[UCI]I804:21031-000002235360

Thesis for the Degree of Doctor of Philosophy

A Study on the Dynamical Mechanism of Meteorological Factors in Multi-analyses

By

Seongkyu Seo

Department of Physics

The Graduate School
Pukyong National University

January 2016

A Study on the Dynamical Mechanism of Meteorological Factors in Multi-analyses

다중분석에서 기상요소의 동역학기작에 관한 연구

Advisor: Prof. Kyungsik Kim

by

Seongkyu Seo

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Department of Physics, The Graduate School, Pukyong National University

January 2016

A Study on the Dynamical Mechanism of Meteorological Factors in Multi-analyses

A dissertation

By

Seongkyu Seo

Approved by:

____

(Chairman: Ki-Ho Chang)

____

(Baek-Jo Kim)

____

(Deok-Ho Ha)

____

Bu-Kyoung Kim)

____

(Kyungsik Kim)

January 11, 2016

다중분석에서 기상요소의 동역학기작에 관한 연구

부경대학교 대학원 물리학과

요약

한반도의 복잡한 지형에서 기상요소들의 지역 및 지형에 따른 동역학적 거동의 특성과 변동성을 살펴보기 위해 안동 및 평창지역, 그리고 낙동강 유역에서 임의의 연구지역(안동: 63*63격자, 평창: 51*51격자, 낙동강유역: 81*81격자)을 설정한 후 그 지역의 5년 동안 여름철 강수량, 최대풍속에 대해 멀티프랙탈 탈경향 변동분석을 실시하였다. 분석을 위한 보다 많은 지점의 시계열 자료를 확보하기 위해 각 지역의 연구지역 내 관측되고 있는 기상청 AWS 지점들의 자료를 기반으로 크리깅 기법을 이용하여 각 지역마다 1 km 간격의 관측되고 있지 않은 지점들(안동: 3,969개, 평창: 2,601개, 낙동강유역: 6,561개)의 시계열 자료를 생성한 후 멀티프랙탈 탈경향 변동분석을 실시하였다. 분석결과, 안동지역과 평창지역의 강수량에 대해서는 연강수량이 많은 지역으로 여름철에도 강수량이 많은 지역에서 멀티프랙탈 세기 $\Delta\alpha$가 강하게 나타났고, 낙동강 유역에서는 연강수량은 적지만 여름철에 강수가 집중되는 지역에 멀티프랙탈 세기 $\Delta\alpha$가 강하게 나타났다. 멀티프랙탈 세기 $\Delta\alpha$가 강하다는 것은 특이성 스펙트럼의 폭이 크다는 의미이기 때문에 변동성이 크다고 할 수 있다. 평창지역의 최대풍속은 동해안지역과 태백산맥 산악지역에서 멀티프랙탈 세기 $\Delta\alpha$가 강하게 나타났으며, 이러한 이류로 해안지역의 경우 해륙풍의 영향으로 풍속의 변화가 크고, 산악지역은 지형에 따른 산곡풍의 영향으로 풍속의 변화가 크게 나타나는 것으로 판단된다. 이와 같은 결과들은 신규 기상관측지점 설치 시 유용한 근거자료가 될 것으로 생각되며, 기존의 신규 관측지점 설치 방법으로 사용된 표준편차에 의한 방법과 비교해보았다. 비교 결과, 세 지역의 강우량에 대해서는 표준편차가 큰 지점과 멀티프랙탈 세기 $\Delta\alpha$가 큰 지점이 차이나 났으나, 평창지역의 최대풍속에서는 두 방법의 결과가 유사한 지역에 나타났다. 향후, 본 연구에 네트워크 이론을 추가하여 관측되고 있지 않은 지점들의 연결성을 살펴볼 생각이다. 네트워크 이론의 허브(hub)와 멀티프랙탈 세기 $\Delta\alpha$가 큰 지점, 그리고 표준편차가 큰 지점이 동일하다면, 그 지점이 최적의 신규 기상관측지점 설치 장소가 될 것으로 사료된다.

Contents

List of Tables

List of Figures

I. Introduction

1. Previous studies

The potential impact of complex systems has recently gained a great deal of interest and importance owing to new and practical computer-simulations for static and dynamical behavior (Peng et al, 1994; Koscielny-Bunde et al., 1998) in natural, social, engineering, and medical sciences. The methods and techniques used for complex systems have usefully contributed to research such as the intermittent nature of turbulence (McCauley, 1990), various financial time-series (Lim et al., 2007), wavelet transform approaches (Debbal and Bereksi-Reguig, 2007; Gallegati, 2008;), growing and non-growing networks (Barabasi and Albert, 1999; Goh et al., 2002; Song et al., 2005) atmospheric phenomena of the climate change, seismic phenomena (Abe and Suzuki, 2006) etc.

Among network theories, interesting subjects are small-world and scale-free networks (Barabasi and Albert, 1999; Kim and Jeong, 2005) that have led to many new insights into complex systems (Kong et al., 2009; Yook et al., 2010; Baek et al., 2012). During the last two decades, have witnessed much effort and progress with efficient network theory for complex systems, as well as several practical attempts in simulating and analyzing the complex network of climate change. The climate of each nation is really caused by several statistical factors (Choi et al., 2009; Koo et al., 2009; Seo, 2009; Jung et al., 2010; Lee et al., 2010) such as rainfall, temperature, humidity, and wind speed. Atmospheric phenomenon on the Korean peninsula, which is surrounded by the East, Yellow, and South Seas, is known to be mainly associated with the air-sea interaction under the influence of its seas in diverse aspects (Jung et al., 2012).

Fractal is also one of the theories for insight into complex system. The French mathematician Mandelbrot introduced fractal concept for the first time through present of the article that "What is the total length of the coastline surrounding the United Kingdom?" in the Science is science magazine published in the United Kingdom (Mandelbrot, 1967). He explained about varied coastline depending on measuring ruler, and pointed out that is a limit to explain the irregular natural phenomena with the classical Euclidean geometry. Furthermore, introduced the fractal as a new tool to explain and understand the natural phenomena.

After the pioneering work of Mandelbrot (Mandelbrot, 1983) many investigations have extended to find a fractal nature in scientific models, such as the coast line, mountains, ocean tomography, cloud drifts, rainfall, deposition model, and so on. So what is the fractal? The meaning of the fractal is a shape, which the small structure in the whole structure repeating infinitely as similar form to the whole structure. That is, as a recurring structure, it has the infinitely repeating properties over self-similarity is to have similar structure with the whole even extract any part. In other words, fractal is which shapes have a self-similarity and self-circularity. For example, Rias shoreline of nature, distribution of animal blood, branch shape, riming on the window and the appearance of mountains has the fractal structure. Finally, in terms of macroscopic, it is not too much to say that all of universe has the fractal structure.

The fractal term was made in the word named fractional dimensions because the fractal structure is fractional dimensions. The usual fractal shapes were divided in monofractal and multifractal considering global dimensions and regional dimensions. If the global dimensions correspond with the regional dimensions, is called the monofractal, and is called the multifractal if correspond with the global dimensions of overall dimensions when each regional dimensions were summed, although the global dimensions and regional dimensions are slightly different.

The multifractal structure is to be each other dimension in the specific system, and dynamics of the system can be described by meeting of various fractal dimensions. The multifractal was mentioned in the study on the turbulent of Mandelbrot for the first time (Mandelbrot, 1974). Mandelbrot studied about various targets such as price fluctuation, income distribution, statistics of phone message error, and statistics of word frequency using fractal models in 1984 (Mandelbrot, 1984). In the statistics physics, established statistical methods were used as a useful tool to investigate various system, and the multifractal format was a technique widely used for determining the probability of fractal scales in these technical methods. Most of the complex systems are consist of many factors have a number of scale exponent, and it can see the multifractal dimensions that look at the overall exponent after these combined. Therefore, the fractal structure of basic dynamics was indicated a generalized dimensions over the statistical description. In other words, the dimensions calculated by fractal structure were indicated by the feature of special dynamics though fractal structure in the phase space of dynamics system. A numerical analysis of fractal was more improved with development of computer, and have been able to be applied to many more models accurately and strictly though calculation using computer.

For over three decades, there has been extensive interest in many models of multifractal structures in scientific fields such as physics, biology, engineering, sociology and medicine (Vicsek, 1992; Bunde and Havlin, 1996; Stanley et al., 1999). It is certainly worthwhile to study a variety of real systems extending from fractals (Mandelbrot, 1983; Barnsley, 1988; Mandelbrot, 1998) to the multifractals (Paladin and Vulpiani, 1987) and to reveal a more complicated structure of universal classes in order to understand their essential structure and natural property. Although analyzing and understanding the elements of particular natural systems is not easy, the mathematical and statistical approaches for the modeling and simulation of natural systems have led to the field of intensive multifractal research. The investigation of multifractals has been to the present a topic of interdisciplinary research and has been presented a formidable challenge. Multifractals are widely believed to possess, intrinsically and numerically, distributions of the singularities of the scaling exponents of interwoven sets of varying fractal dimensions. Until now, the multifractal formalism using the box-counting method has been represented in terms of its generalized dimension and scaling exponent. Many methods and techniques to analyze and simulate multifractals have recently been applied to many ways. However, incorporating some universal behaviors in the scaling mechanism of multifractals is still difficult

(Martinez et al., 1998).

The multifractal property of stochastic elements is based on the assumption for the process of meteorological variables can be modeled as a stochastic turbulent cascade process (Grassberger and Procaccia, 1984). The cascade process in fully developed turbulence is well known to describe a breaking-up of eddies into smaller sub-eddies in terms of energy dissipation (Parisi and Fricsh, 1985). The multifractal formalism (Paladin and Vulpiani, 1987; Vicsek, 1988) is a widely useful technique for the delineation of fractal scaling properties in non-stationary time series. Complicated systems that consist of components with many interwoven fractal subsets of the time series have a multitude of scaling exponents. The generalized dimension and spectrum are introduced in order to extract the dynamic characteristics from the fractal structure in the phase space of a dynamical system (Muzy et al., 1991).

The multifractal detrended fluctuation analysis is one of the main analysis tools for detecting and analyzing fractal scaling properties in non-stationary time series. This analysis is considered as an extension of the conventional detrended fluctuation analysis (Hu et al., 2001), which is a scaling analysis technique for a non-stationary time series (Tessier et al., 1993; Tessier et al., 1998; Jiang and Zhou, 2008). Several published papers (Ivanova et al., 2000; Talkner and Weber, 2000;

Kantelhardt et al., 2002) have recently proposed an alternative approach based on a generalization of the detrended fluctuation analysis method. The alternative approach was basically devised for the analysis of non-stationary time series by incorporating with a detrending procedure.

Since the considerable attention (Lee and Lee, 2007; Lee et al., 2008; Kim et al., 2008; Kim, 2009) has focused on the fractal nature, several studies have unanimously indicated the presence of a fractal nature and the possibility of multi-scaling in atmospheric phenomena. The application of ideas from fractal and chaos theories are to characterize rainfall in one of the most active and exciting areas of research. Many studies performed thus far have yielded evidence for the existence of fractal and chaos properties in rainfall. Kim et al. (2008) presented a multifractal spectrum for a rainfall time series to provide strong evidence for multifractality. Lee et al. (2009) investigated the multifractal property of the rainfall in seven cities of Korea. They mainly estimated the generalized Hurst exponent, the Renyi exponent, and the multifractal spectrum for the tick data of the rainfall, and discussed recent findings that suggest the scaling exponents characterizing the rainfall's multifractality. Lim et al. (2013) used a detrended cross-correlation analysis method to investigate the dynamical behaviors of the time series for the temperature and the humidity. This study noticed that the value of the cross-correlation between the air temperature and the relative humidity could be quantified by way of a detrended cross-correlation analysis in eight cities around the Korean peninsula.

2. Purpose of this study

In previous studies, we confirmed that can be found multifractal property in atmospheric phenomena. Although studies looking for long-term correlation in time series of meteorological factors were much (Zhang et al., 2015; Baranowski et al., 2015), studies looking for volatility (or multifractal) strength in time series of meteorological factors were not much. Thus, we try to identify dynamical behavior and volatility of meteorological factors through analyzing of time series of various meteorological factors in particular area using the multifractal detrended fluctuation analysis which is main analysis tools for detecting and analyzing fractal scaling properties in non-stationary time series. In this paper, our study purpose is three depending on the study area.

