MAUSAM, **67**, 4 (October 2016), 849-860

551.577.3 : 551.579 (510)

The regional features of precipitation variation trends over Sichuan in China by the ESMD method

J. R. LEI, Z. H. LIU*, L. BAI**, Z. S. CHEN**, J. H. XU** and L. L. WANG***

Land and Resources College, China West Normal University, Nanchong Sichuan – 637 009, China

**School of Information Engineering, Nanchang Institute of Technology, Nanchang Jiangxi – 330 099, China*

***The Research Center for East-West Cooperation in China, The Key Lab of GI Science of the Education Ministry PRC, East China Normal University, Shanghai – 200 241, China*

****School of Science, Nanchang Institute of Technology, Nanchang Jiangxi – 330 099, China*

(*Received 15 September 2015, Accepted 10 December 2015*)

e mail : cundasha@126.com

सार – वर्ष 1961 से 2011 तक की अवधि में सिचुआन प्रांत में 49 मौसम वैज्ञानिक स्टेशनों से वर्षा समय श्रृंखला के आधार पर सुदूर-बिंदु सममित प्रणाली वियोजन पद्धति का उपयोग करते हुए वर्षा परिवर्तिता के बहुमान अभिलक्षणों का विश्लेषण किया गया। परिवर्तिता की प्रवृत्तियों में क्षेत्रीय भिन्नताओं और परिवर्तन बिंदुओं पर भी प्रारम्भिक तौर पर विचार-विमर्श किया गया। परिणामों से पता चला है कि पिछले 50 वर्षों में सिचुआन प्रांत में हुई कुल वर्षा में उल्लेखनीय रूप से अरैखिकीय अधोमुखी प्रवृत्ति दिखाई दी और इन परिवर्तनों से स्पष्ट रूप से अंतर-वार्षिक मान (अर्ध 3 और अर्ध 8 वर्ष) और अंतर दशकीय मान (अर्ध 13 वर्ष) का पता चला है। प्रत्येक घटक के परिवर्तनशील योगदान दरों से यह पता चला है कि अंतर वार्षिक परिवर्तन का सिचुआन प्रांत में कुल वर्षा परिवर्तन पर प्रबल प्रभाव रहा है और अध्ययन अवधि के दौरान पुनर्निमित अंतर वार्षिक परिवर्तिता प्रवृत्ति मूल रूप से वर्षा के उतार-चढ़ाव की स्थिति बता सकती है। पुनर्निमित अंतरदशकीय परिवर्तिता से पता चला है कि सिचुआन प्रांत में जलवायु पद्धति को परिसीमाओं के रूप में वर्ष 1973 और 1998 के साथ तीन अलग परिवर्तिता अवधियों में विभाजित किया गया। इसमें अरैखिकीय परिवर्तनों और वर्षा के परिवर्तन बिंदुओं में क्षेत्रीय भिन्नताएँ थी। इसके अतिरिक्त वृद्धि या कमी के अधिक या कम परिवर्तन के बीच संबंधों का अध्ययन करने और मौसम वैज्ञानिक स्टेशनों के भौगोलिक स्थिति (अक्षांश, देशांतर और तुंगता अर्थात) ESMD वियोजन के माध्यम से वर्षा के परिवर्तिता प्रवृत्ति घटको के सीधे कार्क रिंगिग अंतर्वेशन तकनीक प्रयुक्त की गई। इसी समय परिणामों से यह भी सुझाव मिला कि ESMD पद्धति विभिन्न समय मानों में दीर्घावधि वर्षा अनुक्रमों में प्रभावी रूप से परिवर्तिता प्रकट करती है और अरैखीय व अस्थिर सिग्नल परिवर्तनों के संयुक्त निदानों के लिए प्रयुक्त की जा सकती है।

ABSTRACT. Based on a precipitation time series from 49 meteorological stations in Sichuan Province during the period from 1961 to 2011, the multi-scale characteristics of precipitation variability are analyzed using the extreme-point symmetric mode decomposition method (ESMD). Regional differences in variation trends and change-points were also preliminarily discussed. The results indicated that in the last 50+ years, the overall precipitation in Sichuan Province has exhibited a significant non-linear downward trend, and its changes have clearly exhibited an inter-annual scale (quasi-3 and quasi-8-year) and interdecadal scale (quasi-13-year). The variance contribution rates of each component demonstrated that the inter-annual change had a strong influence on the overall precipitation change in Sichuan Province, and the reconstructed inter-annual variation trend could describe the fluctuation state of the original precipitation during the study period. The reconstructed interdecadal variability revealed that the climate mode in Sichuan Province had divided into three distinct variation periods with 1973 and 1998 as the boundaries. Furthermore, there were regional differences in the non-linear changes and change-points of precipitation. In addition, in order to study the relations between the changing more or less of rising or decrease and meteorological station's geographical position (latitude, longitude and elevation) *i.e.*, the Cokriging interpolation technique is applied directly to precipitation variation trend components through ESMD decomposition. At the same time, the results also suggested that the ESMD method can effectively reveal variations in long-term precipitation sequences at different time scales and can be used for the complex diagnosis of non-linear and non-stationary signal changes.

Key words – Sichuan province, Average annual precipitation, Extreme-point symmetric mode decomposition method (ESMD), Intrinsic mode function (IMF), Regional difference.

1. Introduction

With the growing impact of global warming on the environment and socio-economic development, climate change research has attracted broad attention from national government departments and the public (IPCC, 2007). In its latest report for 2013, the Intergovernmental Panel on Climate Change (IPCC) has noted that the average global temperature has increased by 0.85 °C (0.65-1.06 °C) and the annual average temperature from 2003-2012 increased by 0.78 °C relative to 1850-1900, a period of nearly 130 years (1880-2012), indicating that rapid global warming is an indisputable fact (IPCC, 2013). In the context of global warming, the temperature trend in China has also been on the rise, but the warming process is volatile with significant differences in time and space (Sun and Lin, 2007). Meanwhile, the mean annual precipitation has increased by 2% over the whole of China, whereas the frequency of precipitation events has decreased by 10% from 1960 to 2000 (Liu *et al*., 2005).

