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Transient stochastic downscaling of quantitative precipitation estimates for hydrological applications

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SUMMARY

Rainfall fields are heavily thresholded and highly intermittent resulting in large areas of zero values. This deforms their stochastic spatial scale-invariant behavior, introducing scaling breaks and curvature in the spatial scale spectrum. To address this problem, spatial scaling analysis was performed inside continuous rainfall features (CRFs) delineated via cluster analysis. The results show that CRFs from single realizations of hourly rainfall display ubiquitous multifractal behavior that holds over a wide range of scales (from ≈1 km up to 100's km). The results further show that the aggregate scaling behavior of rainfall fields is intrinsically transient with the scaling parameters explicitly dependent on the atmospheric environment. These findings provide a framework for robust stochastic downscaling, bridging the gap between spatial scales of observed and simulated rainfall fields and the high-resolution requirements of hydrometeorological and hydrological studies.

Here, a fractal downscaling algorithm adapted to CRFs is presented and applied to generate stochastically downscaled hourly rainfall products from radar derived Stage IV (∼4 km grid resolution) quantitative precipitation estimates (QPE) over the Integrated Precipitation and Hydrology Experiment (IPHEx) domain in the southeast USA. The methodology can produce large ensembles of statistically robust high-resolution fields without additional data or any calibration requirements, conserving the coarse resolution information and generating coherent small-scale variability and field statistics, hence adding value to the original fields. Moreover, it is computationally inexpensive enabling fast production of high-resolution rainfall realizations with latency adequate for forecasting applications. When the transient nature of the scaling behavior is considered, the results show a better ability to reproduce the statistical structure of observed rainfall compared to using fixed scaling parameters derived from ensemble mean analysis. A 7-year data set of 50 hourly realizations of downscaled Stage IV rainfall fields at 1 km resolution for the IPHEx domain is publicly available from iphex.pratt.duke.edu.

The value of the downscaled products is demonstrated through hydrological simulations of two distinct storm events in the Southern Appalachians, a winter storm that caused multiple landslides and a summer tropical event that caused flashfloods. The simulations are forced by the entire span of plausible fractally downscaled rainfall fields at two distinct resolutions (1 km and 250 m). The results show very good skill against the observed streamflow, especially with regard to the timing and peak discharge of the hydrograph, and the accuracy is enhanced by increasing the target downscaling resolution from 1 km to 250 m. Probabilistic simulations of both events capture the observed behavior indicating that the proposed CRF-based stochastic fractal interpolation provides a generalized framework for producing fast and reliable probabilistic forecasts and their associated uncertainty for extreme events and risk management of hydrometeorological hazards, as well as long-term hydrologic modeling.

1. Introduction

Heavy rain events over mountainous terrain present a great challenge for forecasters and are the leading cause of natural hazards including flashfloods, shallow landslides and debris flows. Predictability of these events depends on access to precipitation products at spatial and temporal resolutions finer than the scales currently resolved by the Numerical Weather Prediction (NWP) models, or the observations used to produce Quantitative Precipitation Estimates (QPE) (e.g. ground-based radar; Tao and Barros, 2013). Consequently, rainfall downscaling methodologies are of

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primary importance for many hydrometeorological applications. Rainfall fields are the result of several nonlinear interactions among physical processes occurring over a wide range of scales, posing a considerable challenge for deterministic interpolation methods to represent the resulting complex rainfall structure. Stochastic downscaling raises as a natural alternative, capable of producing a large span of plausible solutions over a short time period, a crucial requirement for operational forecasts.

Various stochastic interpolation strategies have been developed aiming to reproduce the sub-grid scale rainfall variability by adding (statistically) realistic high-frequency heterogeneity, hence increasing the information content of coarser commonly available datasets that do not meet the high resolution requirements of hydrological modeling and risk assessment and hazard prediction. Ferraris et al. (2003) undertook a comparison of several such methods and found similar ability over all alternatives to generally reproduce the statistics of precipitation fields, but significant errors in their ability to reproduce the statistics of particular fields. While significant efforts have been made over the last 10 years, stochastic downscaling of rainfall fields is still largely an open problem (e.g. Kim and Barros, 2002; Bindlish and Barros, 2000; Rebora et al., 2006; Barros and Tao, 2008; Brussolo et al., 2008; Tao and Barros, 2010; Ebtehaj et al., 2012; Foufoula-Georgiou et al., 2014). The present work aims to address this issue focusing on stochastic downscaling methodologies based on modified fractal interpolation performed in the Fourier spectrum framework, which has been previously shown to preserve the spatial and temporal structure in the coarse resolution information while enhancing variability in the smaller unresolved scales (Bindlish and Barros, 1996, 2000; Kuligowski and Barros, 2001; Kim and Barros, 2002; Rebora et al., 2006; Barros and Tao, 2008; Brussolo et al., 2008; Tao and Barros, 2010).