First purpose is to study the dynamical behavior and volatility strength of rainfalls in the Andong area on the Korean peninsula. Data for the volatility analysis are time series data on the summertime rainfall for five years. The method is simulated from the automatic weather system data of ten stations by using the ordinary kriging interpolation (Lang, 1995; Goovaerts et al., 2005; Simbahan et al., 2006). We analyze the time series data of stations without automatic weather system by using the simulated multifractal detrended fluctuation analysis.

Second purpose is to investigate the dynamical behaviors of two meteorological factors, rainfall and wind speed, in the Pyeongchang region of the Korean peninsula. Pyeongchang, where the 2018 Winter Olympics is scheduled to take place, is the valuable region for simulating and analyzing meteorological predictors. With the observations of the weather volatilities and the stochastic properties at Pyeongchang, this area has established itself as an important one for establishing and operating new automatic weather stations in future. Because of this intuitive importance, we were able to conduct this study after we had selected Pyeongchang as an example of a complicated region. The data for the analysis of the volatile and the chaotic properties are the time series for two meteorological factors during summer for five years from January 2006 to December 2010. The computer simulations were carried out on the basis of the automatic weather system data from twelve stations via the ordinary kriging interpolation (Lang, 1995;

Tonkin and Larson, 2002). We analyze the multifractal strength of non-observing stations without an automatic weather system by using a multifractal detrended fluctuation analysis.

Our last purpose is to examine the dynamical behaviors and volatility strength of rainfall in the Nakdong River basin, nearby areas using the multifractal detrended fluctuation analysis. The data for volatility analysis are time series data on the summertime rainfall during 5 years (2005-2009). We obtained the values of non-observing stations using the ordinary kriging based on nineteen observing stations of KMA (Korea Meteorological Administration). Then, we analyzed the multifractal strength of non-observing stations using the multifractal detrended fluctuation analysis.

One novel viewpoint of the kriging interpolation is to analyze the relation between the kriging interpolation and the multifractal detrended fluctuation analysis as a theoretical background. The kriging interpolation is known to be a powerful tool that may be applied to variation analyses of meteorological factors. The kriging interpolation method can be calculated as some important properties of its weights and variance. Hence, the analyzed method of the kriging interpolation can be applied in several scientific fields by other researchers (Goovaerts et al., 2005). Furthermore, we apply this interpolation to the calculation of meteorological factors (rainfall and maximum wind speed, etc) for stations without an automatic weather system in the Pyeongchang region, Andong region, and Nakdong River basin of the Korean peninsula.

II. Theoretical methods

1. Multifractal Detrended Fluctuation Analysis

We focus on the multifractal strength via the multifractal detrended fluctuation analysis of the time series of the meteorological factors such as rainfall and wind speed in the climate change. The multifractal detrended fluctuation analysis is as follows. Firstly, the difference of the meteorological factor between time t and $t+\tau$ is defined by $x_i(\tau)=S_i(t+\tau)-S_i(t),\ i=1,\ldots,N$, where $S_i(t)$ is the i-th meteorological factor at time t. For the time series of the meteorological factor N, the profile $Y(i)$ is defined by

$$Y(i)=\sum_{k=1}^{i}[x_k-<x>],\quad i=1,\ldots,N, \tag{1}$$

where $x_k\left(=x_k(\tau)\right)$ is the k-the time series for the difference between two meteorological factors and $x_k-<x>$ is the deviation for the difference of two meteorological factors.

The variances are given by

$$F^2(v,s)=\frac{1}{s}\sum_{i=1}^{s}\left\{Y\left[(v-1)s+1\right]-y_v(i)\right\}^2 \quad (2)$$

and

$$F^2(v,s)=\frac{1}{s}\sum_{i=1}^{s}\left\{Y\left[N-(v-N_s)s+i\right]-y_v(i)\right\}, \quad (3)$$

where $Y_v(i)$ is the fitting polynomial described by the local trend, and s is the number of time series, and $v=1,\ldots,N_s$ for each segment of the game v. $N_s\equiv \mathrm{int}(N/s)$ is the number of segments with size s over a time series, and N is the length of the meteorological factor series. The length N of the time series is often not a multiple of the time scale s, *i.e.*, $N=N_s s+N'$. In order to include the information contained in the remaining part N', after the time series is split into N_s intervals of length s starting from the front in Eq. (2), we split the time series into N_s intervals of length s starting from the back in Eq. (3). In order to scan the degree of contribution of a certain segment with size s to fluctuations of a time series, we define the q-the order fluctuation function as

$$F_q(s) \equiv \left\{ \frac{1}{2N_s} \sum_{v=1}^{2N_s} \left[F^2(v,s) \right]^{q/2} \right\}^{1/q} \quad s^{h(q)}, \tag{4}$$

where $h(q)$ is called the generalized Hurst exponent. When $q = 2$, this is the Hurst exponent describing the rainfall and wind speed feature of the time series.

The relation between the Renyi exponent τ_q (Kantelhardt et al., 2002) and the generalized Hurst exponent h_q is analytically obtained as

$$\tau_q = qh_q - 1. \tag{5}$$

The Lipschitz-Hoelder exponent α_q (Benbachir and Alaoui, 2011) is related to the singularity spectrum f_α (Lim et al., 2007) as

$$\alpha_q = h_q + qdh_q / d_q \tag{6}$$

and

$$f_\alpha = q\left[\alpha_q - h_q\right] + 1 \tag{7}$$

via a Legendre transform, where the partition function Z_β scales as ω^{τ_β}, and ω and β mean the length unit and the order, respectively. τ^β is known as the Renyi exponent (Lim et al., 2007). The generalized dimension D_q is defined as

$$D_q = \tau_q / (q-1) = (qh_q - 1)/(q-1), \tag{8}$$

which is used interchangeably with the Renyi exponent.

The multifractal strength $\Delta\alpha$ (Lee et al., 2010) can be quantified by using the difference between the maximum and the minimum values of α_q, which is given by

$$\Delta\alpha = \alpha_{\max} - \alpha_{\min}, \tag{9}$$

where $\Delta\alpha$ is an important parameter describing the width of the multifractal spectrum in the meteorological factor. The larger the $\Delta\alpha$ is, the stronger the multifractality is. Hence, for the time series of the meteorological factor, we can estimate the multifractal strength in terms of the range of α_q in order to identify the multifractal properties of the meteorological factor.

2. Kriging interpolation

Interpolation is a method used when estimate value of non-observing point from observation value obtained by experiments and measurements or find the function value does not exist in the function table of the table of logarithms, etc. Kriging is known as the optimal method of interpolation method (Journel and Huijbregts, 1978). The kriging based on geographic statistics was developed by the French mathematician Georges Matheron based on the Master's thesis of Daniel Gerhardus Krige. Currently, kriging has been used in the geographic statistics as well as in the various fields of environmental science (Bayraktar and Turalioglu, 2005), hydrology (Tonkin and Larson, 2002), the mining industry (Journel and Huijbregts, 1978; Richmond, 2003), natural resource (Emery, 2005), remote sensing (Kerry and Hawick, 1998), etc.

2.1. The concept of kriging interpolation

It is impossible actually that find the value of all the points to want due to the many restrictions exist in reality. Nevertheless, in many studies, it estimate value of non-observing point based on values of observing point exist actually using interpolation method such as kriging to know value of which point can't observe actually. The accuracy of kriging interpolation is high, because can know that they both are well matched if compare actual observation values and estimated values by kriging interpolation (Lang, 1995).

As kriging is one of linear least squares algorithms, it is a weighted linear combination to find value of non-observing point with weighted value according to distance between multiple observing points and non-observing point. It can be expressed by a formula as follows.

$$Z_0^* = Z^*(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i) \qquad (10)$$

where λ_i is a weighted value of x_i point, Z_0^* is an estimated value of x_0, d_i is a distance between x_i and x_0, N is the number of sample values used that estimate the value of non-observing point. The aim of kriging is to minimize error value is called kriging variance in the estimation procedure.

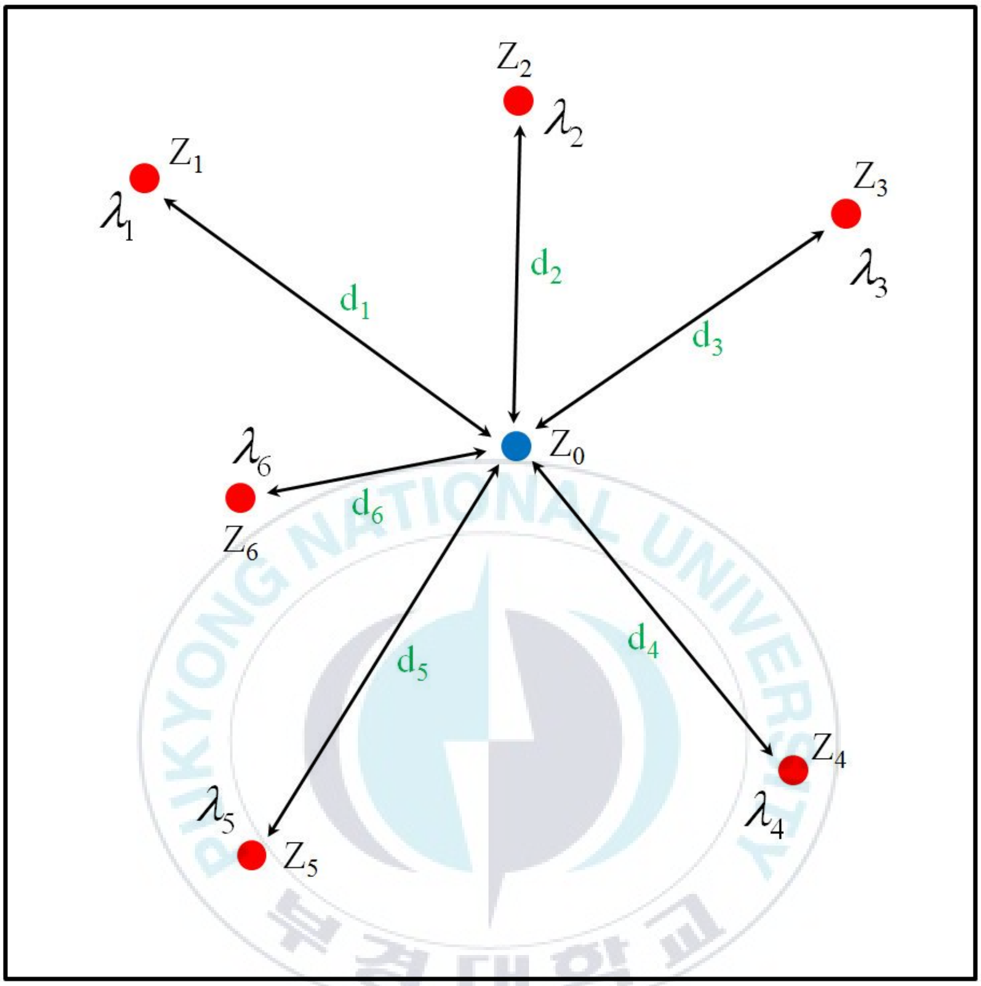


Figure 1: The kriging interpolation to estimate the value of non-observing point.

$$Var(Z_0^*) = E\left[(Z_0^*(x_0) - Z(x_0))^2\right] = 2\sum_{i=1}^{N}\lambda_i\gamma(x_i, x_0) - \sum_{i=1}^{N}\lambda_i\lambda_j\gamma(x_i, x_j) \quad (11)$$

where, assuming a non-biased condition, is presented as follows.

$$E\left[Z^*(x_0) - Z(x_0)\right] = \sum_{i=1}^{N}\lambda_i\mu(x_i) - \mu(x_0) = 0 \quad (12)$$

As Eq. (1) is an equation present the kriging procedure, the weighted value is the key of this equation. Kriging type varies with method yield the weighted value.

The kriging interpolation allows one to tackle problems of making estimates for unsampled locations. The kriging algorithm accounts for data solely being continuously estimated and for incorporating secondary information. From the linear regression paradigm, three of its most important variants are the simple kriging, the ordinary kriging, and the kriging with a trend model. The multivariate collocated cokriging primarily describes several parameters, including the height correction. However, the kriging interpolation method can be used to calculate as some important properties such as weights and variances. The ordinary kriging interpolation (Simbahan et al., 2006) is one of the methods with the least errors among various interpolations, and it interpolates known sample data in the light of the distance and the degree of change. We apply this interpolation to the calculation of the meteorological factors for stations without automatic weather system. Ordinary kriging is the most typical type of kriging types, and it was applied to this paper. The detailed content of ordinary kriging will be described in section 2.3.

