; CERES-Maize, Jones and Kiniry (1986); CERES-Wheat, Ritchie, et al. (1986) and other CERES crop models. Use of these models in agricultural development planning and in selection of production practices has been limited by the requirement for daily climatic data and the difficulty in obtaining all of the required climatic variables.

Considerable research and investigation has been carried out with the objectives of finding ways of successfully operating crop growth and development models with a historical monthly data base comprised of a minimum number of climatic variables. If a simplified monthly data base can be used to generate daily data for use with the yield models without significant reduction in predictive accuracy then crop yield models can become powerful tools to evaluate the influence of different agronomical practices including planting date, deficit irrigation, supplemental irrigation and fertilizer application on final yield.

Yield predictions are made possible by use of weather generation or weather simulation models such as the WGEN model, Richardson (1985), and Richardson and Wright (1984) and the WMAKER model, Keller (1982, 1987). Even though the WGEN model provides reasonably good estimates of crop yields, its application is limited to the availability of local climatological parameters which are not available outside the United States. The WMAKER model requires little local calibration and uses a fairly simple monthly data base and for these reasons was selected for use in this study. This paper describes the WMAKER model and compares yields predicted from WMAKER simulated data with those calculated using the actual daily climatic data.

PROCEDURE

Daily climatic data records were obtained from various countries as part of the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project sponsored by the the Bureau for Science and Technology (S & T) of the Agency for International Development (AID). The daily data were used to create the monthly climatic data base required by the WMAKER model. Yields predicted by models using the actual and simulated data were then compared.

The Monthly Climatic Data Base

The values required in the data base are the long term monthly means of daily potential evapotranspiration or reference crop evapotranspiration (ETo), Temperature, number of rainy days, precipitation amounts and the standard deviations (S.D.) of these values. Means and values of S.D. from long records are preferred. A typical data base table heading is as follows:

Month	Daily ETo		Daily Temp.		Monthly number of rainy days		Monthly precipitation	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.

The data required for each month of each year of record in order to develop the required data base are mean maximum daily temperatures (TMx), mean minimum daily temperatures (TMi), number of rainy days in each month and rainfall amounts for each month. Values of ETo for each month of each year were calculated from the equation for ETo given by

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Hargreaves, et al. (1985) and Hargreaves and Samani (1985). The equation is given as:

$$ETo = 0.0023 \times Ra \times (T^{\circ}C + 17.8) \times TD^{0.50} \quad \ldots\ldots [1]$$

in which ETo and Ra are in the same units (usually mm) of equivalent water evaporation, Ra is extraterrestrial radiation obtained from tables or from a computer routine, T°C is (TMx + TMi)/2, and TD is TMx − TMi or the mean daily temperature range.

A worldwide data base by Hargreaves and Samani (1986) provided rainfall probabilities, mean rainfall, mean temperature and ETo. The monthly records used to produce the worldwide data base were available on computer tape and were used, together with other data sources, to develop the monthly data base required for use in weather simulation.

In preparing a data base for Africa in a format suitable for use with the WMAKER model, the data available on computer tape did not include maximum and minimum temperatures. The long term means of TMx and TMi were, however, available from Her Majesty's Stationery Office (1983) and Food and Agriculture Office of the United Nations (FAO 1984). These data made possible the calculation of the mean values of ETo for the various locations.

It was assumed that values of the S.D. of ETo (SDET) could be correlated with the S.D. of temperature (SDT). This assumption was evaluated using data from various climates and latitudes. The comparisons were made between the coefficient of variation (CV) or the values of S.D. expressed as a percentage of the mean. The average relationship for the locations evaluated can be summarized as follows:

1. At low elevations the CV of ETo at 4° south latitude averages about 2.3 times the CV of temperature in °C. This ratio decreases about 0.15 per 1000 m increase in elevation and about 0.027 times the degrees of latitude departure from 4° S.

2. Monthly variations in the ratio are significant and further evaluation of this relationship is recommended. By using these relationships it was possible to develop a monthly climatic data base so that the WMAKER model could be used at 299 locations in Africa.

Weather Simulation

The weather simulation procedure (WMAKER model) developed by Keller (1982, 1987) begins by generating the mean potential evapotranspiration (ETo) for each day of the year. The ETo values are then randomized to simulate the stoeastic variation observed in actual data. Daily temperature and solar radiation were calculated from randomized ETo values. Random rainfall events were generated to coincide with days of low solar radiation (cloudy days).