The temporal and spatial variations of precipitation changes often have various characteristics in different regions, which reflect its response to global climatic change and is also the research foundation of precipitation prediction, thus precipitation has an important effect on the development of regional ecological system (Huang *et al*., 1998 & 2011; Shouraseni and Robert, 2006; Liu *et al*., 2008). In recent years, the drought and flood disaster take place frequently around the world, with serious social and economic consequences, so the study of precipitation characteristics and regularities has been attached great importance. In fact, precipitation change detection is one of the core issues in climate change research, which plays a crucial role in accurately estimating global and regional climate change trends and understanding their causes (Sun and Lin, 2007). Many scholars found that the change of precipitation possessed time scale characteristic (Chen and Avissar, 1994; Zhang *et al*., 2013; Varikoden, 2013). While the change is influenced by the atmospheric hydrological factors such as cloud, temperature and humidity, it can be predicted to some extent using many statistical model, for example, Sacramento model, Moving average course, Power spectral analysis, Morlet wavelet analysis, Mann-Kendall rank statistic (Hulme, 1994; Gershunov and Michaelsen, 1996; Ichikawa *et al*., 2009; Xu *et al*., 2009; Liu *et al*., 2010; Buttafuoco *et al*., 2011). In recent years, more and more new academics have applied nonlinear methods, such as chaos, fractal, spectral analysis (Andreo *et al*., 2006; Yu and Chen, 2008; Sivakumar 2001; Samuel Selvaraj *et al*., 2010), to be specific, such as correlation dimension, the minimum embedding dimension and maximum Lyapunov index and Kolmogorov entropy characteristics, autocorrelation spectrometry, etc. (Kugiumtzis, 1996; Wang *et al*., 2012). Essentially, the climate system is a complex nonlinear system, and most of the long-term variations in many climatic factors, including precipitation, exhibit nonlinear, non-stationary complex processes of change, accompanied by a variety of scales or periodic oscillations (Palmer, 1999; Wu *et al*., 2007; Xu *et al*., 2013; Xue *et al*., 2013; Liu *et al*., 2014b). Due to the limitations of former methods itself, they cannot give a reasonable and exact diagnosis for natural variability of precipitation change in many researches. So far, the basic form knowledge of the process of climate change is still big problem (Zhao and Xu, 2014). With the rapid development of signal detection technology, Wang and Li (2013) have proposed a new time-series signal processing method: extreme-point symmetric mode decomposition method (ESMD). This method is a new development of ensemble empirical mode decomposition (EEMD) and empirical mode decomposition (EMD) which has stronger self-adaptability and local variation characteristics based on the signal. These attributes can effectively improve the "mode mixing" issue of EMD, making it suitable for non-stationary and non-linear signal detection, and it can gradually separate the oscillations at different scales (intrinsic mode function, IMF) or the trend components from the original signal (Wu and Huang, 2004). ESMD is one of the latest methods to extract signal variation trends, which can screen large- scale circulation and non-linear trend. Compared with other methods, it can more efficiently extract trends and period information (Huang *et al*., 2009; Shao *et al*., 2011; Li *et al*., 2012). Moreover, in recent years, the ESMD method has been gradually applied in the field of climate change research, and some meaningful results have been achieved (Ji *et al*., 2014).

The different regions show significant climatic characteristics and differences in the different atmospheric circulation patterns in China (Zuo *et al*., 2004), in which Sichuan Province is more typical on account of its geographical position and complicated topography. The western part of Sichuan Province is characterized by a very steep topography and consists of mountain chains higher than 5000 m a.s.l. The eastern part is mostly plain and basin and a densely populated region in western China (Fig. 1). The huge thermal difference between the western mountainous regions and eastern Sichuan basin (Li *et al*., 2003; Chuan *et al*., 2003) has resulted in obviously regional climate characteristics and different response sensitivities to climate change. Most previous studies have verified the instability of the climate system, and indicated the complexity of climate in different regions over the Sichuan Province (Zhao *et al*., 2013; Li *et al*., 2003 & 2007; Zhu and Yu, 2003; Shao *et al*., 2005; Chen *et al*., 2010; Zhou *et al*., 2011). However, these scholars do not cover the entirety of the Sichuan Province as a study

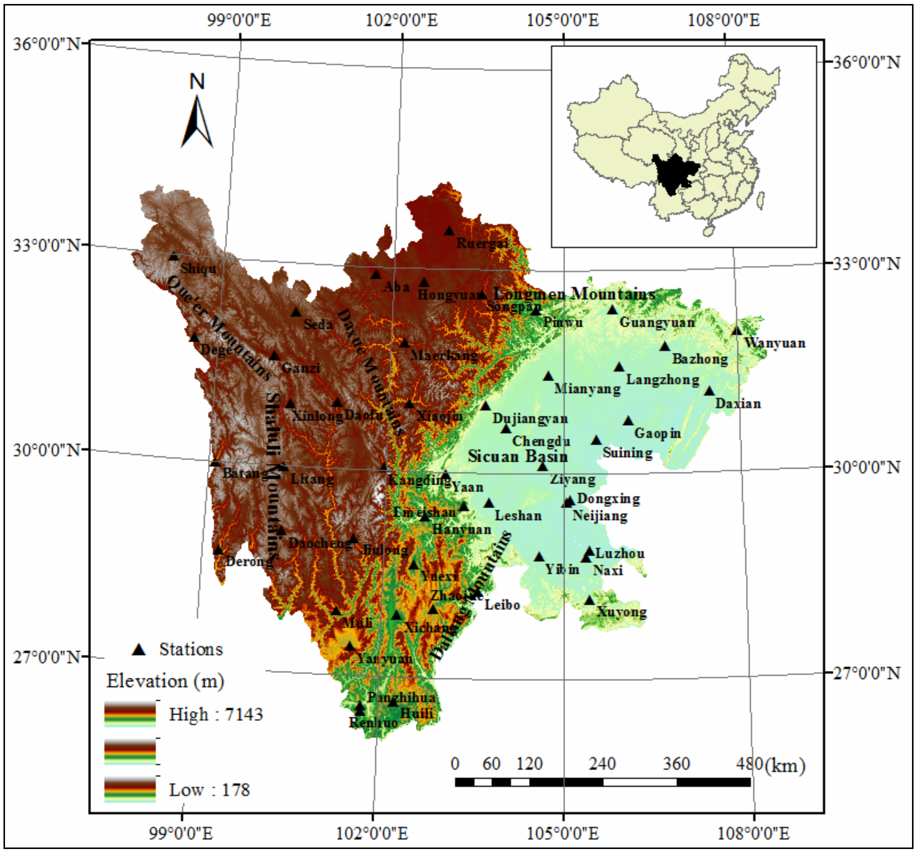


Fig. 1. Location of meteorological station in Sichuan Province

domain. At the same time, the systematic studies of the spatial and temporal precipitation variability across the different regions over the SP have not been extensively conducted (Wang *et al*., 2013).

