5.1 THE GEM (GENERATION OF WEATHER ELEMENTS FOR MULTIPLE APPLICATIONS) WEATHER SIMULATION MODEL

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1. INTRODUCTION

Agricultural, natural resource and engineering management decisions require a variety of climatic information for applications such as land use planning, and ecological and hydrologic modeling. Often climate data requirements are greater than the available information because climate records are either unavailable, very short or have large numbers of missing records. To address the need for readily-available climate data for any location, the model known as GEM (Generation of weather Elements for Multiple applications) was developed by the USDA, Agricultural Research Service and USDA, National Resources Conservation Service to deliver accurate time series of daily or higher temporal resolution weather elements that have the appropriate statistical characteristics for a location (Hanson and Johnson, 1998; Johnson et al., 1996). This paper describes the latest version of the stochastic weather simulation model GEM that can be used to generate daily precipitation amount, maximum and minimum air temperature, average dewpoint temperature, solar radiation, and average wind speed. The GEM programs and the parameter sets required to run GEM can be downloaded from the USDA-ARS, Northwest Watershed Research Center web site at: http://www.nwrc.ars.usda.gov/models/gem/.

2. MODEL

2.1 *Daily Precipitation*

In GEM, the occurrence or non-occurrence of precipitation in a day is described by a two-state Markov process of first order with precipitation amounts on a wet day simulated with a mixed-exponential distribution (Hanson et al., 1989; Johnson et al., 1996). The seasonal variation in the parameters that are required for simulating daily precipitation are described by the polar form of a finite Fourier series. The number of harmonics is limited to three because they sufficiently describe the seasonal variations.

2.2 *Daily Maximum And Minimum Temperature, Solar Radiation, Dewpoint Temperature And Wind Speed*

The procedure used in GEM to describe the multi-variate process of maximum temperature and the other weather elements was taken from Richardson (1981). It is a weakly-stationary, auto-regressive [AR(1)] process used by Matalas (1967) for generating streamflow at multiple sites. The 3x3, **A** and **B** matrices with elements defined to maintain the appropriate serial and cross-correlation coefficients between weather elements described by Richardson & Wright (1984) and Hanson et al. (1994) are 6x6 matrices in GEM. The correlation coefficients computed from the five weather elements and a temperature relationship used to obtain daily wind speed make up the two 6x6, **A** and **B** matrices in GEM. These 6x6 matrices consist of all of the possible correlations between daily maximum and minimum air temperature, solar radiation, mean daily dewpoint temperature, mean daily wind speed and a difference between the maximum air temperature on two consecutive days. The latter variable was added because wind speed is not highly correlated with any of the other elements at most locations and times of year, but often there is a significant relationship between a given day's wind speed and the one-day change in maximum temperature. Meteorologically, this correlation is largely due to the fact that higher winds are often associated with large temperature changes, such as from frontal passages.

The seasonal changes in the means and coefficients of variation are represented by a finite

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Fourier series (Hanson et al., 1994). The mean and standard deviation values of each weather element are conditioned on whether the day is dry or wet, as determined by the Markov chain occurrence model. Values of solar radiation are constrained to be no greater than 90% and no lower than 10% of the potential daily solar radiation (Hanson et al., 1994).

3. DATABASE

The climatological data for Omaha, NE that were used in this study were obtained from the SAMSON (1961-1990) database (USDC-NOAA, 1993). The *t*-test, at the 0.05 significance level, was used in this study to determine when historical monthly and annual means were significantly different from 30 years of simulated monthly and annual means. The same climatic records were used for developing the parameter set for GEM that were used for the monthly and annual mean comparisons.

4. RESULTS AND DISCUSSION

4.1 *Simulation Of Omaha, NE Climate*

A summary of selected monthly and annual weather statistics for Omaha, NE is presented in Table 1. These months were selected for discussion because they represent different seasons of the year.

The historical and simulated mean monthly precipitation amounts shown in Table 1 were within 3 mm which was not a statistically significant difference. The March mean-monthly precipitation difference of 13 mm was the largest monthly difference between any of the historical and simulated monthly precipitation values, it also was not a significant difference. The historical and simulated mean-annual precipitation was less than 1% different. For the months shown in Table 1, the mean number of wet days per month for the historical and simulated values were within 0.8 days per month which was not a significant difference. The largest difference between the historical mean number of wet days and the simulated number was 1.4 days during December which was not a significant difference. The historical and simulated mean-annual number of wet days was the same for this 30-yr simulation.