2.2. Variogram

Before a description of the ordinary kriging, it will be described first on the concept of variogram required to calculate weighted value of the ordinary kriging. The variogram or semivariogram is a space-dependent function of semivariance. As the semivariances to present the spatial dependence degree among sample points, is a half of variance among all points located at a certain place. It can be presented by the following formula.

$$\gamma(h) = \frac{1}{2N_h}\sum_{i=1}^{N_h}(Z_i - Z_{i+h})^2 \tag{13}$$

where, Z_i is an observation value of i point, Z_{i+h} is an observation value of point separated by h from i, and N_h is the number of points having a h distance of all points.

Semivariance is decreased when distance between two point is the shorter, is increased when distance between two points is the longer, but it does not increase infinitely. Semivariance can be calculated by a generally used spherical model of variogram models. Formula is:

$$\gamma(h) = \begin{cases} C_0 + C_1\left(1.5\dfrac{h}{\alpha} - 0.5\left(\dfrac{h}{\alpha}\right)^3\right) & if\ |h| \le \alpha \\ C_0 + C_1 & if\ |h| > 0 \end{cases} \tag{14}$$

where, a distance between any observation point x_i and x_j is $h = x_j - x_i$, $C_0 + C_1$ is the maximum value of semivariance, a is the distance represented the maximum value of semivariance. Figure 1 is to be represented the variogram using the spherical model. As C_0 is called the nugget effect, is to represent the change of smallest size or measuring error, and is the variance in $h = 0$. The sill is a sum of $C_0 + C_1$, is a maximum value of semivariance, and a is a distance yielded the maximum value of semivariance. Thus, the variogram represented using model or solving formula is used when calculate the weighted value in the ordinary kriging will be described to next.

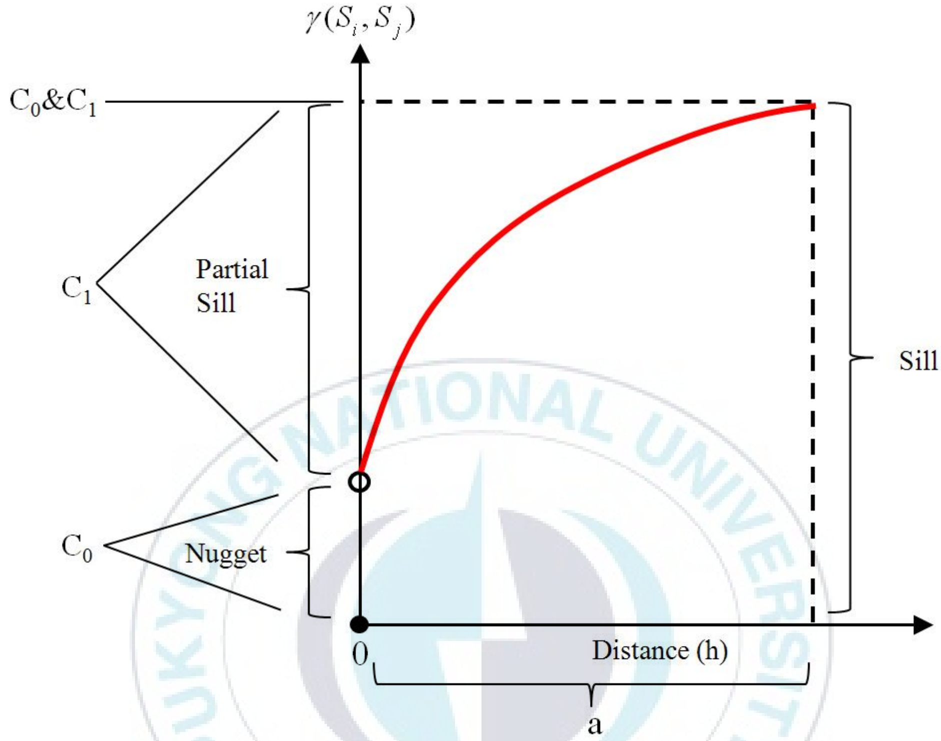


Figure 2: The variogram is represented using spherical model.

2.3. Ordinary kriging

Kriging varies a form of kriging application depending on stochastic characteristics of random field. Accordingly, the type of kriging decides the linear constraints on the weighted value represented depending on non-biased conditions. That is, it is that the linear constraints present in the method to calculate the weighted value depending on the type of kriging. The type of kriging is various, but will be described the most commonly used ordinary kriging in this paper.

Two kinds of typical assumption as following are required in the ordinary kriging process.

(1) It is assumed that parameters of points used in the ordinary kriging are stable.

(2) Enough observation point should be to estimate the variogram or semivariogram.

And, it should be two kinds of mathematical conditions to apply the ordinary kriging additionally.

(1) Average $E\left[Z(x)\right]=\mu$ is a unknown, but is a constant.

(2) Variogram $\gamma(x,y)=E\left[\left(Z(x)-Z(y)\right)^2\right]$ is a known of $Z(x)$.

The weighted value of the ordinary kriging must be satisfied non-biased conditions to minimize kriging errors is called kriging variance. The formula to calculate the weighted value is as follows.

$$\begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \mu \end{pmatrix} = \begin{pmatrix} \gamma(x_1, x_1) & \cdots & \gamma(x_1, x_n) & 1 \\ \vdots & \ddots & \vdots & \vdots \\ \gamma(x_n, x_1) & \cdots & \gamma(x_n, x_n) & 1 \\ 1 & \cdots & 1 & 0 \end{pmatrix}^{-1} \begin{pmatrix} \gamma(x_1, x^*) \\ \vdots \\ \gamma(x_n, x^*) \\ 1 \end{pmatrix} \tag{15}$$

where additional parameter μ is a Lagrange multiplier that used to minimization of kriging variance $\sigma_k^2(x)$ to satisfy non-biased conditions. Applying the weighted value obtained though these process to the ordinary kriging, it can be represented as follows.

$$\hat{Z}(x^*) = \begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_n \end{pmatrix}' \begin{pmatrix} Z(x_1) \\ \vdots \\ Z(x_n) \end{pmatrix} \tag{16}$$

It can be obtained the estimated value of specific point using Eq. 16, and the kriging variance can be obtained using the following equation.

$$Var\left(\hat{Z}(x^*) - Z(x^*)\right) = \begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \mu \end{pmatrix}' \begin{pmatrix} \gamma(x_1, x^*) \\ \vdots \\ \gamma(x_n, x^*) \\ 1 \end{pmatrix} \tag{17}$$

III. Results

1. Andong region

As non-observing stations, we choose 63-by-63 (3,969) stations in the Andong region of the Korean peninsula in order to use the measured rainfalls. The data that used for the volatility analysis are hourly time series of the summertime rainfall of Andong area for five years from Jan 2005 to Dec 2009 from the ten stations with existing automatic weather system. We produced time series data of 3,969 stations without automatic weather systems using the ordinary kriging interpolation, and analyzed the time series data of 3,969 stations using the multifractal detrended fluctuation analysis. We identified the 40 high-ranked stations from the multifractal strength $\Delta\alpha$, which indicates the intensity of multifractals.

Figure 3 is a contour plot of the rainfall calculated by using the ordinary kriging interpolation on the 15th July of 2009 for 63-by-63 (3,969) stations without automatic weather systems. The color bar on the right side represents the height, where the unit is meters above sea level.

Figure 4 show the 40 high-ranked stations without automatic weather systems that were obtained from the values of the multifractal strength $\Delta\alpha$ by using the multifractal detrended fluctuation analysis. Here, the blue squares denote the 40 high-ranked stations with strong multifractal strength, and the red circles denote the 10 stations with automatic weather systems. The values of non-observing stations were obtained by an ordinary kriging interpolation based on data from the actual 10 stations with automatic weather systems. Table 1 summarizes the specific values of the multifractal strength for the 10 stations without automatic weather systems to show how great the values of high-ranked stations are.

Most of the 40 high-ranked stations are distributing at the upstream area of Nakdong River. By the actual observing stations, it was confirmed that the annual precipitation of that area belong to the many side. We think that is likely to the multifractal strength of many annual precipitation area is greater than small annual precipitation area. To be the greater multifractal strength, mean that singularity spectrum is greater, that is, it may be said that rainfall volatility is great. Therefore, it is proper to establish a new automatic weather station at a location observing a large rainfall change.

Figure 5 show that the 40 high-ranked stations have a value of high standard deviation among 3,969 non-observing stations for rainfall. Generally, when install a new observation, it installed as a grid or installed by using standard deviation analysis represent dispersion degree of observation variable. In figure 5, the high-ranked stations of standard deviation analysis are distributed at the mountainous area of the north, unlike the results of multifractal detrended fluctuation analysis are distributed at the many rainfall area. So, we think that the multifractal detrended fluctuation analysis show better the distribution of rainfall in the Andong region during the study period than the standard deviation analysis, and also think which it suggest an additional observation station better.

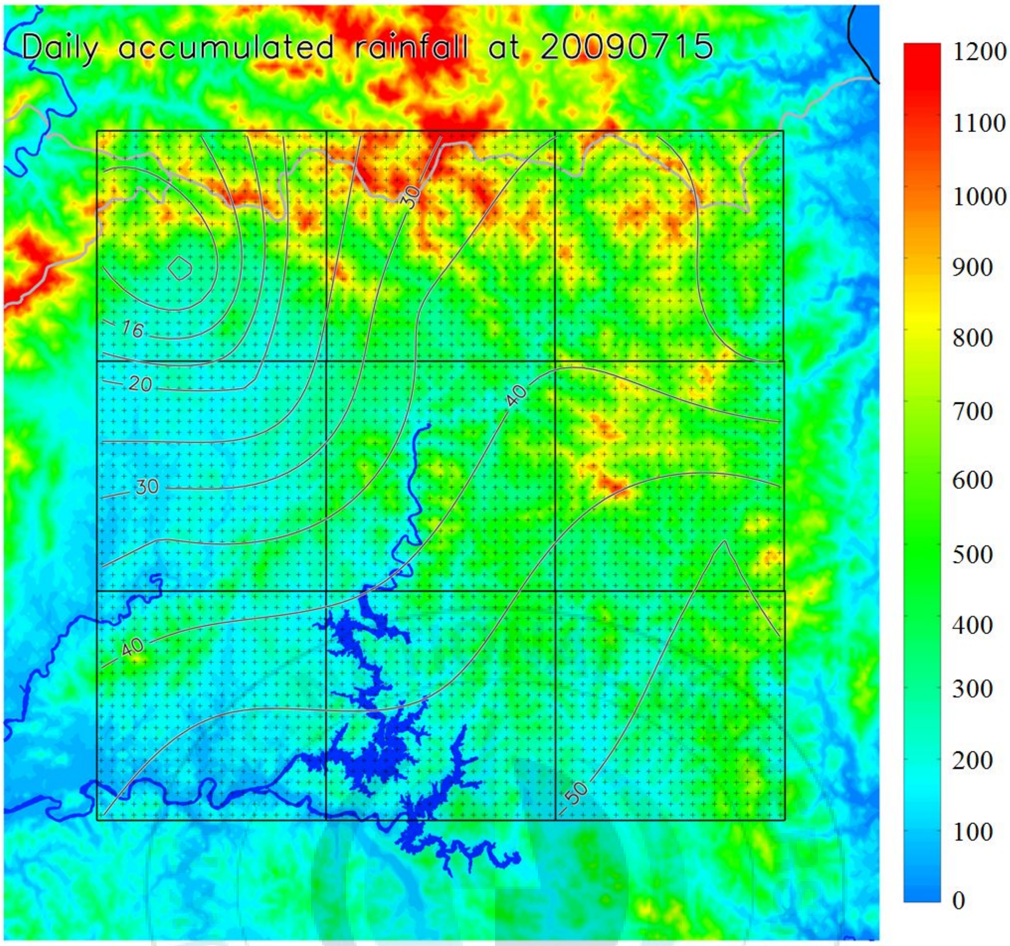


Figure 3: Contour plot of 63-by-63 (3,969) non-observing stations without automatic weather system for the rainfall calculated by using the ordinary kriging interpolation on the 15th July of 2009. The color bar on the right side denotes the height, where the unit is meters above sea level.