The procedure for the WMAKER model with some modification was as follows:

1. Long-term ETo for each day of the year was generated using a procedure developed by Keller (1982). The mean daily ETo values entered for each month were converted to the expected value for the first of each month using numerical integration. The mean daily ETo for each day was then estimated using a fourth order Lagrangian approximation and the expected values for the first of each month. Random deviates for ETo were generated assuming a normal distribution. This assumption is supported by the research findings of Doorenbos and Pruit (1977), Jensen (1974) and Keller (1982).

2. Mean daily temperature was generated using the same procedure, with the exception that a third order Lagrangian function approximation was employed instead of a fourth. Random average daily temperatures were generated based on the ratio of the randomly generated ETo to the mean daily ETo raised to the power of Z given as:

$$Z = \frac{\ln(1 - CVT)}{\ln(1 - CVETo)} \quad \ldots\ldots [2]$$

in which CVT and CVETo are coefficients of variation of temperature (T) and potential Evapotranspiration (ETo) respectively, expressed in decimals. The maximum and minimum daily temperatures were calculated by adding and subtracting half the daily temperature difference from the average temperature. The daily temperature difference (difference between the maximum and minimum temperature) was calculated assuming that it was a function of the square of the ratio of the solar radiation received at the earth's surface to that received at the top of the atmosphere. The relationship of temperature range to solar radiation at the surface required some calibration. However, a useful average relationship is given by Hargreaves, et al. (1985). The equation is:

$$RS = 0.16 \times Ra \times TD^{0.50} \quad \ldots\ldots [3]$$

in which Ra and Rs are in the same units (usually mm of equivalent water evapotranspiration) and TD is in °C.

The daily extraterrestrial radiation (Ra) was calculated by a computer routine requiring latitude as the only input. Random daily solar radiation (RS) was calculated from the Hargreaves (1975) temperature and radiation equation. The equation can be written:

$$RS = \frac{ETo}{0.0135 \times (T^{\circ}C + 17.8)} \quad \ldots\ldots [4]$$

Simulated RS values were then checked against the limits defined by the maximum and minimum fraction of radiation reaching the earth's surface. If beyond the limit, the RS value was set to the appropriate limiting value and the average temperance simulated for that day was adjusted. The boundary values, or limits, can be approximated from an equation given by Doorenbos and Pruitt (1977). The equation is given as:

$$RS = (0.25 + 0.50\,S)\,Ra \quad \ldots\ldots [5]$$

in which S is the fraction of possible sunshine. Equation [5] indicates that on clear days RS may equal 75% of Ra and on completely cloudy days may be 25% of Ra.

3. The number of rainy days in each month was determined as a random deviate of the mean and standard deviations supplied as inputs and assuming a normal distribution. The rainy days in each month were then predicted as those days with the lowest ratio of solar radiation received at the earth's surface to that received at the top of the atmosphere (cloudiest days).

4. Finally, the depth of precipitation for each day

with rain was generated assuming a log-normal distribution and using the monthly means and standard deviations supplied as inputs and adjusted for the simulated number of rainy days.

A psuedo year was used to seed the random number generator which derives the normal and log-normal distribution models. The frequency, in days, of random variate generation can be controlled to range from zero, for mean data only (no randomization), on up. (A frequency of approximately five days was found to give the most realistic results.) Keller (1982), using time series methods discussed by Bowerman and O'Connell (1979), derived an auto regressive function for forecasting ETo data given the ETo for the current day and the long-term mean ETo. This same function was used in WMAKER when the frequency of random variate generation is greater than one day.

Corn Yield Models

Zuniga (1987) used the Hanks (1974) PLANTGRO model and the CERES-Maize model (Jones and Kiniry, 1986) to compare yields calculated from actual daily climatic data with yields estimated using WMAKER simulated daily climatic values. He concluded that yields from actual and data generated did not differ greatly.

The PLANTGRO model predicts relative yields (actual yield divided by maximum possible yield) based on availability of water during the growing season. The CERES-Maize model was used by Zuniga (1987) to also predict actual yields with varying amounts of available water and nitrogen. The PLANTGRO model was selected for this study largely due to its simplicity and was evaluated by the authors using data reported for San Andres, El Salvador by James and Stutler (1982). At more than 50% relative yields, differences between measured and predicted yields were not significant. Differences were, however, significant for conditions of low yields due to considerable water stress.

RESULTS AND DISCUSSION

Research at San Andres, El Salvador, for a period of three years on the interactions of water and nitrogen on corn yields under various types of irrigation was reported by James and Stutler (1982).

The PLANTGRO model predicts relative yields or changes in the probable yields as water stress varies. It is usually assumed that other conditions, including fertility, variety and management, are fairly constant. Water stress was determined from ETo, rainfall, and soil depth and water holding capacity. Soil conditions were reported for San Andres. Use of the PLANTGRO model at other locations required some assumptions relative to soil characteristics. However, the principal purpose of this study was to compare predicted yields from the use of climatic values simulated from a monthly data base with those obtained by using the actual daily climatic data. It was assumed that the relative comparisons are not influenced by the variations in soil conditions.