The standard deviations computed from the simulated monthly and annual precipitation values were all less than those computed from the historical record except for May where the standard deviation for the simulated data was 2 mm greater than that computed from the historical data. The standard deviations calculated for the historical number of wet days per month was close to the values calculated from the simulated record, however, the standard deviation calculated from the historical record for the annual number of wet days was considerably greater than that calculated from the simulated record.

The generated mean-monthly maximum temperatures were within 1 ^{o}C of the historical values with the exception of January, April, October and December. The January and December simulated mean-monthly temperatures were about 2 ^{o}C warmer than the historical temperatures and the April and October were about 1.7 ^{o}C cooler than the historical temperatures. As expected, the mean-monthly generated temperatures did not change much when either more years were used in the simulation or a different seed value was used to start the simulation which suggests that this temperature regime is inherent in the model for this location.

Standard deviations calculated from the simulated maximum-temperature record were equal to or somewhat less than those calculated from the historical record for all monthly and annual values.

Mean monthly and annual simulated and historical daily minimum temperature differences were about the same as the maximum temperatures. They were within 1 ^{o}C for all months except January where the simulated mean was 1.5 ^{o}C warmer (Table 1) and October where the simulated mean was 1.4 ^{o}C colder. The mean-annual simulated and historical minimum temperatures were within 0.1 ^{o}C. Six of the monthly standard deviations calculated from the simulated record were equal or slightly greater than the standard deviations calculated from the historical record.

All but two of the mean monthly and annual simulated and historical dewpoint temperatures were within 1 ^{o}C and only the May dewpoint temperatures were significantly different. The difference between the historical and simulated dewpoint temperatures is the only significant difference for any of the weather elements in Table 1.

Mean monthly historical and simulated daily

Table 1. Monthly and annual summary of a 30-year simulation, Omaha, Nebraska

	January		May		September		Annual	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Precipitation (mm)								
Historical	17	13	115	45	95	65	776	157
Simulation	19	12	118	47	94	40	771	111
Number of wet days								
Historical	6.3	3.1	11.8	3.7	9.2	3.2	104	14
Simulation	7.1	3.0	12.0	3.1	9.8	3.3	104	9.5
Max. Temp. (^{o}C)								
Historical	-1.3	4.1	22.5	2.0	23.7	1.9	15.4	1.0
Simulation	0.7	3.5	22.3	2.0	23.7	1.6	15.6	0.7
Min. Temp. (^{o}C)								
Historical	-11.5	3.7	10.9	1.9	12.4	1.5	4.5	0.9
Simulation	-10.0	2.8	11.2	1.9	12.4	1.6	4.4	0.7
Dewpoint (^{o}C)								
Historical	-10.7	2.8	9.4*	2.3	12.3	1.6	4.1	0.8
Simulation	-9.7	2.6	10.7	2.0	11.6	1.6	4.1	0.7
Solar Rad. (W m^{-2} d^{-1})								
Historical	88	7.1	247	17	186	18	175	7.2
Simulation	85	6.1	253	14	180	13	175	3.2
Wind speed (m s^{-1})								
Historical	4.6	0.5	4.5	0.7	3.9	0.5	4.3	0.4
Simulation	4.8	0.3	4.4	0.5	3.7	0.3	4.3	0.1

*Mean values are significantly different at the 5% level.

solar radiation amounts were within 4% and as shown in Table 1, the annual values were the same. The monthly and annual standard deviations calculated from the simulated solar radiation data were all less than the values calculated from the historical data except for December where the historical value was slightly larger.

Mean monthly and annual simulated and historical daily wind speed differences were less than 0.1 m s^{-1} except February and April. The mean monthly simulated wind speed for February was 0.4 m s^{-1} greater than the historical mean monthly wind speed. The historical mean-monthly wind speed for April was 0.5 m s^{-1} greater than the simulated mean-monthly wind speed. The mean annual simulated and historical wind speeds were within 0.01 m s^{-1}. The monthly and annual standard deviations calculated from the simulated wind speed data were all less than the values calculated from the historical data except for March when the values were equal.