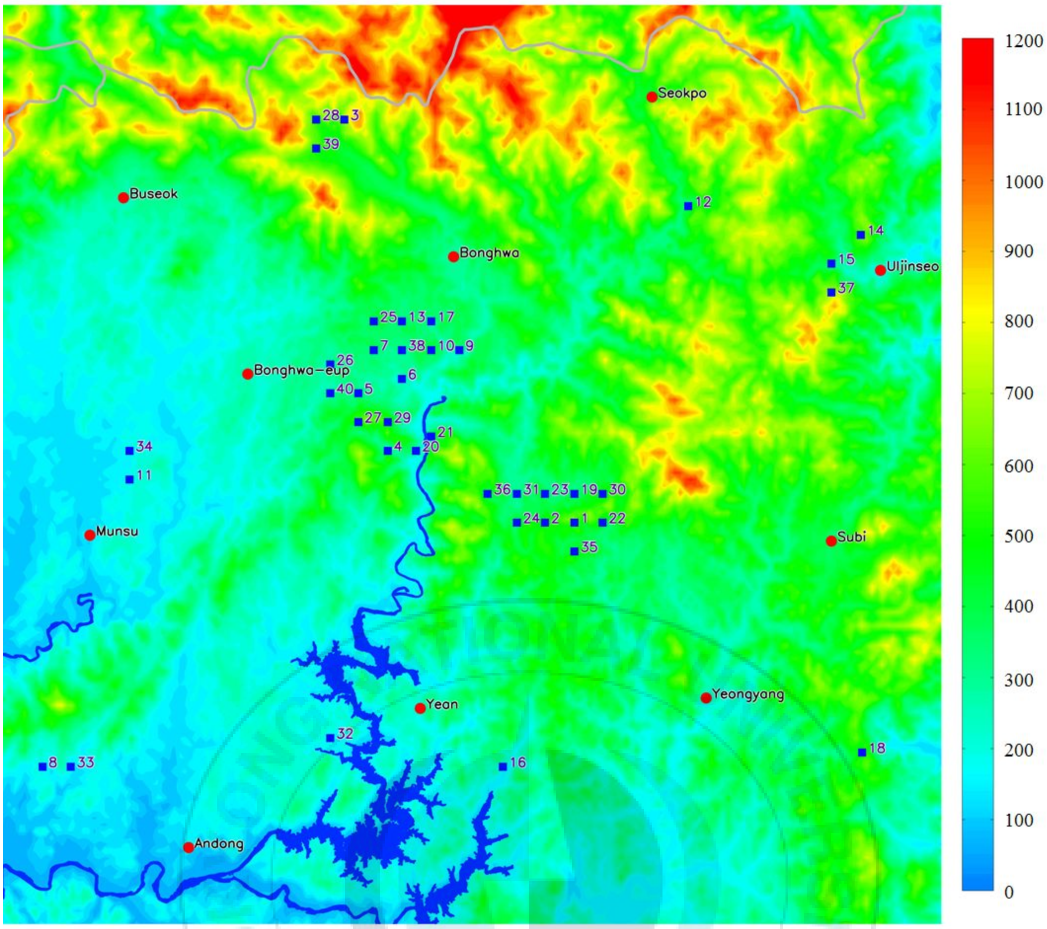


Figure 4: Plot of 40 high-ranked stations (blue squares) obtained from the multifractal strength $\Delta\alpha$ by using a multifractal detrended fluctuation analysis, where the red circles denote the 10 stations with the automatic weather system.

Table 1: Values of the multifractal strength $\Delta\alpha$ of the 10 high-ranked stations.

Number	Latitude	Longitude	$\Delta\alpha$
1	36.77710	129.00900	3.743
2	36.77710	128.98600	3.399
3	37.02940	128.82900	3.388
4	36.82210	128.86300	3.111
5	36.85820	128.84000	3.019
6	36.86720	128.87400	3.016
7	36.88520	128.85200	2.994
8	36.62380	128.59300	2.952
9	36.88520	128.91900	2.938
10	36.88520	128.89700	2.929

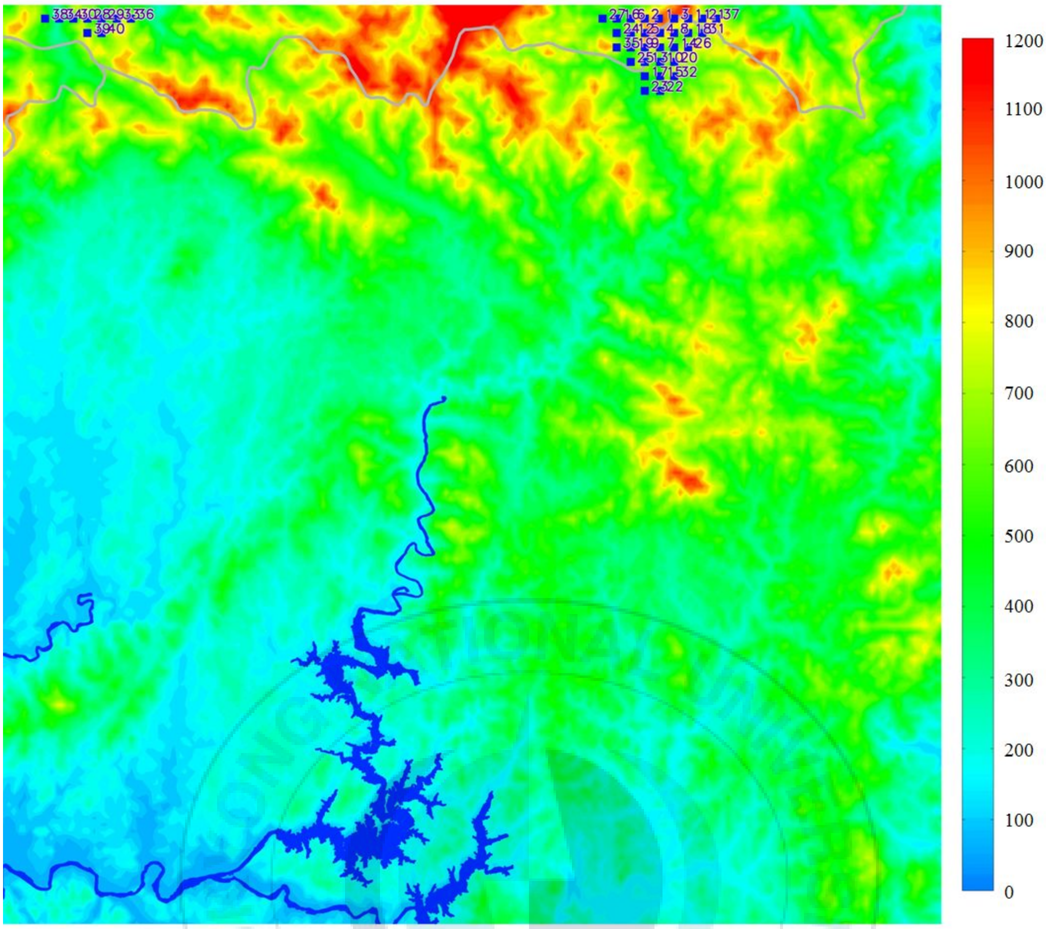


Figure 5: Plot of 40 high-ranked stations (blue squares) have a high value among 3,969 non-observing stations using the standard deviation analysis.

2. Pyeongchang region

In order to use the measurements of two meteorological factors, that is, rainfall and maximum wind speed, our model consist of 51-by-51 (2,601) non-observing stations in the Pyeongchang region of the Korean peninsula. Interpolations are made to areal grid of 1 km of latitude by 1 km of longitude. This lattice is chosen as a compromise between the computational efficiency and the accurate spatial depiction. The Pyeongchang region that we restrict our analyses to the two meteorological variables locates on the most eastern region of Korea, with an area of approximately 2,500 km^2.

The multifractal detrended fluctuation analysis is manipulated for rainfalls and maximum wind speeds recorded at automatic weather systems for the volatile and chaotic volatility analyses in Pyeongchang region. The data that we used for our analysis are hourly time series of the summertime rainfall and wind speed for five years from Jan 2005 to Dec 2009 from the ten stations with existing automatic weather system.

We execute the two-folded simulations and analyses as follows. Firstly, we analyze time series data of 2,601 stations using the ordinary kriging interpolation. Secondly, using the multifractal detrended fluctuation analysis, we identify the 40 high-ranked stations from the multifractal strength $\Delta\alpha$, which indicates the intensity of multifractals.

Figure 5 is the plot of the 12 stations with the automatic weather system in the complex area of Pyeongchang provided by the Korean meteorological administration.

Figure 6 is the plots of rainfall and maximum wind speed calculated by using the ordinary kriging interpolation for 51-by-51 non-observing stations without automatic weather systems. The color bar on the right side represents the height, where the unit is meters above the sea levels.

Figure 7 shows the 40 high-ranked rainfall and wind speed stations without an automatic weather system, which are obtained from values of the multifractal strength $\Delta\alpha$ by using the multifractal detrended fluctuation analysis. Table 2 also summarizes the values of the multifractal strength $\Delta\alpha$ at the 40 high-ranked stations without an automatic weather system.

For the rainfall of two meteorological factors, when the rainfall volatility for all the non-observing stations without automatic weather system is considered in the Pyeongchang region, the high-ranked stations are almost intensively distributed in the eastern area of Taebaek Mountains. As this area has the many annual precipitation usually, it is well known that a lot of snowfall in wintertime, and even a lot of rainfall are distributed in summertime by the Foehn wind. Therefore, we think that the rainfall volatility is greater in the area of higher precipitation as result equal to the result of Andong region.

Furthermore, we found the forty stations on the multifractal strength $\Delta\alpha$ of maximum wind speed using the multifractal detrended fluctuation analysis. The 20 high-ranked stations in the Pyeongchang region are distributed in the mountainous area over 600 m or on the slopes of mountainous area, while the 20 high-ranked are mostly concentrated in low altitude area near the east coast. In particular, the first high-ranked station is located on the slopes of mountainous area, while the second high-ranked station is located at the low area near the east coast.

For why the strong multifractal strength represent in the mountainous area or on the slopes of mountainous area, we think because the mountain and valley wind is one of local wind which appeared in the mountainous area. Generally, wind speed of valley wind blowing from valley to ridge during the day is stronger than mountain wind blowing from ridge to valley during the night. In particular, valley wind becomes stronger by wind caused by temperature difference between Taebaek Mountains and east coast in early summer. Also, because the strength of mountain and valley wind differs depending on terrain, multifractal strength may be stronger in specific terrain. And, for why the strong multifractal strength represent near the east coast, we think because the land and sea wind mainly appeared in the coastal area. The sea wind blowing from sea to land during the day is stronger than the land wind blowing from land to sea during the night. That reason is because the temperature difference between land and sea is small during the night and the surface friction affect in the land wind. Also, the wind speed difference between land wind and sea wind becomes larger because sea wind makes stronger the seasonal wind blowing to land occasionally. Therefore, the multifractal strength within time series may be greater by these wind speed differences between land wind and sea wind.

Figure 9 show that the 40 high-ranked stations have a value of high standard deviation among 2,601 non-observing stations for rainfall, maximum wind speed. In case of rainfall, all of high-ranked stations are gathered at the western area. By using the Takbaek Mountains as a standard, the Youngseo region of Taebaek Mountain west gathered the high-ranked stations of standard deviation have less rainfall than the Youngdong region of Taebaek Mountains east gathered the high-ranked of multifractal detrended fluctuation analysis. Therefore, we may be identified that many areas of rainfall have the stronger multifractal strength such as result of Andong region. In case of maximum wind speed, the high-ranked stations of standard deviation analysis are distributed the Daegwallyeong and Guryongnyeong included in the Taebaek Mountains. This result is similar to the result of multifractal detrended fluctuation analysis. Because both of two locations is the mountainous area, are affected by the mountain and valley wind. In particular, the Daegwallyeong placed the first and second high-ranked stations has the stronger wind speed than different area during the windy day, because of topographical feature placed between two ridges. Therefore, we may be identified that the maximum wind speed is affected many by topography and the location of higher volatility have the greater dispersion degree of data even.