Therefore, on the basis of the annual averaged precipitation data from 49 meteorological observation stations distributed in multiple regions of Sichuan Province, the aim of the present study is to explore the following issues: (*i*) the oscillation and variation of time scale that have characterized precipitation changes in the past 50+ years in Sichuan, in particular, the evolutionary characteristics of oscillation and variation at different scales; (*ii*) the contributions of oscillations at different scales to precipitation changes and their significance or insignificance; (*iii*) the impact of the oscillation at each scale on the overall climate change in different periods; and (*iv*) the relationship between precipitation changes and regional differences. To study the regional features of precipitation variation trends over Sichuan Province in China, we propose the ESMD method to extract variation at different scales in the climatic signals from the climatic time sequence and to conduct multiscale analysis on precipitation changes in the past 50+ years in Sichuan Province. Furthermore, in order to study the relations between the changing more or less of rising or decrease and meteorological station's geographical position (latitude, longitude and elevation) *i.e*., the Cokriging interpolation technique is applied directly to precipitation variation trend components through ESMD decomposition.

2. Data and methodology

2.1. *Study area and data processing*

Located in the Southwest China and covering an area of 4.8 × 105 km^2, Sichuan Province (26°03′ - 34°19′ N, 97°21′ - 108°31′ E) is surrounded by the Tibetan Plateau to the west, Mt. Bayankala, Mt. Min and Daba Range to the north, and the Yunnan and Guizhou Plateau to the south. Northwest plateau and Southwest mountains of Scihuan are consist of a series of mountain ranges from the north to the south, including Mt. Min, Mt. Que'er, Mt. Daxue, Mt. Gongkala, Mt. Shaluli, Mt. Qionglai, Mt. Jiajin, Mt. Jingpin, and Mt. Lunan, in which Mt. Gongga with the highest peak (7556 m) is located in the central parts of Mt. Hengduan (Fig. 1). The topography over the

SP declines from west to east and from the surrounding mountains to the central basin, so the elevation dependency of climate change signals is significant (Wang *et al*., 2013). The western mountain climate and eastern basin subtropical monsoon climate existed simultaneously (Xu, 1991).

The annual average China meteorological station precipitation data from 1961-2011 were provided by China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/), while data from foreign meteorological stations were provided by the National Oceanic and Atmospheric Administration (http://www.climate.gov/). To determine which data have higher quality, the data have been subject to extremum, time consistency and other tests. Furthermore, missing data for individual years from some meteorological stations were interpolated by the ratio method; the uniformity inspection and revision of the precipitation data were conducted *via* RHTest software to eliminate data sequence breakpoints or adverse effects on the quality of the data resulting from migration of stations, instrument replacement, operating error of the observer and other factors. And we apply the Standard normal homogeneity test (SNHT), Buishand and Pettit homogeneity test method to check these data (Pettit, 1979; Buishand, 1982; Alexandersson, 1986). The stepwise multiple linear regression method was employed to revise the inhomogeneity of time series. The geographical distribution of the selected meteorological stations in Sichuan Province and the surrounding areas are shown in Fig. 1.

2.2. *Methodology*

2.2.1. *ESMD method*

The ESMD method is the abbreviation of "extreme-point symmetric mode decomposition" method (Wang and Li, 2013), which is a new development for the well-known method of EMD. ESMD method can smoothly process complex signal, thus inherently different scales or periodic oscillations and trend component of the original signal sequence may be gradually extracted, and get some scale with different characteristics or inherent cycle intrinsic mode functions (IMFs). With the ESMD method, a signal is decomposed into several IMFs and after EMD processing, the frequencies of the IMFs are arranged in decreasing order (high to low), where the lowest frequency of the IMF components represents the overall trend of the original signal or the average of the time series data. Most importantly, each of these IMFs must satisfy two conditions: first, the number of extreme and the number of zero crossings must be equal or differ at most by one; second, at any point, the mean value of the envelope denied by the local maxima and local minima must be zero. For further detail computation, [Wang & Li (2013) and Li *et al*. (2013)]. The ESMD method is anticipated as an effective usage in the fields of atmospheric and oceanic sciences, informatics, economics, ecology, medicine and seismology etc.

The methodology operates on the precipitation, $\{x_t, t = 1, 2, \ldots, n\}$ and n is the length of the series. The algorithm is as follows:

(*i*) Find all the local extreme points (maxima points plus minima points) of the data Y and numerate them by E_i with $1 \leq I \leq n$.

(*ii*) Connect all the adjacent E_i with line segments and mark their midpoints by E_i with $1 \leq I \leq n\text{-}1$. Add a left and a right boundary midpoints F_0 and F_n through a certain approach.

(*iii*) Construct p interpolating curves $L_1,\ldots, L_p$ ($p \geq 1$) with all these $n + 1$ midpoints and calculate their mean value by $L^* = (L_1+\ldots+L_p)/p$.

(*iv*) Repeat the above four steps on x_t- L^*until $|L^*| \leq \varepsilon$ (ε is a permitted error) or the sifting times attain a preset maximum number K. At this time, we get the first mode M_1 of Intrinsic mode function (IMF).

(*v*) Repeat the above five steps on the residual x_t- M_1 and get M_2, $M_3\ldots$until the last residual R (R_0) with no more than a certain number of extreme points.

(*vi*) Change the maximum number K on a finite integer interval $[K_{min}, K_{max}]$ and repeat the above five steps. Then calculate the variance σ^2 of x_t- R_0 and plot a figure with σ/σ_0 and K, here σ_0 is the standard deviation of x_t .

(*vii*) Find the number K_0 which accords with minimum σ/σ_0 on $[K_{min}, K_{max}]$. Then we use this K_0 to repeat the previous six steps and output the whole modes. At this time, the last residual *RES* is actually an optimal adaptive global mean (AGM) curve.

2.2.3. *Kriging and Cokriging method*

Cokriging is a multivariate spatial method to estimate spatial correlated variables and wildly used in soil science (Vauclin *et al*., 1983; Webster, 1985; Webster and Burgess, 1980) which is an extension of the Kriging method and can incorporate secondary information, such as values of gradients in addition to primary function values of the sample points has been utilized for constructing approximation models in a realistic design optimization process (Chung and Alonso, 2002). The

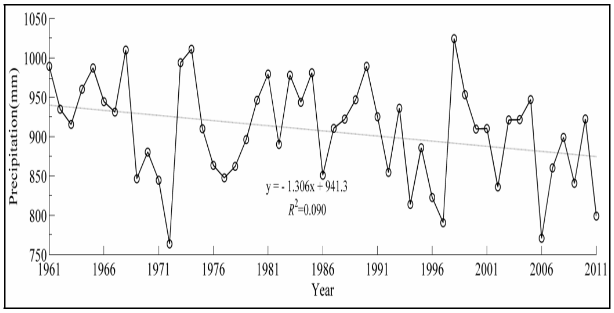


Fig. 2. Linear change trend of annual average precipitation in Sichuan Province from 1961 to 2011

estimation precision may be improved by accounting simultaneously for spatial autocorrelation in population density and impervious surface fraction and the cross-correlation between these spatial variables (Liu *et al.*, 2014a). Moreover, it is suitable when the variable to be estimated (*e.g.*, population density) is under-sampled while other supplementary variables are abundant (*e.g.*, impervious surface fraction) (Wu and Murray, 2005). Ordinary Kriging can mathematically be defined as given in the following:

$$Z_X^* = \sum_{i=1}^{n} \lambda_i Z(X_i) \tag{1}$$

where, Z_X^* is the estimated value, λ_i is the corresponding weight of each observation $Z(X_i)$ on the estimation. The weights are calculated to ensure that the estimator is unbiased and the estimation variance is a minimum. The nonbias condition requires that:

$$\begin{cases} \sum_{i=1}^{n} \lambda_i \gamma(X_i, X_j) - \mu = \gamma(X_i, X^*) \\ \sum_{i=1}^{n} \lambda_i = 1 \end{cases} \tag{2}$$

where, $\gamma(X_i, X_j)$ is the variogram between sampled point i and point j, $\gamma(X_i, X^*)$ is the variogram between sampled point and estimated point, μ is the Lagrange multiplier of minimum condition.

