Precipitation Simulation Models

Timothy O. Keefer
United States Department of Agriculture (USDA), Tucson, Arizona, U.S.A.

INTRODUCTION

The variability of precipitation across a range of spatial and temporal scales, from short-duration high-intensity down-bursts within a localized storm to the seasonal and annual variations at a single location and across the globe is obvious to a casual weather observer. Frequently, in the planning and management of agricultural and engineering activities, precipitation information that reflects this natural variability is needed. Examples include irrigation design and application, evaluation of agricultural runoff for soil erosion and water quality, cropping and seeding patterns, sizing and placement of culverts and dams, scheduling and selection of agricultural and construction equipment. The demands of the particular use of the information vary from within-storm intensities to daily amounts to regional and seasonal accumulations each with different precision. Generally, the source of such information is the precipitation data measured and recorded at a point. Precipitation information for a particular location may not be adequately known or available in the specific time-frame required because of short or nonexistent records of measurements, inaccurate or inconsistent data, or budgetary constraints.

An alternative approach is to use a precipitation simulation model which generates sequences of synthetic precipitation which share the same statistical properties as the observed time series. Three broad categories of precipitation simulation models exist in various degrees of mathematical and statistical complexity which relate to the type of precipitation simulated. Low-resolution, large-area precipitation data can be generated by 3-dimensional dynamic-numerical general circulation models (GCMs); rainstorm event occurrence and intensities are simulated by spatial-temporal models; daily precipitation occurrence and amount are modeled by a family of fairly simple stochastic/statistical algorithms. The latter of these are often part of a larger model called a weather generator, which simulates other weather related land/atmosphere variables such as solar radiation, temperature, or soil moisture. The generated synthetic sequences of precipitation are used for a variety of purposes such as: analysis for water resource engineering applications, climate change scenarios, and as input to other hydrological or natural resource models. This differentiates these models and their results from the class of models which are used in weather prediction and forecasting. All three categories of models are valuable tools for scientific research and agricultural, engineering and hydrological applications. The selection of any one type should fit the intended analysis, level of complexity and scale of required results. Overviews of various precipitation simulation models are Ref. [1] for GCMs, Ref. [2] for rain storm modeling, and Ref. [3] for daily precipitation.

MODELS AND APPLICATIONS

General Circulation Models

General circulation models (also referred to as global climate models and sharing a common acronym, GCM) use the same fundamental equations of conservation of mass, energy and momentum as do numerical weather prediction (NWP) models. These dynamic meteorology models, and similarly structured regional climate models (RCM), attempt to numerically solve systems of simultaneous nonlinear differential equations which themselves are intended to represent the complex physical processes involved in atmospheric dynamics. Whereas NWPs use observations of recent atmospheric dynamics as boundary conditions for model runs and produce weather prediction in the short term (1–10 days), GCMs use arbitrary boundary conditions and alternative atmospheric parameters to simulate climate for the past, current or future. One result of GCM simulations is precipitation over an area, called a grid, which may be on the order of $10^5\,km^2$, whereas for an RCM the spatial resolution may be $10^1\,km^2$–$10^3\,km^2$.

Precipitation is generally simulated in these models by convective processes resolved from radiation, temperature, pressure, and humidity simulated at various atmospheric layers within a gridbox. These simulations of precipitation are useful for evaluating changes in vegetation and surface water resources under different possible climate change scenarios. To increase the resolution of the GCM simulation, downscaling by statistical techniques or incorporating an RCM into the GCM achieves finer resolution precipitation output

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applicable to soil moisture and runoff analysis for subgrid scales. Excellent sources of information about and applications of the models are available at WEB sites such as Intergovernmental Panel on Climate Change,[4] American Institute of Physics,[5] and NASA's Goddard Institute for Space Studies.[6]