Comparisons made using daily climatic records from El Salvador and Brasil for relative yield of corn under rainfed agriculture and generated climatic values with the WMAKER model indicate that relative yields generated with actual data and generated data are roughly comparable. The range in differences in relative yields found for the data evaluated is from zero to only 17%.

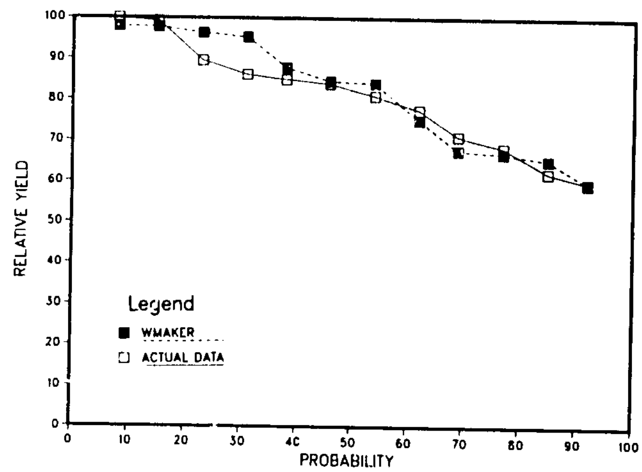

Fig. 1—Probabilities of relative yield of maize at La Union, El Salvador, from the PLANTGRO Model using actual (daily) climatic data and the WMAKER values from monthly data.

Simulated data will differ somewhat from the actual data. The mean and standard deviation does not completely define the full probability distribution. It is possible that a Gamma distribution for rainfall will produce better results than the log-normal distribution. Possible refinements and adjustments may improve the reliability of the WMAKER model.

Figs. 1 through 4 indicate relative yields resulting from use of the PLANTGRO model with daily climatic data and with the WMAKER generated values.

Fig. 5 indicates the influence of one irrigation applied 70 days after planting on the relative yield of maize at Quixeramobim. The irrigation was applied at a critical stage in the production of a 120 day variety planted March 1. In this case the WMAKER model somewhat over-estimates the value of the one irrigation. However, the maximum difference in relative yield from measured daily data and the WMAKER generated data is only about 8%. This clearly indicated the value of the WMAKER model as a planning tool. Comparison with Fig. 4 indicates the probable importance of the one irrigation. In actual practice, the irrigation could be scheduled based on the occurrence of rain during a particular year.

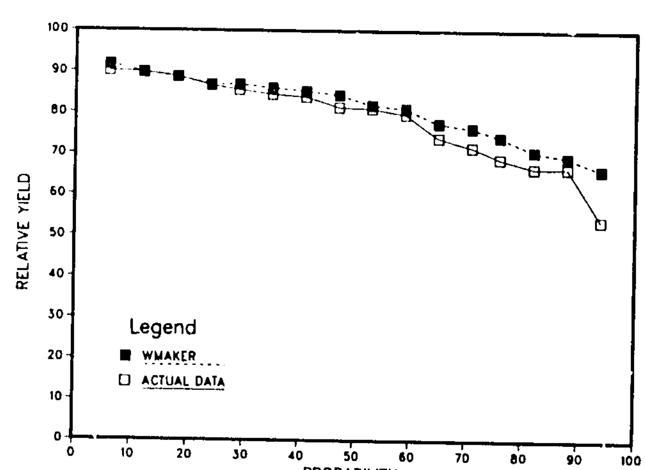

Fig. 2—Probabilities of relative yield of maize at San Andres, El Salvador, from the PLANTGRO model using actual (daily) climatic data and the WMAKER values from monthly data.

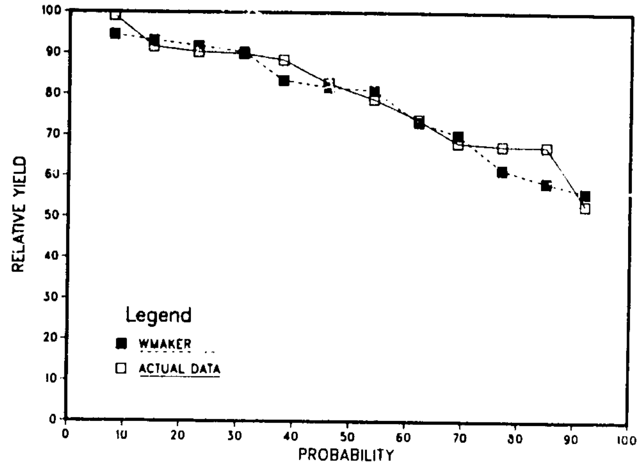

Fig. 3—Probabilities of relative yield of maize at Brasilia, Brazil, from the PLANTGRO model using actual (daily) climatic data and the WMAKER values from monthly data.