The general form of Cokriging equations are:

$$\begin{cases} \sum_{l=1}^{v} \sum_{i=1}^{n_l} \lambda_{il} \gamma_{lv}(X_i, X_j) - \mu_v = \gamma_{uv}(X_i, X^*) \\ \sum_{i=1}^{n_l} \lambda_{il} = \begin{cases} 1, & l=u \\ 0, & l \neq u \end{cases} \end{cases} \tag{3}$$

where, u and v are the primary and covariate (secondary) variables, respectively. In the Cokriging method, the u and v are cross-correlated and the covariate contributes to the estimation of the primary variable. Generally, measuring the covariate is simpler than measuring the primary variable (Xu *et al.*, 2013). For Cokriging analysis, the cross variogram (or cross-variogram) should be determined in prior. Provided that there are points where both u and v have been measured, the cross-variogram is estimated by

$$\gamma_{uv}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z_u(X_i) - Z_u(X_i + h)][Z_v(X_i) - Z_v(X_i + h)] \tag{4}$$

3. Results and discussion

3.1. *Characteristics of precipitation variation trend*

As seen in Fig. 2, the precipitation in Sichuan Province over nearly 50 years presents an overall decreasing trend. Its speed reduction is 1.06 mm/10a though the test of significance. A turning point appeared in the early 1970s and middle 1990s, before which the precipitation was lower and after which the precipitation was higher during which an incidence of extreme precipitation would occur. With respect to the time period, the precipitation in Sichuan Province during 1960s and early 1980s showed small fluctuation was relatively high than that of the other periods. The precipitation in Sichuan Province showed a gradual increase in the Mid-Late 1970s and 1980s, suggesting that the precipitation in Sichuan Province has also experienced two rises in the overall decreasing trend. The overall precipitation remained less in the first 10 years of the 21st century, and it was significantly less in 2006 and may occur drought disaster.

Fig. 2 shows that the precipitation changes are not linear and present a strong nonlinear variation trend; the Sichuan Province precipitation change in the stationary test also shows non-stationary results. Therefore, a nonlinear method should be used to analyze the nonlinear and non-stationary changes of Sichuan Province precipitation.

The ESMD method has characteristics of self-adaptability and locality in time, which is suitable for the time-frequency analysis of nonlinear, non-stationary time series. Therefore, the EEMD method can be used to decompose time series of precipitation anomalies in Sichuan Province during 1961-2011, and three IMF components (IMF1-3) and one trend component (RES) can be obtained (Fig. 3). Each IMF component reflects the fluctuation characteristics from high frequency to low frequency at different time scales and the final trend

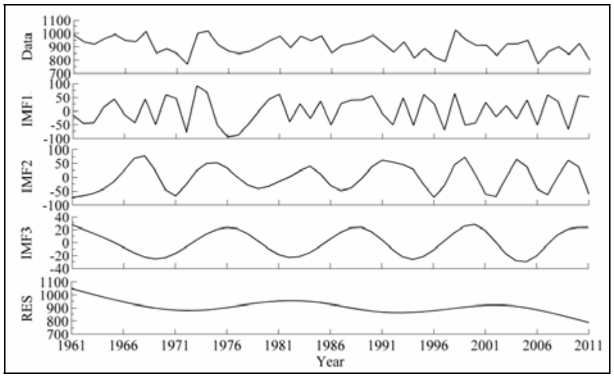


Fig. 3. The IMFs and trend components of ESMD decomposition for mean precipitation in Sichuan Province during the period from 1961 to 2011

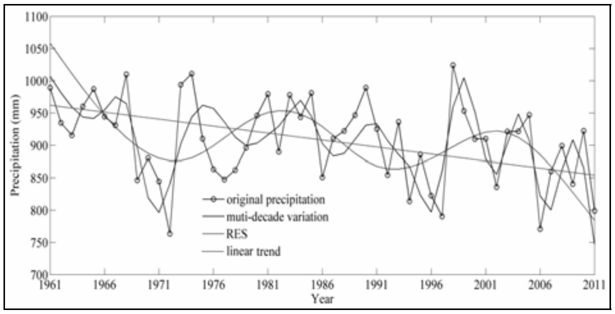


Fig. 4. The trend change of ESMD and their comparison with the linear trend

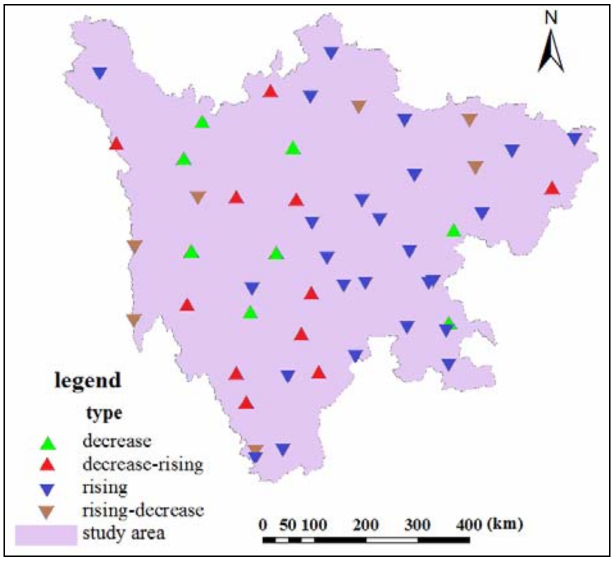


Fig. 5. Geographic distribution of different change trend types of precipitation

TABLE 1

Contribution rates of ESMD decomposition for precipitation time series

IMF components	IMF1	IMF2	IMF3	RES
Period/year	3	8	13	-
Contribution/%	30.42	20.49	12.27	36.82

