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Assessment of CLIGEN precipitation and storm pattern generation in China

Wenting Wang[a,b], Dennis C. Flanagan[b], Shuiqing Yin[a,*], Bofu Yu[c]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[b] USDA-ARS National Soil Erosion Research Laboratory, Purdue University, 275 S. Russell St, West Lafayette, IN 47907-2077, USA
[c] Australian Rivers Institute, School of Engineering and Built Environment, Griffith University, Nathan, Qld 4111, Australia

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ABSTRACT

The applicability of the uncalibrated CLIGEN (CLImate GENerator) model was assessed using long-term precipitation data at 1-min interval from 18 sites in eastern and central China. The model performance was evaluated in terms of daily precipitation depth, storm duration and peak intensities of 1-min (I_1), 5-min (I_5) and 30-min (I_{30}) for all storms and four categories grouped by daily precipitation depth: light (< 10 mm), moderate (10–25 mm), heavy (25–50 mm), and intense (≥ 50 mm) storms. Additionally, the applicability of CLIGEN in generating climate inputs for the Revised Universal Soil Loss Equation (RUSLE) in China and calculating the intensity-duration-frequency (IDF) values for a series of storm duration (5-min to 24-h) and return periods (2 to 100-years) were assessed. Results showed that CLIGEN was able to accurately reproduce the statistics and probability distributions of daily precipitation depth for all storms and the four categories. The mean storm duration was underestimated for 3 of the 4 storm categories but was overestimated for light storms. CLIGEN underestimated I_1 and overestimated I_{30} in general, whereas no obvious bias was observed in I_5 for these 18 sites. In addition, the relative error in the generated duration and peak intensity increased as the magnitude of precipitation increased from moderate to intense storms, which implies that the model does not perform as well for intense storms as other storms. Rainfall erosivity generated with CLIGEN outputs was systematically larger than, but well correlated with, the measured erosivity values (slope = 0.547, R^2 = 0.96 for the R-factor; slope = 0.576, R^2 = 0.81 for the 10-year storm erosivity). Extreme intensities for given duration and return periods were systematically over-predicted using the output from CLIGEN, and the bias between measured and CLIGEN generated intensity-duration-frequency (IDF) values varied with duration intervals. The average of the regression slopes for the six return periods (2-year to 100-year) between measured (X) and generated (Y) intensities (Y = *b* X) increased from 1.19 (5-min) to 1.43 (1-h), then decreased to 1.01 (12-h) and 0.96 (24-h). As a stochastic weather generator, CLIGEN is able to reproduce daily precipitation very well, but its capacity to simulate storm duration and the peak intensity for a given time interval needs to be improved, especially for heavy and intense storms, based on this study.

1. Introduction

Long-term precipitation is one of the most basic and indispensable inputs commonly required by hydrologic and soil erosion models (Kou et al., 2007; Yu, 2003; Zhang and Garbrecht, 2003). Due to various reasons such as short periods of observation or significant numbers of missing records, measured data is often insufficient for modeling applications. Synthetic sequences of daily precipitation depth generated by stochastic weather generators that preserve the statistical characteristics of measured data are commonly used in such situations (Chen and Brissette, 2014a; Chen and Brissette, 2014b). CLIGEN (CLImate GENerator) is a stochastic weather generator which can simulate long-term continuous precipitation depth and the corresponding storm patterns on a daily scale (Nicks et al., 1995). It was initially developed from the weather generator used in the EPIC and SWRRB models (Arnold et al., 1990; Nicks et al., 1995; Williams et al., 1984) and then incorporated as part of the WEPP (Water Erosion Prediction Project) model to provide climate input requirements for runoff and soil loss predictions (Flanagan et al., 2001; Nicks et al., 1995). After decades of development, CLIGEN is now used as a general weather generator to simulate precipitation inputs for other models. For example, Yu (2002) presented a method utilizing CLIGEN-generated daily outputs to provide the R-factor (rainfall erosivity factor) and its monthly distribution, and 10-year storm EI_{30} (storm EI_{30} with a 10-year return period) for the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1997). Furthermore, CLIGEN has been widely adopted as an effective tool to

* Corresponding author.
E-mail address: yinshuiqing@bnu.edu.cn (S. Yin).

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downscale output from GCMs (General Circulation Models) to study climate change impacts (Zhang et al., 2004; Zhang, 2005a; Zhang et al., 2012), as one of the outputs from GCMs is the ratio of monthly rainfall change in the future, that is too coarse at both spatial and temporal scales (Fan et al., 2013; Vaghefi and Yu, 2011).

Intensity-duration-frequency (IDF) values are extensively used in hydrologic engineering to assess the return periods of rainfall events for water resource projects (Koutsoyiannis et al., 1998), the application of which rely on a basic assumption of stationarity where intensities and frequencies of extreme events do not change over time (Mailhot et al., 2007). Recently, an increase in the frequency of extreme precipitation events has been reported in several regions of the world under the background of global warming (Goswami et al., 2006; Mason et al., 1999; Yu and Li, 2012; Zhai et al., 2005). Changes in the extreme rainfall statistics to some degree are expected in the future. The reproducibility of IDF has been an important consideration when assessing a stochastic weather generator (Cameron et al., 2000; Heneker et al., 2001; Yu, 2003). As CLIGEN can simulate storm pattern parameters, it should be expected to be able to estimate the IDF values. Yu (2003) compared rainfall intensities extracted from AR&R (Canterford, 1987, Australia Rainfall and Runoff, vol. 2) and CLIGEN-generated values for two duration intervals, 1 h, and 12 h, and two return periods, 2-year and 50-year. He found that the generated rainfall intensities were greater than the observed AR&R values at the 1 h duration interval for both 2-year and 50-year return periods, whereas no obvious overprediction trend was found for the 12 h duration interval. This indicated that the bias between measured and generated IDF values might change with duration intervals. More evaluation concerning various duration intervals and return periods should be conducted to verify if CLIGEN has the potential to predict IDF values.