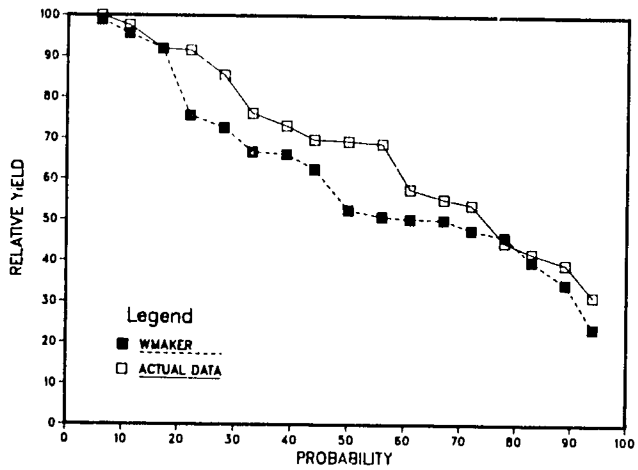

Fig. 4—Probabilities of relative yield of maize at Quixeramobim, Brazil, from the PLANTGRO model using actual (daily) climatic data and the WMAKER values from monthly data.

SUMMARY AND CONCLUSIONS

Various crop growth and development models require the availability and use of daily climatic data. The obtaining of daily climatic values from the developing countries may be both difficult and costly. Efforts have therefore been made to develop weather generation or simulation models capable of producing daily values from a monthly climatic data base.

A weather simulation model (WMAKER) was developed by Keller (1982, 1987). The WMAKER model was used to simulate daily values for use with crop yield models. The procedures used required a simple method for calculating potential evapotranspiration (ETo) that requires a minimum of data, a means of estimating the standard distribution of ETo and procedures for reconstructuring the probability distribution of ETo, temperature, number of days of rain during the month and the rainfall amounts. It was assumed that the standard deviations of these values can be used to reconstruct the frequency distributions.

Fairly long records of daily climatic data were obtained from several countries. Some of these were used to prepare a monthly climatic data base for use with the WMAKER model to generate simulated daily data. The PLANTGRO model was used to predict corn yields from both the actual daily data and the WMAKER simulated daily data.

The results from the PLANTGRO model indicate that, for the purposes of agricultural planning and development, conclusions will be identical or at least very similar when the model is operated with actual daily data or with simulated climatic values. Use of a monthly climatic data base is therefore recommended for widespread use in agricultural development planning both for rainfed and for irrigated agriculture.

In order to facilitate preparation of monthly climatic data base tables, monthly values of daily mean maximum and minimum temperatures for long records are needed. In the absence of long records of maximum and minimum temperatures it will be necessary to estimate the standard deviation of ETo from the standard deviation of temperature. The degree of error probable in this procedure has not yet been evaluated.

The development of the monthly climatic data base and of the CERES crop growth and development models provides a means for rapidly improving agricultural planning and development. Emphasis on the methods and models described above is recommended for the developing countries. Adequate training programs and documentation of the models are recommended for consideration.

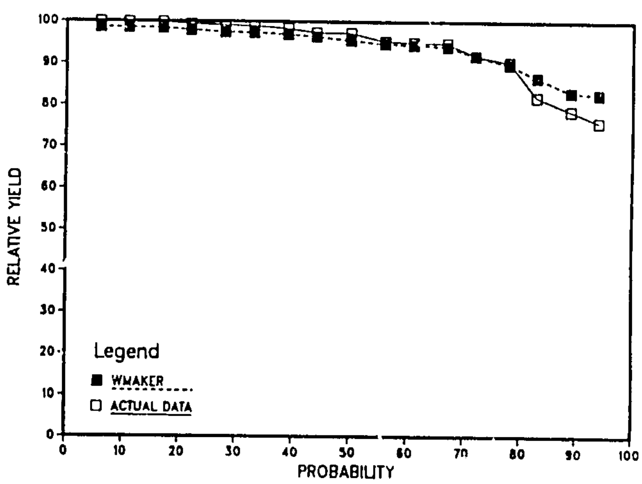

Fig. 5—Probable relative yield of maize at Quixeramobim, Brazil, with one irrigation 70 days after planting from actual (daily) and WMAKER (monthly) climatic data.

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