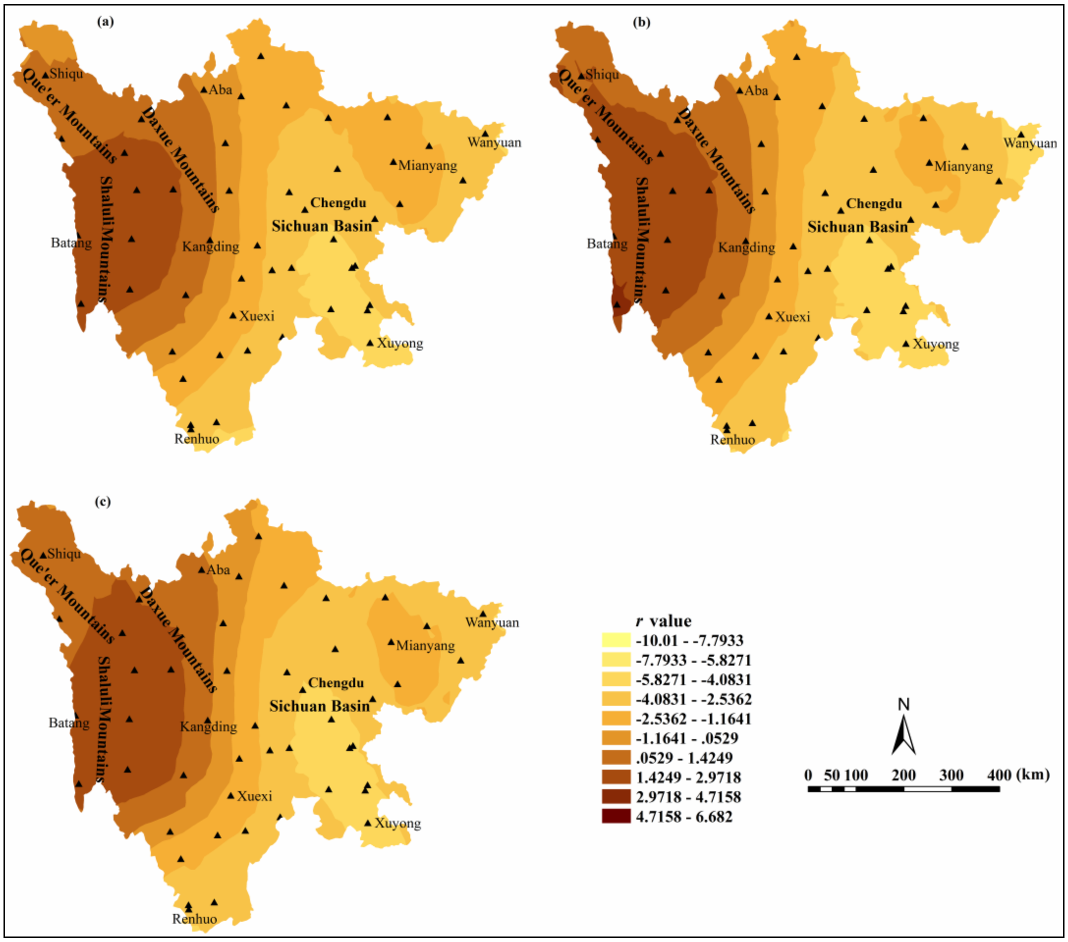
component represents the trend of the original data over time. Generally, each IMF component has a physical meaning, reflecting the oscillation of inherently different characteristic scales in the original series. The actual physical meaning contained in each IMF component at inherently different characteristic scales can be determined by the significance test and different confidence levels indicate the strength of the physical meaning (Bai *et al*., 2015). As seen in Fig. 3, the precipitation changes from 1961 to 2011 in Sichuan Province show relatively stable quasi periodicity; the precipitation in Sichuan Province during the study period has quasi-3-year (IMF1) and quasi-8-year (IMF2) climate variability at the inter-annual scale and and quasi-13-year (IMF3) climate variability at the decadal scale. These IMF components include not only the periodic changes of climatic systems under external forcing but also the non-linear feedback of the climatic system. This result is mostly consistent with the inter-annual scale characteristics determined in this study through the application of the ESMD decomposition method. Long-term observational data of the time series will be required to verify which results are more accurate. It is commonly known that the wavelet transform has been widely used in climate change detection (Gong *et al*., 2005; Xu *et al*., 2011). Therefore, we selected different wavelet bases and decomposition levels for the multiscale decomposition of precipitation anomalies in Sichuan Province and found that if different wavelet bases and decomposition levels are selected, the decomposition results exhibit apparent differences (not shown), indicating that the wavelet transform is not adaptive. Compared with the wavelet transform, the ESMD method has stronger flexibility and adaptability, the decomposition process is simpler and each component can clearly depict the signal variation characteristics at different time scales (Bai *et al*., 2015).

The impact of the signal fluctuation frequency and amplitude in each scale on the general characteristics of the available raw data can be expressed as the variance contribution rate. Table 1 shows the variance contribution rate of each component for the precipitation. It is noted that although there is less information with actual physical meaning included in IMF2 and IMF3, they are also involved in the calculation of the variance contribution rate to maintaining the total energy of the signal. When connecting Fig. 3 and Table 1, the contribution of IMF1 towards precipitation variance of the quasi-3-year is

