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On temporal stochastic modeling of precipitation, nesting models across scales

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ABSTRACT

We analyze the performance of composite stochastic models of temporal precipitation which can satisfactorily reproduce precipitation properties across a wide range of temporal scales. The rationale is that a combination of stochastic precipitation models which are most appropriate for specific limited temporal scales leads to better overall performance across a wider range of scales than single models alone. We investigate different model combinations. For the coarse (daily) scale these are models based on Alternating renewal processes, Markov chains, and Poisson cluster models, which are then combined with a microcanonical Multiplicative Random Cascade model to disaggregate precipitation to finer (minute) scales. The composite models were tested on data at four sites in different climates. The results show that model combinations improve the performance in key statistics such as probability distributions of precipitation depth, autocorrelation structure, intermittency, reproduction of extremes, compared to single models. At the same time they remain reasonably parsimonious. No model combination was found to outperform the others at all sites and for all statistics, however we provide insight on the capabilities of specific model combinations. The results for the four different climates are similar, which suggests a degree of generality and wider applicability of the approach.

1. Introduction

Stochastic simulation of precipitation time series at a site is demanded for numerous applications where precipitation is a key variable, e.g., watershed hydrology, urban drainage design, natural hazard assessment, agricultural and ecological applications, etc. These requirements have led to the formulation of many stochastic models of temporal precipitation. One of the fundamental problems with existing models is that they are designed to perform best within a limited range of time scales and for selected statistics for which they are calibrated. Often key statistics such as intermittency, correlation structure, extremes, etc., are not satisfactorily reproduced at multiple scales. The premise behind this study is that a simultaneous correct reproduction of key statistics over a wide range of hydrologically relevant time scales from minutes to months is fundamental. We argue that even when simulated precipitation time series are to be used for instance for impact studies at fine resolutions, we should require models at the same time to provide good results at coarser resolutions, e.g., to preserve storm internal variability, intermittency and inter-storm clustering properties, seasonality, etc.

Early rainfall modeling focused on the simulation of daily precipitation time series. The most common processes adopted in hydrology for stochastic simulation of precipitation were Markov chains [1–5], Alternating renewal processes [6,7] etc. Capabilities of such models have been recently enhanced using the concept of generalized linear models (GLMs) (e.g., [8,9]). Those processes served as precipitation simulation tools for some of the most widely used weather generators (e.g., [10,11]). A common deficiency of these models was that they were generally not able to reproduce higher order statistics and statistics across different temporal scales. Furthermore, they were not designed for temporal scales finer than daily, with some exceptions (e.g., [12]).

In order to improve precipitation simulations at fine resolutions and for higher order statistics, new approaches were introduced. Among them point processes have been widely used [13,14]. These models appeared as an ideal candidate for precipitation modeling, since they reproduce a structure of storm arrivals and persistence that mimics the physics of the precipitation process. Developments on the initial ideas led to the implementation of Poisson cluster models based on the concepts of storms, cells, and clustering [15–25]. Their main advantage was that statistics were reasonably reproduced across scales from 1 h to several days, with the exceptions of intermittency and correlation at high resolutions. These models have also been introduced into last generation weather generators (e.g., [26]) and used to solve practical problems in

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real-world applications (e.g., [27]). Another class of models that was found to give promising results for rainfall simulation at various temporal scales, even though often used for rainfall simulation at the daily scale only, is the Hidden Markov class of models (e.g., [28–30]).

The concept of self similarity, widely known as fractal or scaling behavior [31,32] combined with the quest for rainfall stochastic models that perform well across scales has led to an additional category of precipitation modeling. Self similarity has been identified in precipitation time series and precipitation spatial fields (e.g., [33–36]). The concept of scale invariance has its origins in the study of turbulence [37,38] and it allows one to link statistical properties of a certain process (e.g., precipitation) across scales. The extension of the self similarity concept into multi-scaling behavior, widely known as multifractals [39,40] has found many interesting applications in rainfall simulation (e.g., [41–44]). One of the modeling tools for the simulation of multifractals, Multiplicative Random Cascades (MRC), has been widely used for precipitation disaggregation and downscaling [45–51].

Despite the large number of available approaches and models mentioned above, none is free of problems when multiple scales and statistics are considered. Markov chains, Alternating renewal processes, and GLMs serve as reliable simulation tools for precipitation only for coarse aggregation scales and are often poor in reproducing extremes. Poisson cluster models have been found to reproduce well the statistics only for the scales at which they are calibrated (typically between one hour and a few days). The self-similarity assumption and multifractal behavior have several limitations, posing doubts on the generality and validity of the approach. Temporal scaling regimes were found to be limited [52,53] and scaling relations themselves imperfect [54]. In the MRC it was shown that weights do not follow iid (independent and identically distributed) assumptions required by the model [55,56], all of which pose restrictions on the global scaling behavior of precipitation.