Spatial-Temporal Rainstorm Models

Stochastic simulation models of rain storm events in space and time attempt to reproduce the statistical properties of the event across a range of temporal and spatial scales. Two of the most advanced modeling concepts are: i) stochastic representation of the physical process of rainstorm temporal and spatial evolution and ii) scale-invariance or self-similarity of the spatial rainfall field. The stochastic approach defines the arrival of the rain cells within a rain storm by a point cluster process[7] represented by one of two common models, the Neyman–Scott process or the Bartlett–Lewis process. The former uses a Poisson distribution for the cluster centers, a random number of cells and a distribution of the distance of cell from the cluster center. The latter assumes a Poisson process for arrival of storms, and distributions for the number of cells per storm, intercell intervals, duration and intensity within a cell. For each characteristic, a statistical distribution must be assumed and numerous parameters identified. Alternatively, scale-invariant models[8] exploit the properties of multiplicative random cascades developed in turbulence theory. Observations of rainfall fields suggest that there are certain spatial and temporal properties that behave similarly over a range of scales differing only by a scale parameter. Thus a hierarchy of attributes (e.g., rainfall intensity) can be developed such that larger areas of lower intensity have embedded within them smaller areas of higher intensity and these in turn have even smaller areas of yet higher intensities. Applications of these models are design storms for engineering and water resources and continuous time hydrologic modeling.

Other statistical storm models of simpler structure are derived empirically. One method is to disaggregate daily rainfall amounts to within-storm intensities for the duration of a storm. These models have parameters that are location specific. Another approach is the regionalization of probabilities associated with storm interarrival time, duration, and amount.

Daily Precipitation Models

Daily precipitation simulation models are the most common for use in a variety of agricultural and engineering applications. These models describe the occurrence (wet) or nonoccurrence (dry) of precipitation on a day and subsequently the amount of precipitation given the day was wet. The occurrence process is modeled most frequently by a first-order, two-state Markov chain. Linked to this occurrence process is a statistical description of precipitation on a wet day, often a gamma or exponential distribution.[9] This family of fairly simple models of daily precipitation is referred to as chain-dependant processes. Equations for these models are given in a companion article in this chapter, "Precipitation Stochastic Processes," and are not duplicated here. The models can be parsimonious in the necessary parameters, are easily parameterized with a sequence of observed daily precipitation (a commonly recorded observation for many stations) albeit for many years. Seasonal variation of model parameters can be accomplished by writing them as Fourier series or by assuming they vary step-wise on a monthly or seasonal basis. The structure of the model provides simple generation of multiple realizations of daily time series. Model output is generally used as input to hydrologic, natural resource, or agricultural models requiring daily time step precipitation. The model parameters are location specific with limited transferability to neighboring locations that do not share the same stochastic precipitation structure, e.g., to a location with a large elevation change. Another limitation of the model is the underestimation of interannual variability. One approach to resolve this has been determining the appropriate order of the Markov chain indicating that for particular seasons and geographic locations a second-order or higher conditional dependence may be required, although not all such variability is explained. Markov chains of more than two states may explain more of the variability and a continuum of states may be best.

Other methods to model daily precipitation occurrence have been advanced, among them: alternating renewal process, discrete auto-regressive moving average, Markov–Bernoulli process, dependence on weather type, Markov-renewal. Some recent weather generator models use multivariate techniques to simulate precipitation conditioned on other weather variables or simultaneously with other weather variables or using semiempirical distributions. Although numerous inter-comparisons have been done, no single model provides simplicity, ease of parameterization, and the best fit for all weather types and locations.

An example of a particular precipitation simulation model is provided. The Markov chain-mixed exponential model (MCME) is used to simulate daily precipitation for two stations with different climates in the western United States. This model is the precipitation algorithm embedded in the United States Department of Agriculture-Agricultural Research Services (USDA-ARS) weather generator, Generation of Weather Elements for Multiple Applications (GEM).[10] This model is an enhanced version of a series of weather generators developed by the USDA-ARS.[11] Daily precipitation model parameters are estimated from an observed time series of daily data. The optimized

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parameters are used in the model in conjunction with a random number generator to synthesize a 30-yr period of daily precipitation occurrence and amount. Daily values are summed to seasonal values and the annual averages and variances of these are compared to observations. Fig. 1 shows the results for Tombstone, Arizona plotted as a cumulative distribution function for two 3 month seasons, United States Department of Agriculture, January, February and March (JFM) and October, November and December (OND); Fig. 2 is the same for Eugene, Oregon. The mean is fairly well preserved for both seasons and both the amount and number of occurrences at Tombstone, but the variance is underestimated especially for JFM. The mean is not as well preserved at Eugene, and the variance is underestimated for OND. This is one of the limitations mentioned previously and it may be due to low-frequency ocean-atmospheric signals, such as the El Niño-Southern Oscillation, which have varying influences seasonally and regionally and which are not adequately identified in the daily parameters.