TABLE 2

The trend change of ESMD for 49 stations in Sichuan Province

ID	Station	Latitude (N)	Longitude (E)	Elevation (m)	Period/year	RES	Trend type	Transition time
56038	Shiqu	32.98	98.1	4200	3, 8, 13	-2.742	decrease	1998
56079	Ruergai	33.58	102.97	3439.6	3, 9, 12	-4.133	decrease	1998
56144	Dege	31.8	98.58	3184	3, 8, 13	0.639	rising-decrease	1998
56146	Ganzi	31.62	100	3393.5	3, 8, 12	3.101	rising	1975
56152	Seda	32.28	100.33	3893.9	3, 7, 14	4.16	rising	1972
56167	Daofu	30.98	101.12	2957.2	3, 7, 13	-0.595	rising-decrease	1998
56171	Aba	32.9	101.7	3275.1	3, 8, 14	-0.217	rising-decrease	1971
56172	Maerkang	31.9	102.23	2664.4	3, 6, 15	1.557	rising	1973
56173	Hongyuan	32.8	102.55	3491.6	3, 7, 11	-2.298	decrease	1998
56178	Xiaojin	31	102.35	2369.2	3, 6, 11	0.015	rising-decrease	1998
56182	Songpan	32.65	103.57	2850.7	3, 8, 15	0.082	decrease-rising	1998
56188	Dujiangyan	31	103.67	706.7	3, 8, 14	-2.902	decrease	1998
56193	Pinwu	32.42	104.52	893.2	3, 6, 13	-6.377	decrease	1998
56196	Mianyang	31.45	104.73	470.8	3, 7, 15	-3.638	decrease	1998
56247	Batang	30	99.1	2589.2	3, 8, 14	1.468	decrease-rising	1971
56251	Xinlong	30.93	100.32	3000	3, 8, 13	2.299	decrease-rising	1998
56257	Litang	30	100.27	3948.9	3, 8, 13	2.983	rising	1975
56287	Yaan	29.98	103	627.6	3, 7, 13	-4.297	decrease	1998
56294	Chengdu	30.67	104.02	506.1	3, 8, 13	-8.68	decrease	1998
56298	Ziyang	30.12	104.65	357	3, 8, 13	-6.562	decrease	1998
56357	Daocheng	29.05	100.3	3727.7	3, 7, 14	0.183	rising-decrease	1996
56374	Kangding	30.05	101.97	2615.7	3, 8, 15	5.695	rising	1974
56376	Hanyuan	29.35	102.68	795.9	3, 6, 12	2.507	rising-decrease	1998
56385	Emeishan	29.52	103.33	3047.4	3, 6, 12	-8.104	decrease	1998
56386	Leshan	29.57	103.75	424.2	3, 8, 13	-5.528	decrease	1998
56441	Derong	28.72	99.28	2422.9	3, 8, 14	6.682	decrease-rising	1971
56459	Muli	27.93	101.27	2426.5	3, 8, 14	-0.424	rising-decrease	1994
56462	Jiulong	29	101.5	2987.3	3, 7, 13	2.378	rising	1976
56475	Yuexi	28.65	102.52	1659	3, 7, 14	0.97	rising-decrease	1988
56479	Zhaojue	28	102.85	2132.4	3, 8, 13	-0.948	rising-decrease	2002
56485	Leibo	28.27	103.58	1255.8	3, 8, 14	-1.224	decrease	1998
56492	Yibin	28.8	104.6	340.8	3, 8, 15	-7.087	decrease	1998
56565	Yanyuan	27.43	101.52	254.5	3, 8, 15	-0.533	rising-decrease	1997
56571	Xichang	27.9	102.27	1590.9	3, 8, 15	-6.391	decrease	1998
56666	Panzhihua	26.58	101.72	1190.1	3, 7, 15	-10.01	decrease	1998
56671	Huili	26.65	102.25	1787.1	3, 8, 13	-5.891	decrease	1998
56674	Renhuo	26.5	101.73	1108	3, 8, 14	0.029	decrease-rising	1971
57206	Guangyuan	32.43	105.85	492.4	3, 7, 13	0.419	decrease-rising	1998
57237	Wanyuan	32.07	108.03	674	3, 8, 13	-8.643	decrease	1998
57306	Langzhong	31.58	105.97	382.6	3, 8, 13	-0.097	decrease-rising	1995
57313	Bazhong	31.87	106.77	417.7	3, 8, 14	-2.129	decrease	1998
57328	Daxian	31.2	107.5	344.9	3, 8, 15	-1.381	rising-decrease	1998
57405	Suining	30.5	105.55	278.2	3, 9, 16	2.447	rising	1975
57411	Gaopin	30.78	106.1	309.3	3, 8, 13	-1.527	decrease	1998
57503	Dongxing	29.62	105.12	349.7	3, 8, 13	-4.427	decrease	1998
57504	Neijiang	29.58	105.05	347.1	3, 8, 14	-2.784	decrease	1998
57602	Luzhou	28.88	105.43	334.8	3, 8, 14	-5.389	decrease	1998
57604	Naxi	28.78	105.38	367.3	3, 7, 13	-5.538	rising-decrease	1977
57608	Xuyong	28.17	105.43	377.5	3, 8, 13	-3.762	decrease	1998



Figs. 6(a-c). The change of slope values of RES with (a) longitude, (b) latitude and (c) elevation

greatest, reaching 30.42%. The amplitude of the precipitation strongly oscillates from a increase-decrease-increase trend and is significantly lower in the early 1970s, late1980s, early 1990s and Mid-21th Century than those of other time periods. IMF2 contributes to approximately 20.49% of the precipitation variance of the quasi-8-year cycle, indicating higher precipitation in the late 1980s and mid 1990s; IMF3 contributes to 12.27% of the precipitation variance of the quasi-13-year cycle, indicating that the precipitation amplitude decreases and the instability of variation decreases on this time scale. The trend components contribute up to 33.82% of the variance, indicating that the overall average annual precipitation in Sichuan Province during 1961-2011 has a non-linear rise with greater precipitation decreases from the late 1980s. Furthermore, studies have shown that with global temperature changes over nearly 100 years, precipitation in China have also experienced a non-linear complex process of change (Yan *et al*., 2006; Bryan and Adams, 2002; Feng *et al*., 2009; Luan *et al*., 2010).

Fig. 4 shows the muti-decade precipitation variations in comparison with the original precipitation series. Compared to the original precipitation series trend, the trend component through ESMD decomposition can fully reflect the overall trend of the average annual precipitation variation in the Sichuan Province region from 1961-2011. In addition, the reconstructed muti-decadal precipitation variation does not adequately portray the precipitation series variation throughout the study period, which may be due to small-scale oscillations excluded from the reconstructed muti-decadal precipitation variation. Although the reconstructed muti-decadal precipitation variation does not adequately portray the precipitation variations in the early 1970s and late 1980s, it effectively shows that the precipitation variation process within the study period can be divided into two distinct variation periods with 1973 and 1998 as the boundary, before which the precipitation falls slowly and after which the precipitation rises rapidly, suggesting that the climate mode in Sichuan Province before and after turning points have changed significantly from the downward trend dominated climate mode to the significant rising trend large-precipitation mode.

3.2. *The types of precipitation variation trend and their spatial distribution*

As shown by the analysis in section 2.1, the precipitation in Sichuan Province presents an overall increasing trend. In fact, precipitation variation trends in different regions are not the same due to the complex topography, circulation type & strength and other factors. For a more detailed analysis of precipitation variation trends in each meteorological station, this paper has provided a morphological analysis of precipitation trend components through ESMD decomposition and has found that morphological variations can be broadly divided into four categories: rising type, rising-decrease type, decrease-rising type and decrease type. Table 2 and Fig. 5 shows the classification results of 49 meteorological stations in Sichuan Province used in this paper, which includes a total of 23 meteorological stations for decrease type, 12 for rising-decrease type, 7 for decrease-rising type and 7 for rising type. To further study the relations between the changing more or less of rising or decrease and meteorological station's geographical position (latitude, longitude and elevation) *i.e.*, the Cokriging interpolation technique is applied directly to precipitation variation trend components through ESMD decomposition and then we fit their slopes ordered by longitude, latitude and elevation respectively as shown in Figs. 6(a-c).