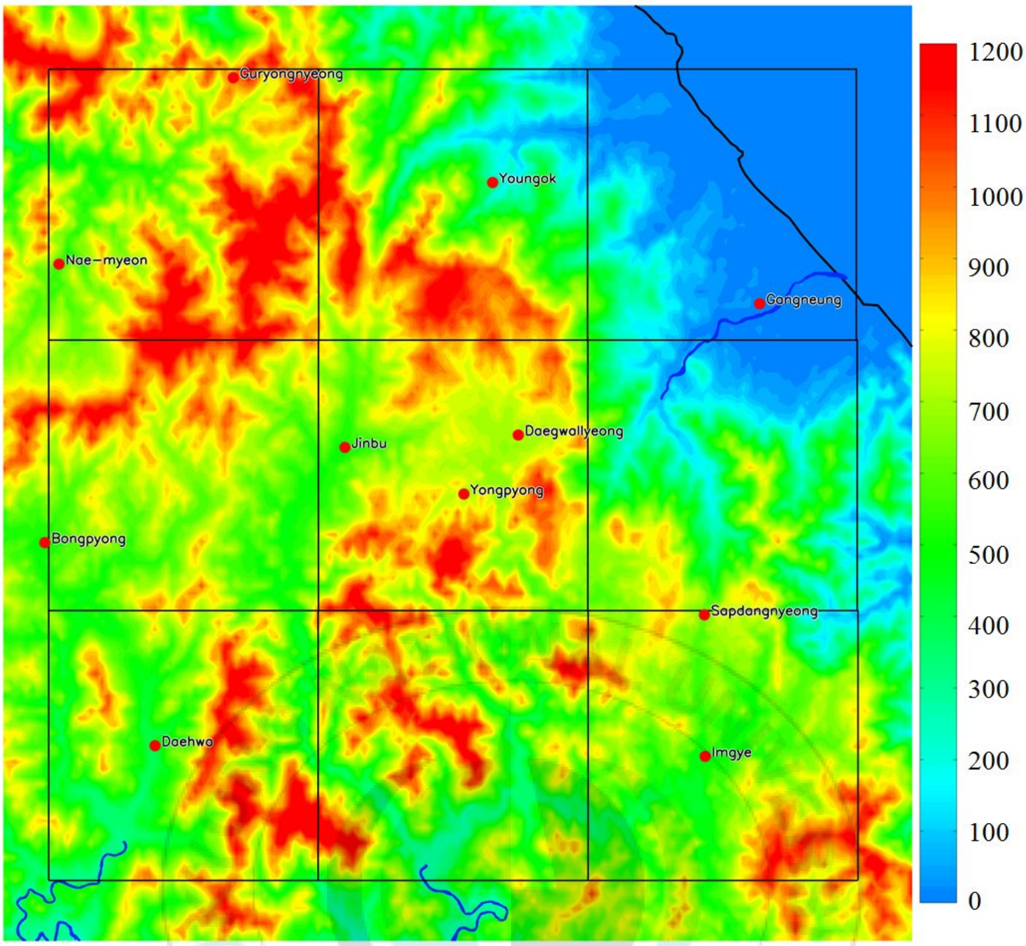
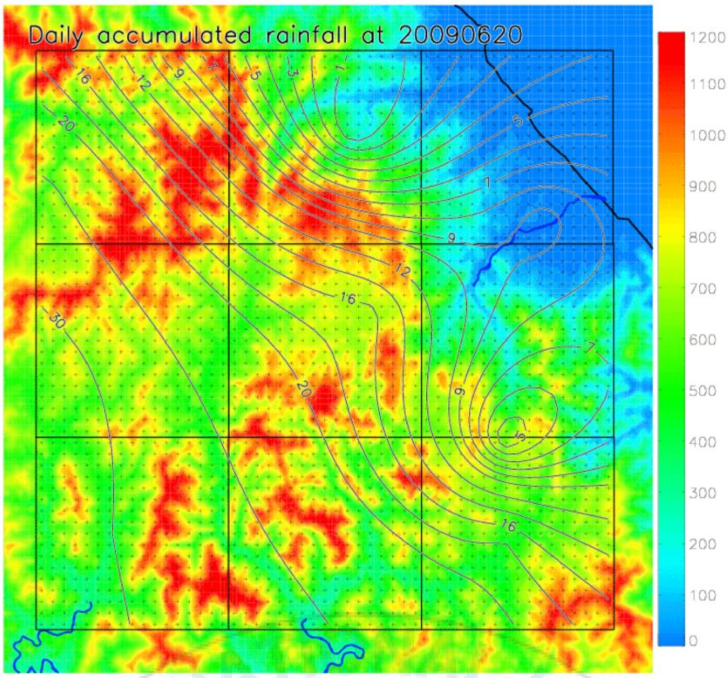


Figure 6: Plot of the twelve stations with the automatic weather system in the complex region.



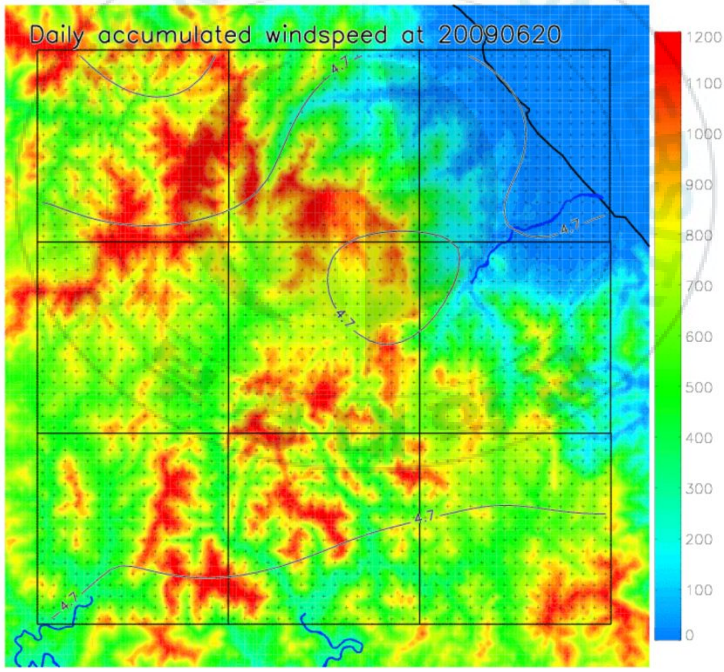


Figure 7: contour plot of the 51-by-51 non-observing stations without an automatic weather system for the rainfall (top) and the wind speed (down) on the 20th June of 2009 in the Pyeongchang region considered in this work.

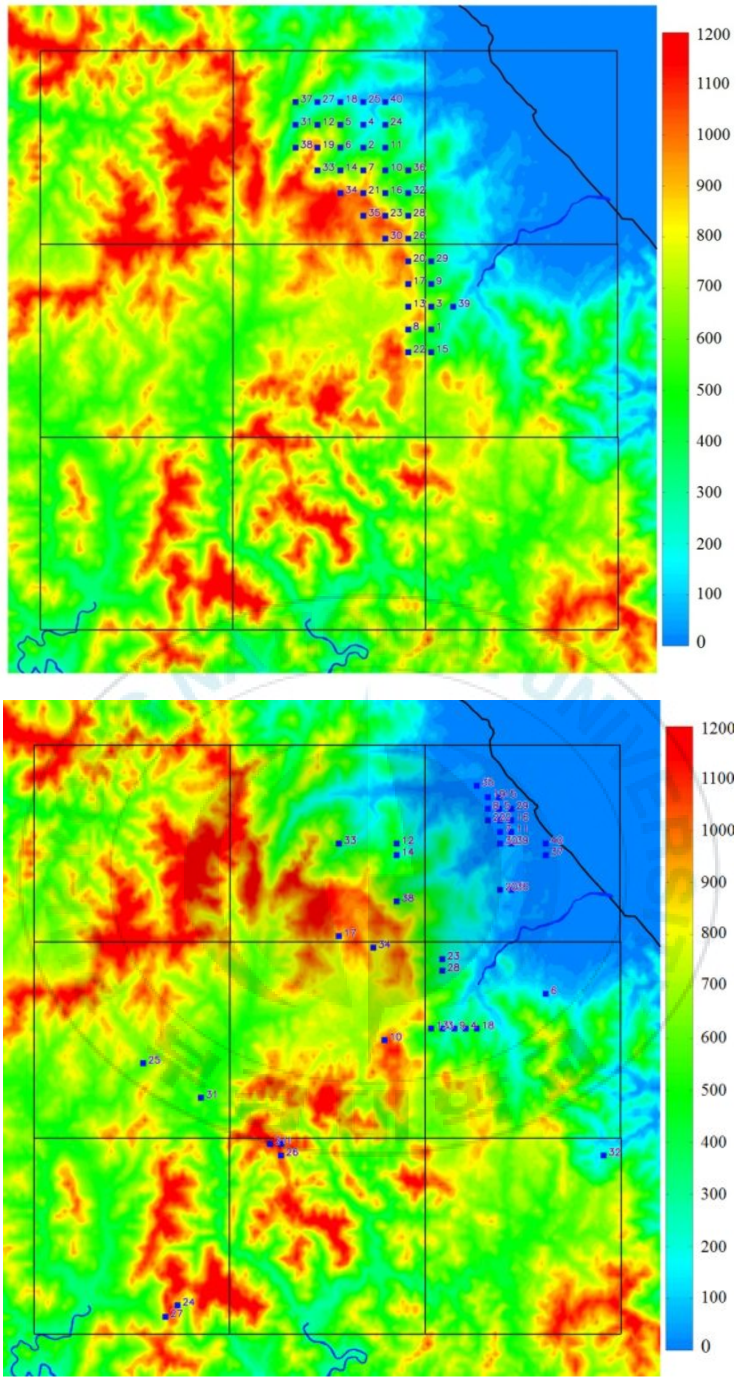


Fig. 8: Plot of the 40 high-ranked stations (blue squares) obtained from the multifractal strength $\Delta\alpha$ of the rainfall (top) and the wind speed (down) by using a multifractal detrended fluctuation analysis.

Table 2: Values of the multifractal strength $\Delta\alpha$ of the rainfall (top) and the wind speed (down) at the 40 high-ranked stations.

rank	Latitude	Longitude	$\Delta\alpha$
1	37.66320	128.77400	1.7385
2	37.80740	128.70600	1.7378
3	37.68130	128.77400	1.7276
4	37.82550	128.70600	1.7257
5	37.82550	128.68300	1.7172
6	37.80740	128.68300	1.7131
7	37.78940	128.70600	1.6947
8	37.66320	128.75100	1.6702
9	37.69930	128.77400	1.6684
10	37.78940	128.72800	1.6661
11	37.80740	128.72800	1.6649
12	37.82550	128.66000	1.6595
13	37.68130	128.75100	1.6555
14	37.78940	128.68300	1.6546
15	37.64520	128.77400	1.6540
16	37.77140	128.72800	1.6531
17	37.69930	128.75100	1.6491
18	37.84350	128.68300	1.6438
19	37.80740	128.66000	1.6437
20	37.71730	128.75100	1.6423
21	37.77140	128.70600	1.6422
22	37.64520	128.75100	1.6380
23	37.75340	128.72800	1.6315
24	37.82550	128.72800	1.6305
25	37.84350	128.70600	1.6275
26	37.73530	128.75100	1.6273
27	37.84350	128.66000	1.6185
28	37.75340	128.75100	1.6093
29	37.71730	128.77400	1.6066
30	37.73530	128.72800	1.6007

31	37.82550	128.63800	1.5932
32	37.77140	128.75100	1.5927
33	37.78940	128.66000	1.5864
34	37.77140	128.68300	1.5858
35	37.75340	128.70600	1.5852
36	37.78940	128.75100	1.5773
37	37.84350	128.63800	1.5732
38	37.80740	128.63800	1.5685
39	37.68130	128.79600	1.5666
40	37.84350	128.72800	1.5646

rank	Latitude	Longitude	$\Delta\alpha$
1	37.57310	128.62600	1.88103
2	37.82550	128.84200	1.85894
3	37.66320	128.78500	1.75017
4	37.66320	128.80800	1.70333
5	37.83450	128.84100	1.67053
6	37.69030	128.88700	1.61985
7	37.81650	128.84200	1.55391
8	37.83450	128.83000	1.54051
9	37.66320	128.79700	1.53561
10	37.65420	128.72800	1.52035
11	37.81650	128.85300	1.51302
12	37.80740	128.74000	1.50556
13	37.66320	128.77400	1.50091
14	37.79840	128.74000	1.49337
15	37.84350	128.84100	1.49168
16	37.82550	128.85300	1.49153
17	37.73530	128.68300	1.48126
18	37.66320	128.81900	1.47498
19	37.84350	128.83000	1.46817
20	37.77140	128.84200	1.46251

21	37.57310	128.61500	1.46193
22	37.82550	128.83000	1.45749
23	37.71730	128.78500	1.45302
24	37.44690	128.52400	1.45036
25	37.63620	128.49000	1.44640
26	37.56410	128.62600	1.44045
27	37.43790	128.51200	1.44034
28	37.70830	128.78500	1.43472
29	37.83450	128.85300	1.42375
30	37.80740	128.84200	1.41117
31	37.60920	128.54700	1.40479
32	37.56410	128.94400	1.40478
33	37.80740	128.68300	1.40241
34	37.72630	128.71700	1.40140
35	37.85250	128.81900	1.39930
36	37.77140	128.85300	1.39683
37	37.79840	128.88700	1.39545
38	37.76240	128.74000	1.38821
39	37.80740	128.85300	1.38718
40	37.80740	128.88700	1.38617