A large number of investigations over the past 30 years reported spatio-temporal stochastic scale-invariant behavior of rainfall fields (and other geophysical quantities) across scales (see Lovejoy and Schertzer, 2007 for a review). This scaling behavior implies that statistical properties of rainfall fields at different scales are related by power laws, and physically based models and downscaling algorithms should reproduce this scaling behavior if they are to generate realistic fields.

Bindlish and Barros (1996) developed and applied a fractal interpolation method to map digital elevation maps at different spatial resolutions using a modified fractional Brownian surface (fBs) to match the correct spectral scaling as the interpolating surface. While such approach preserves well the spatial structure of the data, the generation of the fBs introduces a random component at the sub-grid scales where the Fourier phase is unknown. To tackle this problem Bindlish and Barros (2000) modified the fractal interpolation scheme to include the spatial properties of regional topography and NWP simulated hourly winds thus adding physical constraints to the fBs generation. Subsequently Kim and Barros (2002) and Barros and Tao (2008) used fields of physically related variables at higher spatial resolutions to estimate the sub-grid scale variability of fields at coarser scales conditional on the underlying conceptual physical model of precipitation processes. While this strategy circumvents the need to estimate the random phase component by providing deterministic physically-based constraints to precipitation variability, it requires high-resolution fields with scaling behavior physically linked to rainfall, thus severely restricting the application and target resolutions of the downscaling schemes, in particular for forecasting applications that require short latency times.

Rebora et al. (2006) presented a rainfall downscaling algorithm similar to Bindlish and Barros (1996) but including the time dimension and assuming that the exponents remained constant throughout the chosen period. More recently, Tao and Barros (2010) also applied a method similar to Bindlish and Barros (1996) to downscale TRMM 3B42 quantitative precipitation estimates (QPE) without using high-resolution ancillary data that are generally unavailable. Their results showed that fractal interpolation methods are limited by the quality of the coarse resolution information content as expected, and by the ability to determine the correct scaling properties for each particular storm. Despite these limitations, fractal methods generally performed consistently better in downscaling rainfall fields than other widely used interpolation methods, which are unable capture the correct subgrid scale statistical structure. Furthermore, fractal methods provide an unambiguous framework to generate ensembles of rainfall fields at high spatial resolution, and therefore provide an explicit description of uncertainty. This issue will be revisited in Section 5.

A further source of complexity comes from the fact that some geophysical fields, such as rainfall and clouds, exhibit very strong physical thresholds, and thus intermittency, that result in large fractions of zero values both in time and space. Moreover, any measurement no matter how precise has an associated minimum detection threshold that contributes to increasing the fraction of zeroes in measured fields, and thus distinguishing between measurement and physical zeroes becomes virtually impossible for most applications and datasets. It has been known for some time that large fractions of zeroes influence scaling behavior (Harris et al., 1996; Schmitt et al., 1998), but this fact has received little attention in rainfall field analysis until recent work of Montera (2009) reporting that the presence of numerous zero rainfall values in the data is associated with deformations of temporal scaling behavior, causing scaling breaks and biasing the estimation of scaling parameters. Verrier et al. (2011) reached a similar conclusion using high temporal resolution disdrometer data over France, while Verrier et al. (2010) and Gires et al. (2012) found that the presence of large portions of zeros also deformed the spatial scaling behavior in high-resolution radar data and multifractal synthetic simulations. Verrier et al. (2010) suggested that single universal parameters could be found only when looking at near space filling events, though Gires et al. (2012) found clearly distinct scaling parameters between two different rainfall events even after explicitly taking the zero problem into account. In this manuscript, existing fractal downscaling methodology is modified to account for the zero problem in spatial downscaling of rainfall. A summary description of the data sets used in this study is presented in Section 2.

The question of whether the spatial (and temporal) scaling parameters of rainfall are universal properties estimated from ensemble analysis, or dynamical quantities that depend on the particular system state and forcing remains open. The dynamical scaling scenario is supported by the widespread range of values for the scaling parameters for rainfall fields that can be found in the relevant literature. Furthermore, several investigations found evidence that scaling behavior holds to a very good approach in single realizations over considerable ranges of scales with dynamically variable scaling parameters that have been linked to underlying atmospheric properties such as mean rainfall rate (Over and Gupta, 1994; Deidda et al., 2004), atmospheric stability (Perica and Foufoula-Georgiou, 1996; Nogueira et al., 2013), mean wind speed (Nogueira et al., 2013) and underlying terrain forcing (Barros et al., 2004; Nykanen, 2008; Nogueira et al., 2013). Whereas *a priori* determination of the correct scaling parameters faces many challenges due to the highly transient and nonlinear nature of the linkages among different atmospheric fields (Nogueira and Barros, 2014), in the case of *a posteriori* downscaling applications this is not an issue as the scaling parameters can be calculated independently for each field.

In particular, we take advantage of the NSSL (National Severe Storms Laboratory) Multi-Resolution Multi-Sensor QPE (also