Figs. 6(a-c) clearly shows that longitude and altitude had very significant effect on the slope values, while the latitude effect is weak. Slope values basically presents ladder form decreased trend from west to east ladder or from high to low, the decreasing trend, the regional differences significantly, similar to precipitation in the Yellow River Basin and the middle part of Inner Mongolia (Liu *et al.*, 2008; Zhu and Meng, 2010). The high values of the slope are western region of the Western Sichuan Province Plateau with centered around Ganzi, Xinlong, Litang, Daocheng etc., and the low are the eastern Sichuan Chengdu and Chongqing past area centered around Dujiangyan, Ziyang etc. In Figs. 5 and 6 (a-c), combined circulation and topographic analysis, the production of the high value area is contributed by the high altitude and the effect of complex local terrain, while that of the low is contributed by the control of the subtropical high. The distribution characteristics are caused by such factors as the surrounding atmospheric circulation systems and the complex topography. Furthermore, the Western Sichuan Plateau belonging to the Qinghai Tibet Plateau extending, its topography is higher, so the strengthened southwest monsoon cross the Hengduan Mountains further inland to bring more water vapor (Zhao *et al*., 2013). The western Sichuan is mainly impacted by such factors as the tropical monsoon and plateau monsoon. Meanwhile, the area was located in the southern areas of western edge of Western Pacific subtropical high, warm moist air flow conveys the abundant water vapor (Shao *et al*., 2005). The precipitation in eastern part of the basin impacted by the tropical monsoon is more than that of the western mainly by the subtropical high control, with arid and rainless and nearly 50 years of precipitation decreased significantly. There is obvious blend feature in the middle Sichuan Plateau between the eastern and western areas. Mountain area of southwest Sichuan Plateau belongs to climate of dry hot river valley, which reflects that the larruping regional characteristics of precipitation change are mainly determined by its unique geographical environment.

4. Conclusions

Based on the precipitation time series from 49 international exchange stations in Sichuan Province from 1961 to 2011, the multi-scale characteristics of precipitation variability were analyzed using the ESMD method. The main findings include the following:

(*i*) In the last 50+ years, the overall precipitation in Sichuan Province exhibited a significant non-linear downward trend, and its changes clearly exhibited an inter-annual scale (quasi-3 and quasi-8-year) and interdecadal scale (quasi-13-year). The contribution of IMF1, towards precipitation variance of the quasi-3-year is greatest, reaching 30.42%; IMF2 and IMF3 contribute to approximately 20.49% and 12.27% of the precipitation variance of the quasi-8-year cycle and quasi-13-year cycle, respectively. These results implied that the inter-annual change had a strong influence on the overall precipitation in Sichuan Province.

(*ii*) The trend component through ESMD decomposition revealed that the precipitation in Sichuan Province during 1961-2011 was an approximately linear (but actually non-linear) evolution process and that the average annual precipitation in Sichuan Province had decreased trend significantly. Through Kriging and Cokriging method, we found that longitude and altitude had very significant effect on the slope values of the trend component, while the latitude effect is weak. Slope values basically presents ladder form decreased trend from west to east ladder or from high to low, the decreasing trend, and the regional differences significantly.

(*iii*) The annual average precipitation trend had clear regional differences, which can be summarized into four types : rising type, rising-decrease type, decrease-rising type and decrease type. In addition, the transition time of variations were quite different between the single stations and all of Sichuan Province, indicating that the precipitation at each meteorological station in Sichuan Province, were not fully synchronized and that the precipitation in Sichuan Province at each station was controlled to a large extent by the inherent change mechanism of the climate system and the local environment. The deeper reasons for the significant regional differences in temperature variation trend and transition time need to be further explored.

(*iv*) ESMD is one of the signal analysis methods applicable to nonlinear and non-stationary series similar to EEMD, which has significant advantages in data analysis. When ESMD is applied to time series of climatic elements, the reliable and real signals of climate change can be extracted; in particular, the intrinsic time scales of climate change can be available, which facilitates the separation of inter-annual and interdecadal trends from observation sequences in several years and the separation of the general trend of climate change from the time series of climatological observations for several years, which will aid exploring global or regional climate change issues. As climate change is mainly controlled by internal variations of the climate system at the inter-annual scale, it shows significant natural variability. However, at the interdecadal scale, climate change is affected by the combined effects of various factors and often mixed with external information, resulting in more complex changes. Therefore, the results of this study confirm that the ESMD method, which is more effective for the decomposition of inter-annual scale of climatic elements, can truly reflect the natural characteristics of climatic elements.

Acknowledgments

The research is supported by the key project of Education Department of Sichuan Province, China (13ZA0018) and key R&D project of Jiangxi Provincial Department of Science and Technology (20161BBF60061).

References

Alexandersson, H., 1986, "A homogeneity test applied to precipitation data", *International Journal of Climatology*, **6**, 6 661-675.

Andreo, B., Jiménez, P. and Durán, J. J., 2006, "Climatic and hydrological variations during the last 117~166 years in the south of the Iberian peninsula from spectral and correlation analyses and wavelet continuous analyses", *Journal of Hydrology*, **324**, 1-4, 24-39.

Bai, L., Xu, J. H., Chen, Z. S., Li, W. H, Liu, Z. H., Zhao B. F. and Wang, Z. J, 2015, "The regional features of temperature variation trends over Xinjiang in China by the ensemble empirical mode decomposition method", *International Journal of Climatology*, **35**, 11, 3229-3237.

Bryan, B. A. and Adams, J. M., 2002, "Three-dimensional neurointerpolation of annual mean precipitation and temperature surfaces for China", *Geographical Analysis*, **34**, 2, 93-111.

Buishand, T. A., 1982, "Some methods for testing the homogeneity of rainfall records", *Journal of Hydrometeorology*, **58**, 1-2, 11-27.

Buttafuoco, G., Caloiero, T. and Coscarelli, R., 2011, "Spatial and temporal patterns of the mean annual precipitation at decadal time scale in southern Italy (Calabria region)", *Theoretical and Applied Climatology*, **105**, 3, 431-444.

Chen, C., Pang, Y. M. and Zhang, Y. F., 2010, "On the characteristics of climate change in Sichuan basin in the recent 50 years", *Journal of Southwest University (Natural Science Edition)*, **32**, 9, 115-120.

Chen, F. and Avissar, R., 1994, "Impact of land-surface moisture variability on local shallow convective cumulus and precipitation in large-scale models", *Journal of Applied Meteorology*, **33**, 12, 1382-1401.

Chuan, L. I., Chen, J. and Zhu, Y. J., 2003, "Preliminary research on climatic change of west Sichuan Plateau in recent fifty years", *Plateau Meteorology*, **22**, S1, 138-144.

Chung, H. S. and Alonso, J. J., 2002, "Using gradients to construct cokriging approximation models for high-dimensional design optimization problems", *AIAA paper*, **317**, 14-17.