Several evaluations of CLIGEN-generated daily precipitation depth and storm patterns have been reported before. CLIGEN could reproduce precipitation occurrence and the distribution of annual and monthly precipitation depth satisfactorily (Elliot and Arnold, 2001; Kou et al., 2007; Zhang et al., 2008; Fan et al., 2013). The main statistics of measured daily precipitation depth were well preserved, but the probability distribution of daily precipitation depth could not be successfully reproduced. Significant differences in the probability distribution between measured and generated daily precipitation depth were found at the $p = 0.01$ level using the Kolmogorov-Smirnov (K-S) and the Wilcoxon rank sum tests (Chen et al., 2009; Zhang and Garbrecht, 2003; Zhang et al., 2008). Storm duration and peak storm intensity are not always well simulated by CLIGEN. Previous studies reported that the mean storm durations are underestimated (Chen et al., 2009; Fan et al., 2013; Zhang and Garbrecht, 2003) and peak rainfall intensities at short intervals, e.g. I_5 (maximum 5-min intensity) and I_{30} (maximum 30-min intensity) are overestimated (Fan et al., 2013; Yu, 2003). Note that all evaluations conducted in previous studies were made based on all storms. Simulation quality for different storm groups classified by precipitation depth has not been reported in the literature. Determination of the performance of CLIGEN for infrequent, highly intense events which are dominant in the soil erosion and hydrological processes (Coppus and Imeson, 2002; González-Hidalgo et al., 2007) is more critical to runoff and soil loss predictions.

The uncalibrated CLIGEN model has been evaluated in China and results reported in the literature (Chen et al., 2009; Kou et al., 2007; Shi et al., 2006; Zhang et al., 2008), but the study area of these evaluations (Table 1) was restricted to the Loess Plateau (highlighted area in Fig. 1). The remaining regions, especially the southeast coastal area with annual rainfall exceeding 1000 mm and influenced by typhoon disasters are lacking in assessments (Shen et al., 2013). Testing of the uncalibrated CLIGEN generator with weather data collected from sites in various Chinese climate zones with a wider range of annual precipitation will be beneficial for the application of both CLIGEN and the related hydrologic and soil erosion models in China.

The objective of this study was to systematically evaluate the performance of CLIGEN in terms of precipitation-related variables for all storms as well as four storm categories grouped by precipitation depth, especially the heavy (25–50 mm) and extreme (≥50 mm) storms in the eastern and central China. CLIGEN input parameter files were prepared using observed daily and 1-min precipitation data from 18 weather sites located in eastern and central China, and then used with CLIGEN to generate 100-years of daily precipitation depth and related storm patterns for each of the 18 sites. Observed and CLIGEN-generated precipitation depth and storm patterns were evaluated in terms of direct assessment: 1) Probability distributions of precipitation depth, and main statistics of precipitation depth, storm duration and peak intensity for all storms as well as for four storm categories; and indirect assessment: 2) the R-factor, its monthly distribution, and the 10-year storm erosivity values, and 3) intensity-duration-frequency values for given duration interval and return period.

2. CLIGEN storm pattern generation (v5.3)

CLIGEN generates daily precipitation occurrence, precipitation depth (mm) and three storm pattern variables: storm duration (h), the ratio of peak intensity over average intensity, i_p, and time to peak as a fraction of storm duration, t_p (Nicks et al., 1995; Yu, 2002). It also generates six non-precipitation daily variables (Chen et al., 2009; Zhang et al., 2008). Considering that the precipitation variables are independent of the other variables, and this study is focused on precipitation and the related storm pattern, only precipitation-related variables were evaluated here.

In order to simplify the storm pattern generation, three assumptions are used in CLIGEN to simulate storm-related variables: (1) there is only one storm occurring on a wet day, which means the storm duration is limited to 24 h; (2) for each generated storm, there is only a single peak; (3) all storm profiles can be described by a double-exponential function.

In CLIGEN, simulation of precipitation occurrence is based upon a first-order and two-state Markov chain. This method utilizes two conditional probabilities: the probability of a wet day following a dry day Prob (W/D), and the probability of a wet day following a wet day Prob (W/W). If a random number drawn from a uniform distribution is less than the given previous day status, precipitation will be predicted to occur. For a predicted wet day, a skewed normal distribution is then used to generate daily precipitation depth,

$$x = \frac{6}{g}\left\{\left[\frac{g}{2}\left(\frac{P-u}{s}\right)+1\right]^{\frac{1}{3}}-1\right\}+\frac{g}{6} \tag{1}$$

where x is the standard normal variate, P is the daily precipitation depth (mm), and u, s, and g are the mean, standard deviation, and skewness coefficients for the daily precipitation depth for a wet day for

Table 1
Information of rainfall data used in previous published studies on the assessment of CLIGEN precipitation generation in China.

Study area	Data resolution	Stations	Data length (years)	Annual rainfall (mm)	References
Loess Plateau	Daily	5	30	300–626	Kou et al., 2007
Loess Plateau	Daily/breakpoint	6/6	46/21–28	316–512	Zhang et al., 2008
Loess Plateau	Daily/breakpoint	12/10	45–53/6–28	193.4–576.4	Chen et al., 2009
Loess Plateau	Daily	1	18	541.2	Shi et al., 2006