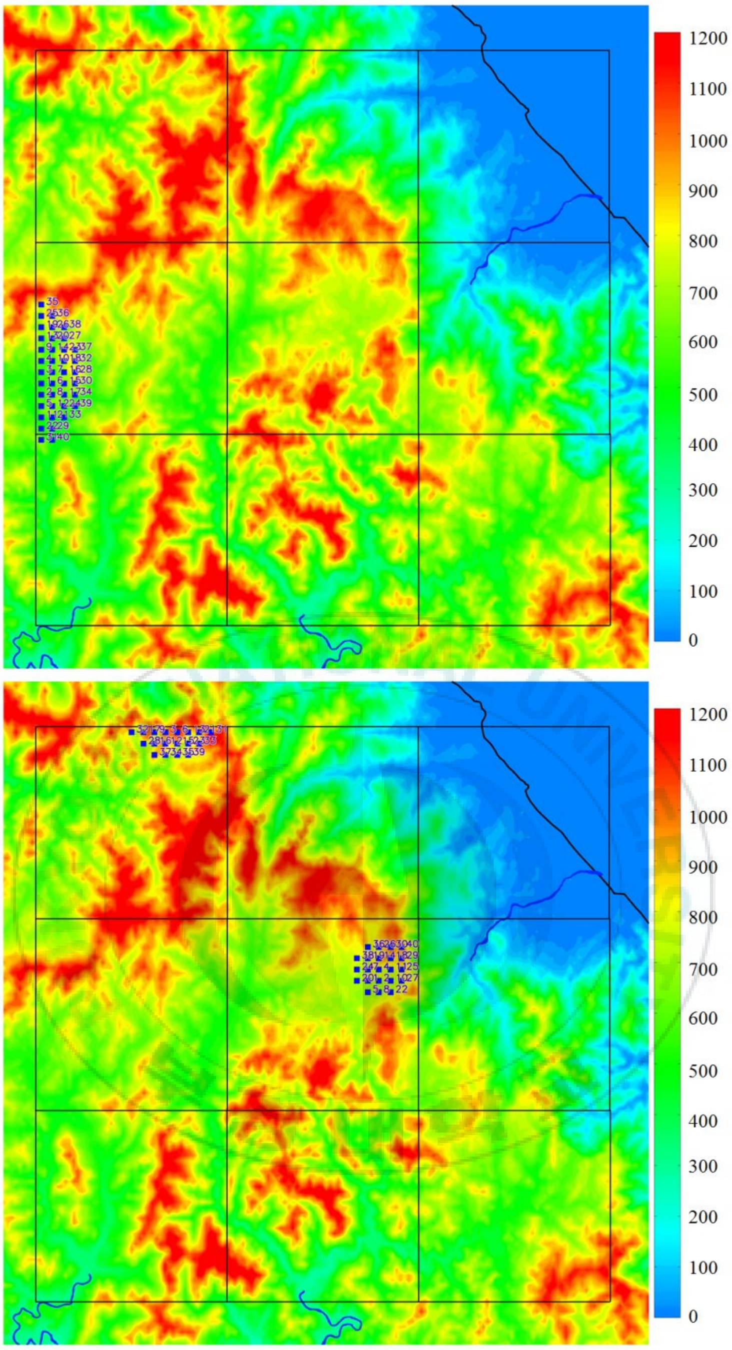


Fig. 9: Plot of the 40 high-ranked stations (blue squares) have a high value among 2,601 non-observing stations using the standard deviation analysis for rainfall (top) and maximum wind speed (bottom).

3. Nakdong River basin

To investigate the volatility of rainfalls in the Nakdong River basin and nearby regions, we set up a grid of width 81 km and length 81km. Data of actual observing 19 stations of KMA (Korea Meteorological Administration) were used to produce time series data of 81-by-81 (6,561) non-observing stations with 1 km distance. The data is the rainfalls of summertime during 5 year from 2005 to 2009. As in the preceding analysis, we produced time series data of 6,561 non-observing stations using the ordinary kriging based on 19 observing stations. The more actual observing stations applied to the interpolation, the accuracy of ordinary kriging increase. Thus, the interpolation values of Nakdong River basin will be close to actual value than the previous two regions.

Figure 10 shows locations of the 19 observing stations in the Nakdong River basin and nearby regions provided by the Korea meteorological administration. The color bar on the right side represents the height, where the unit is meters above the sea levels.

Figure 11 is the contour plots of rainfall calculated by using the ordinary kriging interpolation for 81-by-81 non-observing stations at 1 June 2005. The small cross point is the interpolated non-observing station. It was conducted interpolation using ordinary kriging for each 460 days of summertime during 5 years, thus each of 6,561 non-observing stations were have the time series data of 460 days.

Figure 12 show the 60 high-ranked stations without automatic weather systems that were obtained from the values of the multifractal strength $\Delta\alpha$ by using the multifractal detrended fluctuation analysis. If represented 40 high-ranked stations equal to different study area, we thought that found out the significance representing the area because of the Nakdong River basin is wider area than different study area. So, we represented 60 high-ranked stations in the Nakdong River basin. Here, the red circles display 60 high-ranked stations. Many of the 60 high-ranked stations are gathered in the Daegu metropolitan, plains of northeast area, and Nakdong River basin of north area. Gyeongsangbuk-do Province included the three areas is the region of lower precipitation typically. However, a common of the three areas placed high-ranked stations is that 60% of the annual precipitation is concentrated in the summertime. So, may be said that those areas were the areas of higher precipitation during the study period, because of used data of summertime during 5 years (2005-2009). Therefore, as result equal to the results of previous two study region, may be indentified that the area of strong multifractal strength is the higher precipitation area.

Table 3 also summarizes the values of the multifractal strength $\Delta\alpha$ at the 60 high-ranked non-observing stations.

Figure 13 show that the 60 high-ranked stations have a value of high standard deviation among 6,561 non-observing stations for rainfall. Those stations are concentrated at the end of south area in the figure. To be concentrated those stations in the area of lower precipitation, we think that rainfall of the area during the study period is very dispersed by irregular localized heavy rain and drought, but is needed an additional study about this result.

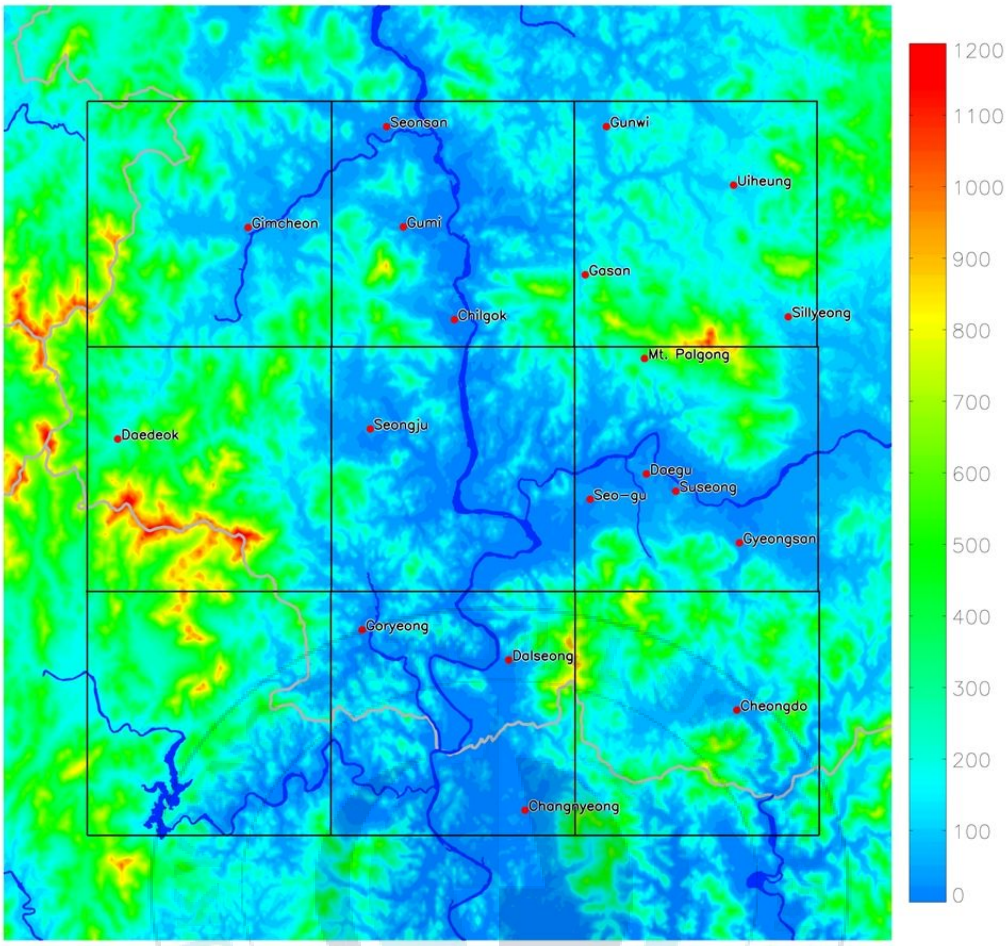


Figure 10: Plot of the 19 observing stations of KMA used for kriging interpolation of the Nakdong River basin.

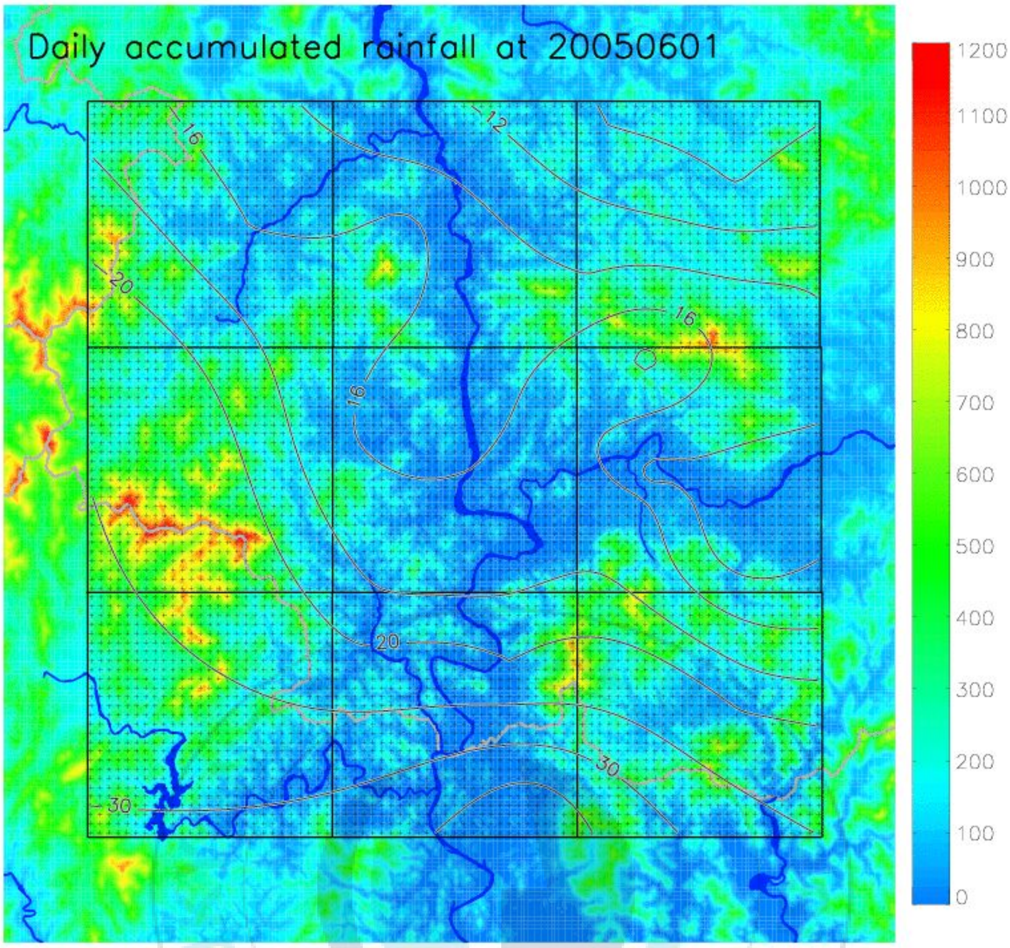


Figure 11: Contour plot of 81-by-81 (6,561) non-observing stations obtained by kriging interpolation for the rainfall of 1 June 2005. Small cross points are the non-observing stations.

