論文の内容の要旨

Thesis Summary

論文題目(Title of Dissertation)

An stochastic approach for the multiscale analysis and reproduction of rainfall data at high spatial resolutions (確率手法を利用した高い空間分解能の降雨情報の多重スケール解析と再生)

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本文 (Body)

Modeling the water cycle has become a more comprehensive procedure due to the developments in computer capability and the scientific understanding of the involved processes. However, because hydrological models and numerical weather prediction models are mostly mathematical solutions of nonlinear equations, the simulations are sensitive to spatial and temporal variations of the input data, being rainfall intensity one that causes considerable impact (Bell and Moore, 2000; Beven, 2001; Arnaud et al, 2002, 2011; Smith et al., 2004; Schuurmans and Bierkens, 2007; Younger et al., 2009; Liu et al., 2012; Song et al., 2015; Weijian et al., 2015). Despite the scientific contribution of physically-based models, there still remains the problem of spatial distribution of field measurements and the consequent sub-grid parameterization of land properties and atmospheric forcing data at small scales (high resolutions). Therefore, the use of this kind of models becomes futile in regions without the resources to afford the installation and operation of weather radars or dense meteorological stations.

Satellite-based products are an alternative source of estimations of rainfall intensity. The validation of these products is mostly done by comparing them with rain gauge measurements and, if available, with weather radars at various temporal and spatial scales. As a result, systematic errors, which generally show regional and seasonal trends, were identified by many researchers. The number of validation studies is probably immensurable considering the many available satellite-based products, and that only a fair number of rain gauge stations are needed to conduct such study (Ebert et al., 2007; Tian et al., 2007; Hossain and Huffman, Tian et al., 2009; Pombo et al., 2015; Rudlosky et al., 2016; and Maggioni et al., 2016). Motivated by how important it is to have accurate rainfall fields at high-resolutions, even in poorly gauged regions, this research aimed to conduct a stochastic analysis of the spatial structure of rainfall before establishing a strategy for the combination of the rain gauge measurements and satellite products. In this sense, Chapter 1 introduces the methodology and establishes the specific objectives of the research.

Rainfall intensity portrays distinctive spatial features which include intermittency, abrupt discontinuities, parallel bands and high-intensity clusters surrounded by consecutive larger areas of each time lower-intensity. One way of studying this extreme variability is to perform a multiscale stochastic characterization of the rainfall process. The hypothesis is that certain statistical aspects have a scale-invariant behavior. A particular kind of scale-invariance is called self-similarity or simple-scaling, which implies that a single parameter can describe the inter-scale relationship of the probability distributions. If a process is qualified as self-similar in distribution, it means that the type of distribution does not change in spite of scaling transformations. Early stochastic models representing multiscale variability of rainfall were based on empirical evidence (radar-based estimations of intensity) that self-similarity was present in certain statistical properties of the rainfall process.

Kumar and Foufoula-Georgiou (1993a, 1993b) proposed to conduct the multiscale analysis by decomposing the rainfall process into large- and small- scale components, where the small-scale components represent the details (fluctuations of intensity) that differentiate a process at high-resolution from the same process at lower resolutions. For this purpose, Chapter 2 makes a description of the filters used for the decomposition, which have been largely used in computer sciences for image processing and edge detection. A benefit of using these filters is that the algorithm can be easily inverted, which means that rainfall at high resolutions can be reproduced from low-resolution rainfall and information about the fluctuations.

Rainfall intensity fields are normally discretized into two-dimensional grids for representation purposes. The filters described in Chapter 2 are used in Chapter 3 with the purpose of characterizing the components of the rainfall field and prove the presence of self-similarity.

Specifically, the two–dimensional Discrete Wavelet Transform extracts directional wavelet coefficients using orthonormal bases constructed from wavelet functions. The probability distributions of the wavelet coefficients depict a large amount of values around zero (as a result of adjacent boxes with similar intensity) and positive and negative outliers representing the abrupt jumps of intensity. Because of these two conditions, distributions with non-Gaussian behavior (thick tails), like symmetric α-stable distributions, have proved to be a better fit (Perica and Foufoula-Georgiou, 1996; Ebtehaj and Foufoula-Georgiou, 2011). Perica and Foufoula-Georgiou (1996), however, demonstrated the presence of self-similarity in the distributions of standardized wavelet coefficients. Standardization was defined as the wavelet coefficients divided by their corresponding low-pass coefficients (local means). The standardization of wavelet coefficients, which flattened the tails making the distributions quasi-Gaussian, allowed to qualify the fluctuation processes as self-similar.