Significant effort has been undertaken to modify and improve the original models. For example Katz and Parlange [12] applied a chain dependent process for hourly precipitation. Recently, Cowpertwait et al. [57] introduced modifications to a Poisson cluster model in order to overcome the common problem of inadequate representation of small scale (sub-hourly) variability. Other authors provided several variants of the initial MRC model in order to take into account dependencies of the MRC weights (e.g., on scale, rainfall intensity) [45,54,58–60]. However, these approaches have the tendency to become increasingly difficult to parameterize. In summary, a single stochastic model which reproduces precipitation statistics across a wide range of temporal scales of hydrological interest is difficult to find.

An alternative approach which we explore in this study is to combine several types of stochastic precipitation models at the scale for which they perform well. The nesting of an internal and external model is expected to strongly enhance the performance of the precipitation generator across scales, without requiring excessive parameterization if the nested models are appropriately chosen. Although most studies in the literature have focused on improving a specific model type, there are some attempts at model combinations. Menabde and Sivapalan [61] successfully applied a combination of an Alternating renewal process with a bounded MRC in order to reproduce rainfall extremes at fine temporal scales. Fatichi et al. [26] combined an autoregressive model with a Poisson cluster model to introduce into the latter the interannual variability that it failed to capture. Veneziano and Iacobellis [62] obtained encouraging results combining an external model of conventional renewal type with an internal model based on the iterated random pulse process. Furthermore, Rodriguez-Iturbe et al. [15], Onof and Wheater [63] and Gyasi-Agyei and Willgoose [64] improved the fine-scale properties of the Poisson cluster models by perturbing their realizations with an independent multiplicative noise stochastic process called jitter. Finally, Koutsoyiannis [65] developed a model-free theoretical framework in order to couple different stochastic models.

The novelty in our work is to show that for stochastic modeling of temporal precipitation a composite model – consisting of a point-process or Markov chain as an external model and a nested Multiplicative Random Cascade as an internal model – performs better across a wider range of scales than the individual models alone and at the same time remains reasonably easy and parsimonious to calibrate. In order to make our point we extensively investigate and compare different model types and structures for a wide range of statistics and temporal scales. We then apply the composite models to four sites representing very different climatological regions around the world to verify their performance.

2. Data

Data from four meteorological stations with long records of reliable high resolution precipitation were used. Each station belongs to a different climatological region of the world (Fig. 1 and Table 1).

Two of the stations are located in Europe. The first station, Zurich (Switzerland), is representative of a temperate continental climate with distinct seasonality and a mean annual precipitation of about 1130 mm. The gauge has a heated tipping bucket recording mechanism, and its temporal resolution is 10 min. Precipitation in Zurich mainly consists of stratiform events during the cold season and intense convective events during the warm season [66]. Data from this station have been used previously in several studies [45,56,67]. The second station, Florence (Italy), is representative of a Mediterranean climate with a less pronounced seasonality, dry summers, and mean annual precipitation of about 800 mm. The tipping bucket gauge in Florence records with a temporal resolution of 5 min. Data from this station have also been extensively analyzed in the past [68–70,62,71].

Outside of Europe we chose two stations with contrasting precipitation regimes. Lucky Hills (Arizona, USA) is representative of a semiarid climate in southwestern USA. It is located within the Agricultural Research Service (ARS) Walnut Gulch Experimental Watershed [72]. Precipitation at Lucky Hills has a pronounced seasonality with a wet monsoon season in the summer and rare stratiform events during the dry season. Mean annual precipitation is about 340 mm. The gauge is a weighing gauge with a temporal resolution of 1 min. Finally, the station Mount Cook (New Zealand) is representative of the oceanic climate of southern New Zealand with a uniform distribution of precipitation throughout the year, accumulating an average of about 3900 mm per year. This high precipitation total is the result of the orographic enhancement imposed by the southern Alps which leads to considerable precipitation amounts in the entire southwestern area of New Zealand. The gauge is a tipping bucket with a temporal resolution of 10 min. Data were obtained from the National Climatic Database operated by NIWA (National Institute of Water and Atmospheric Research).

Stronger diurnal patterns of precipitation intensity are only present in the Mt. Cook and Lucky Hills stations (Fig. 1). These diurnal patterns are mostly due to convective afternoon rain in the summer, JJA for Lucky Hills and DJF for Mt. Cook.

3. Methods

The stochastic models which are used as building blocks for the composite model are presented in this section (Fig. 2). The composite model consists of an external model which captures the