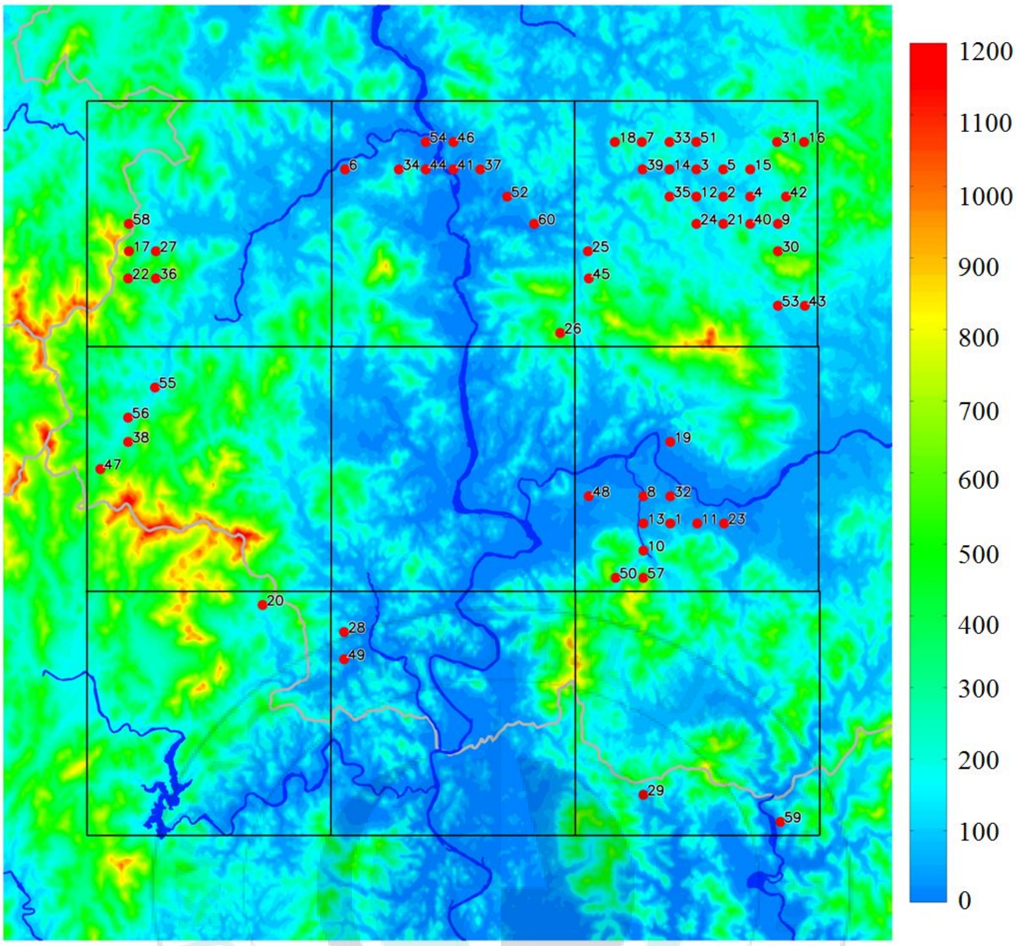


Figure 12: Plot of the 60 high-ranked stations (red circles) obtained from the multifractal strength $\Delta\alpha$ of the rainfall by using a multifractal detrended fluctuation analysis.

Table 3: Values of the multifractal strength $\Delta\alpha$ of the rainfall at the 60 high-ranked stations.

Rank	Latitude	Longitude	$\Delta\alpha$
1	35.83590	128.64800	3.9032
2	36.16040	128.71300	3.7151
3	36.18740	128.68000	3.5211
4	36.16040	128.74600	3.3436
5	36.18740	128.71300	3.3162
6	36.18740	128.24900	3.1813
7	36.21450	128.61300	3.1220
8	35.86300	128.61500	3.1154
9	36.13340	128.78000	3.0824
10	35.80890	128.61500	3.0648
11	35.83590	128.68100	3.0434
12	36.16040	128.68000	3.0313
13	35.83590	128.61500	3.0208
14	36.18740	128.64700	2.9948
15	36.18740	128.74600	2.9906
16	36.21450	128.81200	2.9627
17	36.10630	127.98400	2.9533
18	36.21450	128.58000	2.9244
19	35.91700	128.64800	2.8832
20	35.75480	128.14800	2.8811
21	36.13340	128.71300	2.8767
22	36.07930	127.98300	2.8430
23	35.83590	128.71400	2.8203
24	36.13340	128.68000	2.7986
25	36.10630	128.54700	2.7927
26	36.02520	128.51300	2.7829
27	36.10630	128.01700	2.7687
28	35.72780	128.24800	2.7609
29	35.56550	128.61500	2.7569
30	36.10630	128.78000	2.7501

31	36.21450	128.77900	2.7487
32	35.86300	128.64800	2.7354
33	36.21450	128.64700	2.7328
34	36.18740	128.31500	2.7300
35	36.16040	128.64700	2.7160
36	36.07930	128.01700	2.7048
37	36.18740	128.41500	2.7004
38	35.91700	127.98300	2.6936
39	36.18740	128.61400	2.6898
40	36.13340	128.74600	2.6897
41	36.18740	128.38200	2.6684
42	36.16040	128.77900	2.6548
43	36.05220	128.81300	2.6512
44	36.18740	128.34800	2.6502
45	36.07930	128.54800	2.6498
46	36.21450	128.38200	2.6351
47	35.89000	127.94900	2.6341
48	35.86300	128.54800	2.6196
49	35.70070	128.24800	2.6013
50	35.78180	128.58100	2.5993
51	36.21450	128.68000	2.5957
52	36.16040	128.44800	2.5875
53	36.05220	128.78000	2.5820
54	36.21450	128.34800	2.5732
55	35.97110	128.01600	2.5715
56	35.94410	127.98300	2.5661
57	35.78180	128.61500	2.5652
58	36.13340	127.98400	2.5646
59	35.53850	128.78300	2.5604
60	36.13340	128.48100	2.5560

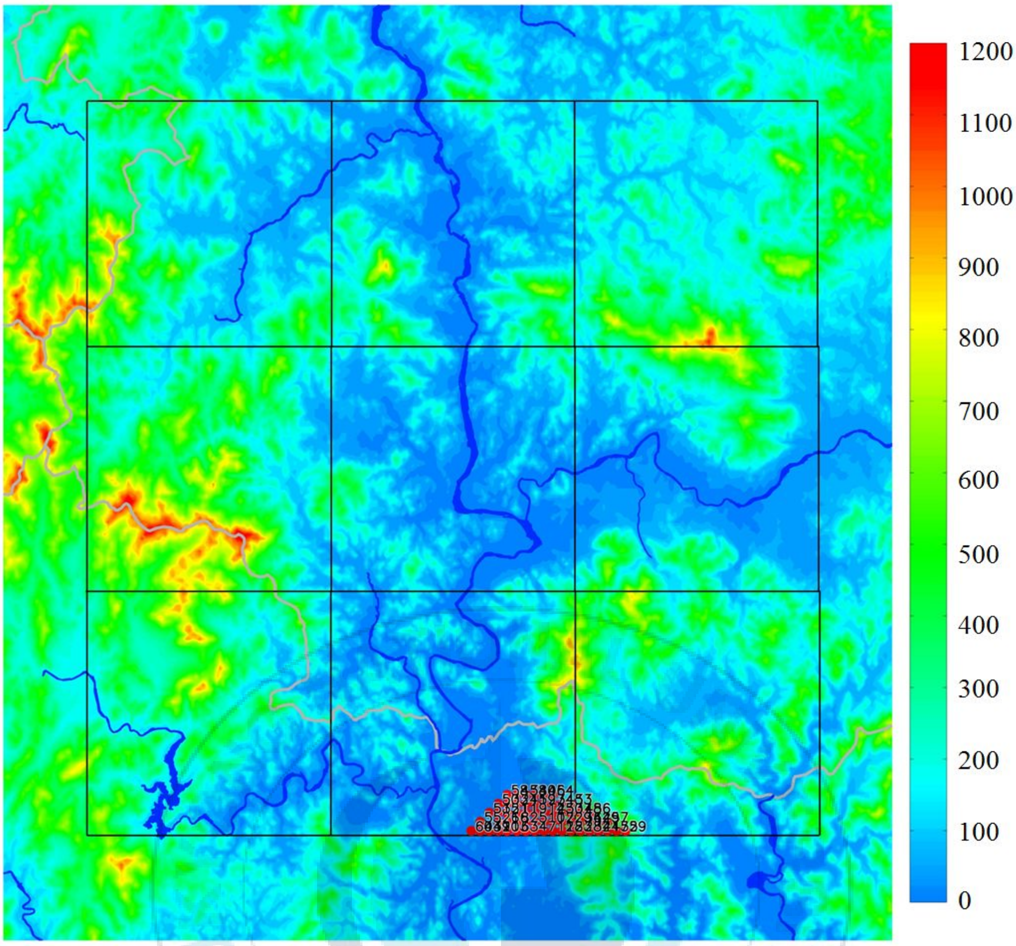


Figure 13: Plot of the 60 high-ranked stations (red circles) have a high value among 6,561 non-observing stations using the standard deviation analysis.

IV. Summary and conclusions

We have studied the multifractal features of rainfalls for the summer season in the Andong area of the Korean peninsula. We found the 10 stations (among the 40 stations) based on the multifractal strength $\Delta\alpha$ of rainfalls obtained by using a multifractal detrended fluctuation analysis, as shown in Figure 4. The larger the value of the multifractal strength $\Delta\alpha$ is, the stronger the observing multifractal property is (or the more its volatility changes). When the rainfall volatility for all the stations without automatic weather system is considered in the Andong area, the 10 high-ranked stations are found to be mostly concentrated in areas near Nakdong River upstream. The area placed 1st, 2nd, and 5th – 7th high-ranked stations have been well known that the localized heavy rainfalls is observed in the area year by year by automatic weather stations. Furthermore, if meteorological quantities are to be measured, our results should be particularly useful and effective in determining new automatic weather stations and establishing the meteorological apparatus.

According to increased correlation between meteorological variables and elevation, a much improved result may be obtained. We anticipate that our capability can be extended to a study of using the multivariate collocated cokriging to map meteorological variables for cases without automatic weather system.

For the sake of a more detailed investigation of the multifractality, we need to extend our research to other regions of our peninsular in the future. This multifractal detrended fluctuation analysis formalism can be extended to encompass both the discrimination and the characterization of rainfall, temperature, wind speed, and humidity.

We have ascertained the multifractal feature of rainfall and wind speed on the summer season (from January 2006 to December 2010) in the Pyeongchang region of Korean peninsula. Time series data of two meteorological factors for stations without an automatic weather system are obtained from those of other stations with automatic weather system via the ordinary kriging interpolation method (Seo et al., 2012; Seo et al., 2013).

As a main point of view, the larger the value of the multifractal strength $\Delta\alpha$ is, the more volatile its meteorological variable changes. This study leads to the major finding that our method may be useful and effective in order to determine and establish the locations of new automatic weather stations for meteorological factors in a complicated region. A much improved result may be obtained from our methods and techniques, according to the increase of the correlation between the meteorological variable and the geographical elevation.

In future, we will extend our capability to study the multivariate collocated cokriging in mapping of meteorological factors on the locations without an automatic weather system. For the sake of a more detailed investigation of the multifractal analysis, we need to extend our research to several meteorological factors of our peninsula and other nations in the future.

We studied on the multifractal feature or volatility of rainfall in the Nakdong River basin and nearby areas during 5 years (from 2005 to 2009). Used data for this study is time series data of rainfall on the summertime (from June to April) during 5 years. To estimate the multifractal feature of rainfall of more many stations within the study areas, we obtained 6,561 non-observing stations of 81-by-81 grid through interpolation by 1 km using ordinary kriging based on 19 actual observing stations, and analyzed the time series data of 6,561 non-observing stations using the multifractal detrended fluctuation analysis.

As the results of analysis, we found that the 60 high-ranked stations with a large multifractal strength $\Delta\alpha$ are distributed in Daegu metropolitan and in the northeast areas, which have lower altitude than Mt. Palgong. The results of this study leads to the principal conclusion that our method may be useful and effective in order to determine and establish the locations of new weather stations for meteorological factors in a complicated region.