In this study, we revise the adjustment of the distributions of wavelet coefficients to symmetric α-stable distributions, which are described by two parameters: the characteristic exponent α, and the scale parameter γ. The characteristic exponent α determines the frequency of extreme values, and hence, it is an indicator of the degree of variability. We handle the hypothesis that this parameter can be an indicator of the degree of spatial variability of rainfall fields. Two conditions are necessary to demonstrate the existence of self-similarity when considering symmetric α-stable distributions. First, the characteristic exponent α should be the same at all scales, meaning that the type of distribution is invariant under these transformations. Second, the scale parameter γ should have exponential growth with a constant rate (power-law behavior) as the scale becomes larger (lower resolutions).

The estimation of the parameters of α-stable distributions is hampered by the absence of closed-formed expressions for the probability density function, which means that it can only be expressed as an infinite series or using improper integrals. Consequently, common methods of estimation (e.g., method of moments or maximum likelihood) cannot be applied and alternative techniques have been developed. These techniques usually require large samples with values of frequency evenly located along the real line. Unfortunately, samples of wavelet coefficients usually show a large amount of near-zero values at small scales, and (the samples) are greatly reduced at large-scales as a result of the scaling transformations. These two unfavorable situations happen to affect the existing estimation techniques, as they either fail to give a result or generate very different values of α between scales.

A thorough study of the properties of symmetric stable distributions lead to the theoretical development of a new technique of estimation, presented in Chapter 3. Nolan (2013) defined the “amplitude” of multivariate α-stable distributions in such way that for the univariate case the amplitude becomes a distribution of absolute values. An expression for the Fractional Absolute

Moments (FAM) were presented previously by several authors (e.g., Nikias and Shao, 1995). This expression relates the fractional absolute moments to the parameters α and γ. During this study, an expression that represents the evaluation of the FAM in the cumulative distribution function of the "amplitude" (of a univariate stable distribution) was derived. This expression happened to be a function of the parameter α and independent of the scale parameter γ. Therefore, the parameter α could be estimated using the empirical FAM evaluated at the empirical cumulative distribution function. Then, the estimation of the parameter γ can be done using the FAM expression and the estimated parameter α. This technique of estimation and the existing ones were compared through a Monte Carlo simulation. The results showed that the new technique can be even more accurate than the existing ones with reduced times of computation. The performance when applied to samples of wavelet coefficients is detailed.

This research examined the possibility of retaining the degree of variability expressed by the characteristic exponent α, by demonstrating that self-similarity can be revealed in the marginal distributions of wavelet coefficients without the need to standardize them. For this purpose, wavelet coefficients were adjusted to symmetric α-stable distributions with the new technique described above. With the purpose of encompassing different types of rainfall, five analysis sites in Japan were identified for the multiscale spatial analysis of fluctuations: Kanto (KAN), South Tohoku (STO), Hokkaido (HOK), Kyushu (KYU), and Shikoku (SHI). Each domain covers a 256 km × 256 km surface. The period of analysis is between the 2006 and 2009.

During the analyzed period, Radar-AMeDAS data was produced with a 1-km resolution. The multiscale two-dimensional discrete wavelet transform was applied to these datasets. Three sets of directional wavelet coefficients are extracted at each scale representing the fluctuations of intensity that are more prominent in the longitudinal, latitudinal and diagonal direction, respectively.

The empirical probability distribution of each set of wavelet coefficients can be adjusted to a symmetric α-stable distribution. Common techniques of estimation failed to estimate the parameters at small-scales because of the large number of near-zero fluctuations, which are generated as a result of vast areas with the same value of rainfall intensity.

Throughout the analyzed scale range, which is between 1-km to 64-km resolution, two conditions need to be fulfilled in order to qualify the rainfall fluctuation processes as self-similar. First, the estimated values of the characteristic exponent α need to be almost invariant. Second, the scale parameter γ must have a power-law behavior. The second condition can be verified by adjusting the values of γ to a log-linear curve with logarithmic slope H, which is often called the self-similarity index (Samorodnitsky and Taqqu, 1994; Embrechts and Maejima, 2000). Only adjusted curves that showed a coefficient of determination, R^2, greater than 0.75 in all three directions were accepted. He results of this analysis is presented in Chapter 3.

The multiscale two-dimensional discrete wavelet transform can be inverted with relative simplicity, allowing to construct an algorithm that is able to generate high-resolution rainfall with a spatial distribution consistent with that of the true event. The input of this algorithm is (i) the rainfall-intensity measurement of only one rain gauge, (ii) a large-scale gridded dataset containing the location of high- and low- intensity areas, and (iii) the parameters of the probability distribution of wavelet coefficients. The structure of the algorithm has two main processes: estimation of the mean rainfall intensity and disaggregation. Chapter 4 is a complete description of such algorithm and presents the validation of its structure by computing fidelity metrics.