CONCLUSION

Precipitation simulation models generate synthesized sequences of precipitation at a range of spatial and temporal scales. Three broad categories are general circulation models, stochastic spatial-temporal rainstorm models, and daily precipitation models. Model selection and use should be justified by the desired resolution of

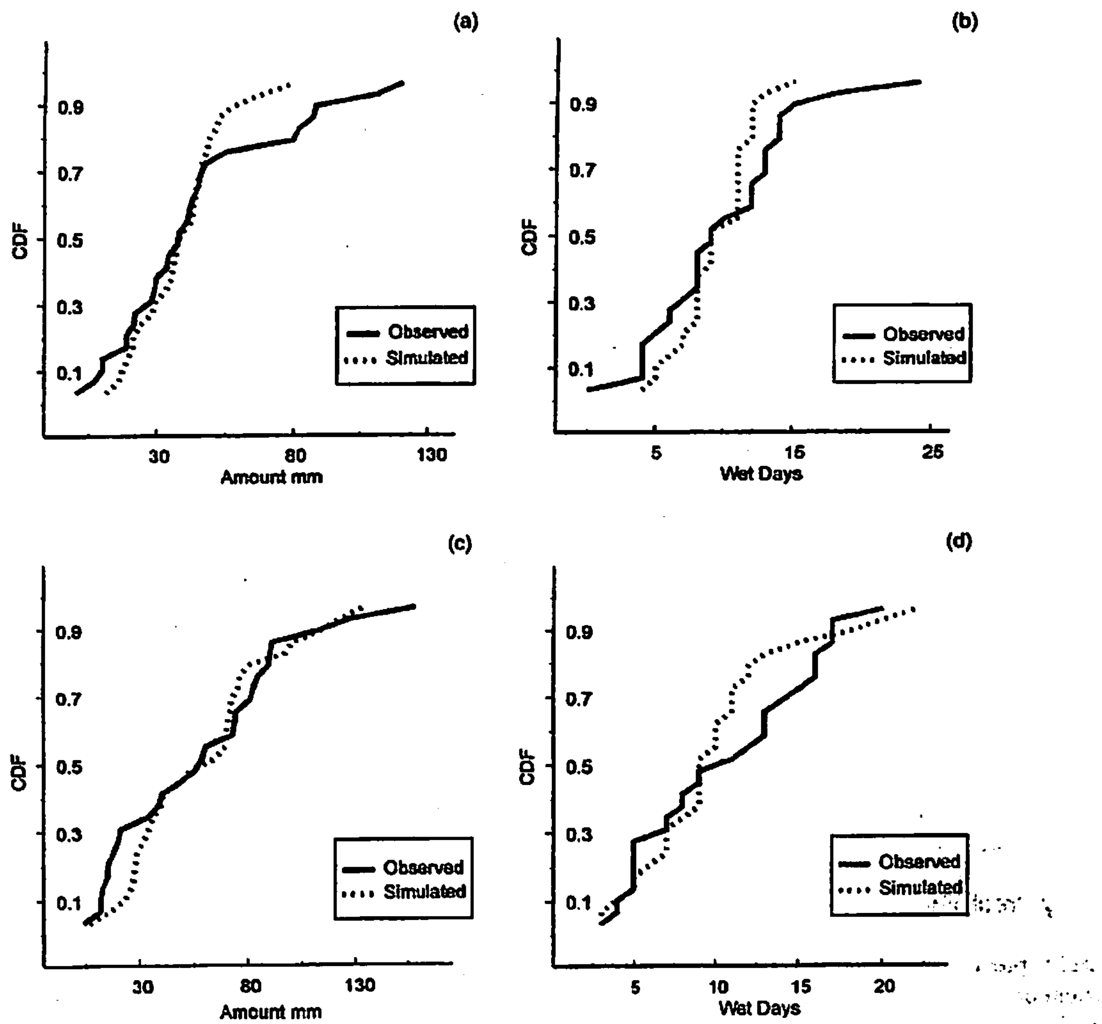

Fig. 1 Empirical cumulative distribution function (CDF) of simulated and observed precipitation for Tombstone AZ 1961–1990. a) January, February and March (JFM) amount; b) JFM number of wet days; c) October, November and December (OND) amount; d) OND number of wet days.