4.2 *A Review Of The M_0 And M_1 Matrices*

The GEM model is an updated and enhanced version of the WGEN (Richardson, 1981; Richardson and Wright, 1984), CLIMATE.BAS (Woolhiser et al., 1988) and USCLIMATE.BAS (Hanson et al., 1994) models. Each of these models used the same $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices to compute the **A** and **B** matrices that are used in these models to simulated daily weather for all seasons and all locations in the contiguous United States. These models can be used to generate daily precipitation, maximum and minimum temperature and solar radiation. When GEM was developed to include the generation of mean-daily dewpoint temperature and wind speed, monthly $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices were computed from weather data for each of 226 weather stations in the United States. $\mathbf{M}_0$ is a matrix of coefficients between variables on the same day, while $\mathbf{M}_1$ is a matrix of intercorrelations with a 1-day lag (e.g., today's maximum temperature and yesterday's solar radiation) (Johnson et al., 1996). An evaluation of these matrices indicated that most of the weather-element correlations in the $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices vary both annually and spatially; some considerably more than others as shown on Fig. 1. Monthly $\mathbf{M}_0$ values computed from the Omaha, NE climate record show a distinct annual pattern for the correlations between daily total solar radiation and daily maximum temperature that vary from -0.02 during January and December and 0.49

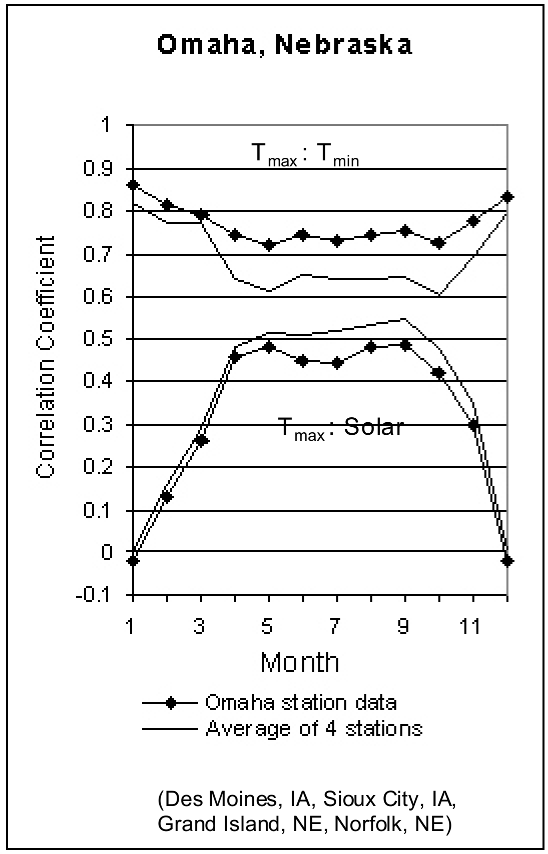

FIG. 1. $\mathbf{M}_0$ matrix values for maximum : minimum temperature correlations, and maximum temperature : solar radiation correlations for Omaha, NE and the averaged stations.

during September with a value near 0.46 from April through September. The $\mathbf{M}_0$ values for the correlation between daily maximum and minimum temperatures show an annual pattern with the values ranging from 0.86 in January to 0.72 in May. The daily maximum-minimum temperature correlations were also very uniform during the summer months. Because of these annual correlation patterns, the monthly values were computed for the GEM parameter file and are used in the present version of GEM for generating daily weather series.

This preliminary investigation was done: 1) to determine if average values of the $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices from nearby stations could be used to generate weather series for a location with no weather data; and 2) to use Omaha, NE data to do a preliminary study to determine if annual $\mathbf{M}_0$ and

$\mathbf{M}_1$ matrices, as used in the previous models, can be used to generate weather series that are as representative of a location as weather series generated using monthly $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices.

$\mathbf{M}_0$ and $\mathbf{M}_1$ matrices were computed from the Des Moines, IA, Sioux City, IA, Grand Island, NE and Norfolk, NE climatic record. The correlations in each of these matrices were averaged to obtain average $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices that were used to generate a 30-yr weather series to compare to the 30-yr weather series generated from the Omaha climate record. As can be seen from Fig. 1, the four-station average correlations are close to the actual correlation patterns obtained from the Omaha climate record. As expected, other spatial-average correlations were also close to the correlations computed from the Omaha record. Preliminary analyses of GEM-generated time series indicate that annual means of maximum and minimum temperatures, dewpoint temperature, solar radiation and wind speed were all within 1% of the annual means calculated using actual observed Omaha data, whether monthly average $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices (12 of them) or just annual average $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices (one each) were used. Monthly values for these same weather elements have not been fully analyzed yet, but preliminary analyses suggest that monthly values were close to those obtained from the Omaha record.

Using average correlations from several nearby weather stations to obtain $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices appears to be a good approach in the Great Plains but this method undoubtedly will not work as well in mountainous regions of the United States and other areas where climate is not spatially homogeneous. However, it does appear that reasonable results can be obtained from GEM when $\mathbf{M}_0$ and $\mathbf{M}_1$ matrices can be obtained from station(s) which have a similar climate regime to the location in question.

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