As an additional study, we compared the results of multifractal detrended fluctuation analysis and standard deviation analysis. Both the results of the analysis methods were similar for the maximum wind speed of Pyeongchang region. Thus, may be said that is represented well a localized property of the maximum wind speed in Pyeongchang region. However, both the results of the analysis methods were different completely for the rainfall of three study areas. We think that the multifractal detrended fluctuation analysis is better method than the general standard deviation to establish a new weather station. Because, as well as the multifractal detrended fluctuation analysis may be found out the volatility strength of observation variable, also may be found out a pattern of it through detecting a long-term correlation of it unlike the standard deviation analysis find out just a dispersion degree of it.

In future, we need to extend our research to other regions of our peninsular, and will analyze more various meteorological factors. Also, we will apply the network theory in our research with the expansion of research range. Using the network theory, we can make up network based on non-observing stations obtained by kriging interpolation, and then can obtain hub station through getting connectivity of non-observing stations. Finally, if a hub station of network theory and a station of larger multifractal strength and a station of larger standard deviation are equal, that station is considered to be the best location for establishment of new meteorological station.

References

Abe, S., and N. Suzuki, 2006; Complex-network description of seismicity, *Nonlin. Processes Geophys.,* 13, 145-150.

Baek, W. H., G. Lim, K. Kim, Y.-J.Choi, K.-H.Chang, J.-W.Jung, M. Yi, D.-I.Lee and D.-H. Ha, 2012; Analysis of topological properties in a seismic network, *Physica A*, 391(6), 2279-2285.

Barabasi, A.-L.and R. Albert, 1999; Emergence of scaling in random networks, *Science*, 286(5439), 509-512.

Baranowski, P., J. Krzyszczak, C. Slawinski, H. Hoffmann, J. Kozyra, A. Nierobca, K. Siwek and A. Gluza, 2015; Multifractal analysis of meteorological time series to assess climate impacts, *Clim Res*, 65, 39-52.

Barnsley, M., 1988; Fractals everywhere, *Academic Press*.

Bayraktar, H., and F. S. Turalioglu, 2005; A Kriging-based approach for locating a sampling site - in the assessment of air quality, *Stochastic Environmental Research and Risk Assessment*, 19(4), 301-305.

Benbachir, S., and M. E. Alaoui, 2011; A multifractal detrended fluctuation analysis of the Moroccan Stock Exchange, *International Research Journal of Finance and Economics*, 78, 6-17.

Bunde, A., and S. Havlin, 1996; Farctals and disordered systems, *Springer*.

Choi, K.-S., D.-W.Kim and H.-R.Byun, 2009; Statistical model of seasonal prediction of tropical cyclone frequency around Korea, *Asia-Pac. J. Atmos. Sci.*, 45(1), 21-32.

Debbal, S. M. and F. Bereksi-Reguig, 2007; Time-frequency analysis of the first and the second heartbeat sounds, *Applied Mathematics and Computation*, 184(2), 1041-1052.

Emery, X., 2005; Simple and ordinary multigaussian kriging for estimating recoverable reserves, *Mathematical Geology*, 37(3), 295-319.

Gallegati, M., 2008; Wavelet analysis of stock returns and aggregate economic activity, *Computational Statistics & Data Analysis*, 52(6), 3061-3074

Goh, K.-I., E. Oh, H. Jeong, B. Kahng and D. Kim, 2002; Classification of scale-free networks, 99(20), *Proc. Nat. Acad. Sci. U.S.A.*,12583-12588.

Goovaerts, P., G. AvRuskin, J. Meliker, M. Slotnick, G. Jacquez and J. Nriagu, 2005; Geostatistical modeling of the spatial variability of arsenic in groundwater of southeast Michigan, *Water Resources Research*, 41(7).

Grassberger, P., and I. Procaccia, 1984; Dimensions and entropies of strange attractors from a fluctuating dynamics approach, *Physica D*, 13(1-2), 34-54.

Hu, K., P. Ch. Ivanov, Z. Chen, P. Carpena and H. E. Stanley, 2001; Effect of trends on detrended fluctuation analysis, *Phys. Rev. E*, 64, 011114.

Ivanova, K., M. Ausloos, E. E. Clothiaux and T. P. Ackerman, 2000; Break-up of stratus cloud structure predicted from non-Brownian motion liquid water and brightness temperature fluctuations, *Europhys. Lett.*, 52(1), 40.

Jiang, Z.-Q., and W.-X. Zhou, 2008; Multifractality in stock indexes: Fact or Fiction?, *Physica A*, 387(14), 3605-3614.

Journel, A. G., and Ch. J. Huijbregts, 1978; Mining Geo-statistics, *Academic Press*.

Jung, S. A., J. H. Jung, D.-I.Lee, J.-W.Jung, K.-H.Chang, D.-H. Ha, S. Y. Kim and K. Kim, 2010; Dynamical behavior in earthquake structures, *J. Korean Phys. Soc.,* 56(6), 1877-1879.

Jung, W. S., D.-I.Lee, Y.-J.Choi, K.-H.Chang, J.-W.Jung, S.-K.Seo, M. Yi and K. Kim, 2012; Analysis of the network mechanism for sea surface temperatures around the Korean Peninsula, *J. Korean Phys. Soc.,* 60(4), 566-569.

Kantelhardt, J. W., S. A. Zschiegner, E. Koscielny-Bunde, S. Havlin, A. Bunde and H. E. Stanley, 2002: Multifractal detrended fluctuation analysis of nonstationary time series, *Physica A*, 316(1-4), 87-114.

Kerry, K. E., and K. A. Hawick, 1998; Kriging interpolation on high-performance computers, *High-Performance Computing and Networking*, 429-438, Springer Berlin Heidelberg.

Kim, D.-H. and H. Jeong, 2005; Systematic analysis of group identification in stock markets, *Phys. Rev. E*, 72(4), 046133.

Kim, J. S., B. Kahng and D. Kim, 2008; Self-similarity in fractal and non-fractal networks, *J. Korean Phys. Soc.,* 52(2), 350-356.

Kim, S.-H., 2009; Transition temperature of a homogeneous and dilute Bose gas between two and three dimensions, *J. Korean Phys. Soc.,* 54(2), 809-811.

Kim, S. Y., G. Lim, K.-H.Chang, J.-W. Jung, K. Kim and C. H. Park, 2008; Multifractal analysis of rainfalls in Korean peninsula, *J. Korean Phys. Soc.,* 52(3), 669-672.

Kong, J., W. Seok, J. Lee and B. Kim, 2009; Designing a grid network resource management system for e-science applications, *J. Korean Phys. Soc.,* 55(5), 2248-2252.

Koo, M.-S., S.-Y. Hong and J. Kim, 2009; An evaluation of the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) data over South Korea, *Asia-Pac. J. Atmos. Sci.*, 45(3), 265-282.

Koscielny-Bunde, E., A. Bunde, S. Havlin, H. E. Roman, Y. Goldreich and HJ.Schellnhuber, 1998; Indication of a universal persistence law governing atmospheric variability, *Phys. Rev. Lett.,* 81(3), 729-732.

Lang, C., 1995; Kriging interpolation, *Department of Computer Science, Cornell University*.

Lee, D.-I., C.-H.You, S. Y. Kim, I.-H. Park and K. Kim, 2009; Dynamical importance of rainfall analysis in Korean cities, *J. Korean Phys. Soc.,* 55(6), 2344-2347.

Lee, D.-I., C.-H.You, J.-W.Jung, K.-H. Chang, S. Y. Kim and K. Kim, 2010; Multifractal structures in temperature and humidity, *J. Korean Phys. Soc.,* 57(2), 296-299.

Lee, K. E., and J. W. Lee, 2007; Scaling and multiscaling properties in the Korean stock market, *J. Korean Phys. Soc.,* 50(1), 178-181.

Lee, S.-G.and S. B. Lee, 2008; Nontrivial critical behavior of lattice models with a conserved field on a checkerboard fractal, *J. Korean Phys. Soc.,* 52, 209-215.

Lim, G., S. Y. Kim, H. Lee, K. Kim and D.-I.Lee, 2007; Multifractal detrended fluctuation analysis of derivative and spot markets, *Physica A*, 386(1), 259-266.

Mandelbrot, B. B., 1967; How long is the coast of Britain? Statistical self-similarity and fractional dimension, *Science*, 155, 636-638.

Mandelbrot, B. B., 1974; A population birth-and-mutation process, I: Explicit distributions for the number of mutants in an old culture of Bacteria*, Journal of Applied Probability*, 11(3), 437-444.

Mandelbrot, B. B., 1983; The fractal geometry of nature, Freeman Press, 1-450.

Mandelbrot, B. B., D. E. Passoja and A. P. Paullay, 1984; Fractal character of fracture surfaces of metals, *Nature*, 308, 721-722.

Mandelbrot, B. B., P. Pfeifer, O. Biham, O. Malcai, D. A. Lidar and D. Avnir, 1998; Is natural fractal?, *Science*, 279, 783.

Martinez, V. J., S. Paredes, S. Borgani and P. Cloes, 1998; Multiscaling properties of large-scale structure in the universe, *Science*, 269, 1245-1247.

McCauley, J. L., 1990; Introduction to multifractals in dynamical systems theory and fully developed fluid turbulence, *Phys. Rep.,* 189(5), Elsevier, 225-266.

Muzy, J. F., E. Bacry and A. Arneodo, 1991; Wavelets and multifractal formalism for singular signals: Application to turbulence data, *Phys. Rev. Lett.,* 67(25), 3515-3518.

Paladin, G., and A. Vulpiani, 1987; Anomalous scaling laws in multifractal objects, *Phys. Rep.*, 156(4), 147-225.

Parasi, G., and U. Frisch, 1985; in turbulence and predictability in geophysical fluid dynamics, ed. M. Ghil, R. Benzi and G. Parasi, North-Holland.

Peng, C.-K., S. V. Buldyrev, S. Havlin, M. Siomons, H. E. Stanley and A. L. Goldberger, 1994; Mosaic organization of DNA nucleotides, *Phys. Rev. E,*49(2), 1685-1689.

Richmond, A., 2003; Financially efficient ore selections incorporating grade uncertainty, *Mathematical Geology*, 35(2), 195-215.

Seo, E.-K., 2009; The uncertainty of background brightness temperatures in microwave land rainfall algorithm, *Asia-Pac. J. Atmos. Sci.*, 45(4), 463-472.

Seo, S. K., K. Kim, K.-H.Chang, Y,-J. Choi, K. Song and J.-K. Park, 2012: Determination of the dynamical behavior of rainfalls by using a

Multifractal detrended fluctuation analysis, *J. Korean Phys. Soc.*, 61(4), 658-661.

Seo, S. K., K. Kim, K.-H.Chang and J.-K. Park, 2013: Volatility analysis of rainfall, wind speed, and temperature by using the multifractal detrended fluctuation analysis, *New Physics*, 63(8), 872-881.

Simbahan, G. C., A. Dobermann, P. Goovaerts, J. Ping and M. L. Haddix, 2006, Fine-resolution mapping of soil organic carbon based on multivariate secondary data, *Geoderma*, 132(3-4), 471-489.

Song, C., S. Havlin and H.-A Makse, 2005; Self-similarity of complex networks, *Nature*, 433, 392-395.

Stanley, H. E., L. A. N. Amaral, A. L. Goldberger, S. Havlin, P. Ch. Ivanov and C.-K. Peng, 1999; Statistical physics and physiology: Monofractal and multifractal approaches, *Physica A*, 270(1-2), 309-324.

Talkner, P., and R. O. Weber, 2000; Power spectrum and detrended fluctuation analysis: Application to daily temperatures, *Phys. Rev. E*, 62, 150.

Tessier, Y., S. Lovejoy and D. Schertzer, 1993; Universal multifractals: Theory and observations for rain and clouds, *J. Appl. Meteor.,* 32(2), 223-250.

Tessier, Y., S. Lovejoy, P. Hubert, D. Schertzer and S. Pecknold, 1996; Multifractal analysis and modeling of rainfall and river flows and scaling, causal transfer functions, *Journal of geophysical research*, 101(21), 26427-26440.

Tonkin, M. J., and S. P. Larson, 2002; Kriging water levels with a regional-linear and point-logarithmic drift, *Groundwater*, 40(2), 185-193.

Yook, S.-H., Y.-K. Yun and Y. Kim, 2010; Biased random walk sampling on assortative Networks, *J. Korean Phys. Soc.*, 56(3), 990-993.

Vicsek, T, 1992; Fractal growth phenomena, *World Scientific*.

Zhang, C., Z. Ni and L. Ni, 2015;Multifractal detrended cross-correlation analysis between PM2.5 and meteorological factors, *Physica A*, 438, 114-123.