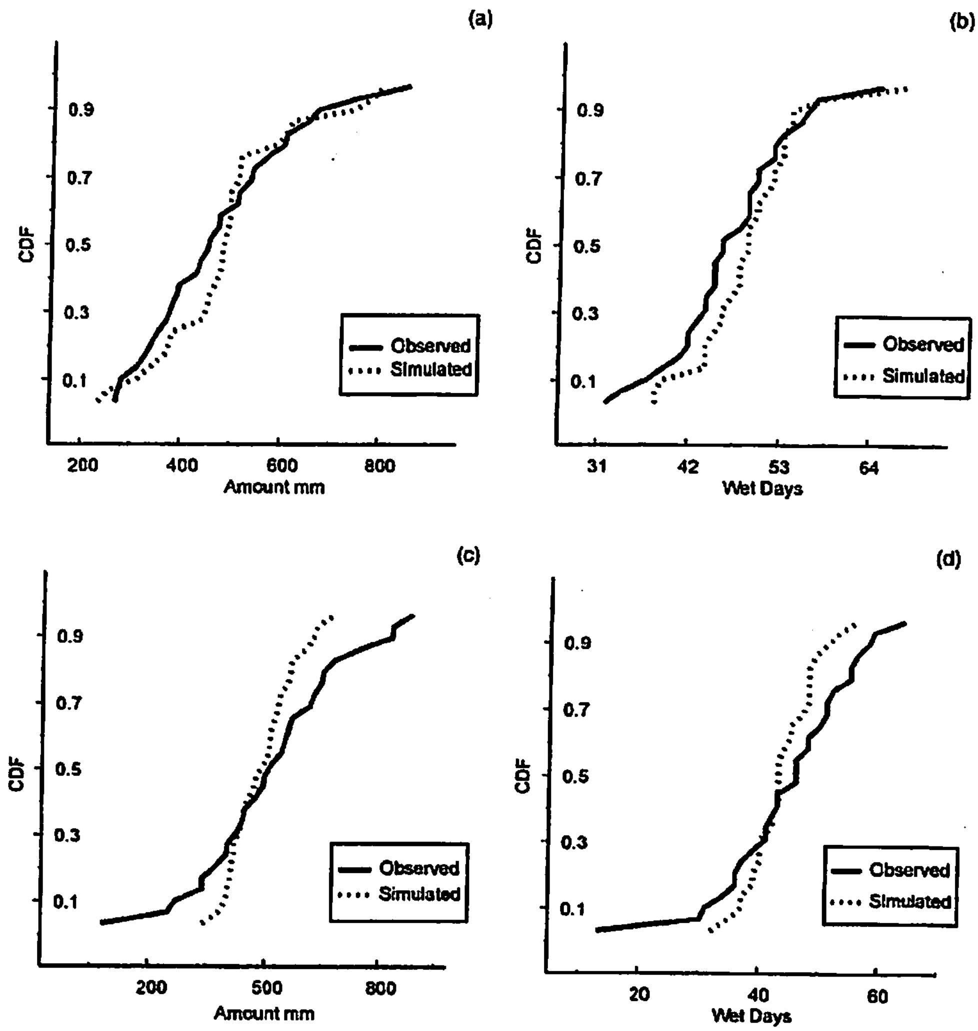

Fig. 2 Empirical cumulative distribution function (CDF) of simulated and observed precipitation for Eugene OR 1961–1990. a) JFM amount; b) JFM number of wet days; c) OND amount; d) OND number of wet days.

results and ability to fully estimate the required parameters. Future developments to precipitation simulation models will be downscaling techniques which link regional and local scales, improved algorithms to more faithfully represent the stochastic and physical dynamics of precipitation, and the inclusion of low-frequency oscillations and spatial distribution of parameters in daily precipitation models.

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