Feng, G., Wan, S., Rong, Z. and Wang, Q. G., 2009, "Nonlinear dynamical structure of precipitation in China and its regional climatic characters.Fuzzy Systems and Knowledge Discovery", FSKD '09 - Sixth International Conference on IEEE, 57-64.

Gershunov, A. and Michaelsen, J., 1996, "Climatic-scale space-time variability of tropical precipitation", *Journal of Geophysical Research*, **101**, D21, 26297-26307.

Gong, Z. Q., Zou, M. W., Gao, X. Q. and Dong, W. J., 2005, "On the difference between empirical mode decomposition and wavelet decomposition in the nonlinear time series", *Acta Physica Sinica*, **54**,3947-3958.

Huang, N. E., Wu, Z. H., Arnold, K. C., Kenneth, C., Arnold, K. C., Chen, X. C. and Blank, K., 2009, "On instantaneous frequency", *Advances in Adaptive Data Analysis*, **1**, 2, 177-229.

Huang, N. E. and Liu, H. H., 1998, "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis", *Proceedings of the Royal Society of London (Series A: Mathematical, Physical and Engineering Sciences)*, **454**, 1971, 903-995.

Huang, Y., Feng, G. L. and Dong, W. J., 2011, "Temporal changes in the patterns of extreme air temperature and precipitation in the various regions of China in recent 50 years", *Acta Meteorologica Sinica*, **69**, 1, 125-136.

Hulme, M., 1994, "Global Precipitations and Climate Change", *Springer Berlin Heidelberg*, **29**, 387-405.

Ichikawa, H., Masunaga, H. and Kanzawa, H., 2009, "Evaluation of precipitation and high-level cloud areas associated with large-scale circulation over the tropical pacific in the CMIP3 models", *Journal of the Meteorological Society of Japan*, **87**, 4, 771-789.

IPCC, 2007, "Climate change 2007: the physical science basis", contribution of working group I to the fourth assessment report of the IPCC, Cambridge University Press, Cambridge, United Kingdom.

IPCC, 2013, "Climate change 2013: the physical science basis", contribution of working group I to the fifth assessment report of the IPCC, Cambridge University Press, Cambridge, United Kingdom.

Ji, F., Wu, Z. H., Huang, J. P. and Chassignet, E. P., 2014, "Evolution of land surface air temperature trend", *Nature Climate Change*, **4**, 6, 462-466.

Kugiumtzis, D., 1996, "State space reconstruction parameters in the analysis of chaotic time series - the role of the time window length", *Physica D Nonlinear Phenomena*, **95**, 1, 13-28.

Li, B. F., Chen, Y. N. and Shi, X., 2012, "Why does the temperature rise faster in the arid region of northwest china?", *Journal of Geophysical Research Atmospheres*, **117**, 81-81.

Li, C., Cheng, J. and Zhu, Y., 2003, "Preliminary research on climatic change of west Sichuan plateau in recent fifty years", *Plateau Meteorology*, **22**, S1, 138-144.

Li, H. F., Wang, J. L. and Li, Z. J., 2013, "Application of ESMD method to air-sea flux investigation", *International Journal of Geosciences*, **4**, 5B, 8-11.

Liu, B. H., Xu, M., Henderson, M. and Qi, Y., 2005, "Observed trends of precipitation amount, frequency, and intensity in China, 1960-2000", *Journal of Geophysical Research: Atmospheres (1984-2012)*, **110**, D08103.

Liu, Q., Yang, Z. F. and Cui, B. S., 2008, "Spatial and temporal variability of annual precipitation during 1961-2006 in Yellow River Basin, China", *Journal of Hydrology*, **361**, 3-4, 330-338.

Liu, Z. H., Xu, J. H., Chen, Z. S., Nie Q. and Wei, C. M., 2014a, "Multifractal and long memory of humidity process in the Tarim River Basin", *Stochastic Environmental Research and Risk Assessment*, **28**, 6, 1383-1400.

Liu, Z. H., Xu, J. H. and Shi, K., 2014b, "Self-organized criticality of climate change", *Theoretical and Applied Climatology*, **11**, 3-4, 685-691.

Liu, Z. H., Zhang, B., Liu, G. C., Qin, F. C., Wang, L. L. and Deng, M. L., 2010, "A mathematical-statistical prediction model of precipitation in Yuanmou Dry-hot Valley", *Journal of Mountain Science*, **2**, 4, 422-430.

Liu, Z. Y., Wang, Y., Ding, Y. Y., Yang H. Y. and Du, Z. X., 2005, "Multiple time-scale analysis of precipitation variation in Zhengzhou during last 54 years", *Scientia Meteorological Sinica*, **33**, S1, 123-126.

Li, X., Xiao, T. G. and Wang, L., 2007, "Seasonal division and change characteristic in Sichuan area during past 44 years", *Journal of Chengdu University of Information Technology*, **22**, 4, 530-538.

Luan, Q., Chen, L. X. and Cheng, Y., 2010, "Analysis and comparing of the complexity distributions of precipitation in two typical regions in Changing environment, China", IWCFTA, Chaos-Fractals Theories and Applications, International Workshop on, Chaos- Fractals Theories and Applications, International Workshop on 2010, 391-394.

Palmer, N. T., 1999, "Signature of recent climate change in frequencies of natural atmospheric circulation regimes", *Nature*, **398**, 6730, 799-802.

Pettit, A. N., 1979, "A non-parametric approach to the change-point detection problem", *Journal of the Royal Statistical Society (Series C: Applied Statistics)*, **28**, 2, 126-135.

Samuel Selvaraj, R., Gayathri, R. and Tamilselv, S., 2010, "Fractal analysis : Annual rainfall in Chennai", *Mausam*, **61**, 1, 35-38.

Shao, J., Lv, S. Y. and Qian, X. Y., 2011, "Multi-scale analysis of hydrological series using ensemble empirical mode decomposition", *Journal of Huazhong University of Science and Technology (Natural Science Edition)*, **39**, 11, 105-108.

Shao, Y. K., Shen, T. K., You, Y. and Kang, L., 2005, "Precipitation features of Sichuan Basin in the recent 40 decades", *Journal of Southwest Agricultural University (Natural Science)*, **27**, 6, 749-751.

Shouraseni, S. R. and Robert, C. B. J. R., 2006, "Analysis of spatial patterns of trends in the frequency and intensity of Indian precipitation", *Mausam*, **57**, 3, 431-436.

Sivakumar, B., 2001, "Is a chaotic multi-fractal approach for rainfall possible?", *Hydrological Processes*, **15**, 6, 943-955.

Sun, X. and Lin, Z. S., 2007, "The regional features of temperature variation trends over China by empirical mode decomposition method", *Acta Geographica Sinica*, **62**, 11, 1132-1141.

Varikoden, H., 2013, "Long term trends of seasonal and monthly rainfall in different intensity ranges over Indian subcontinent", *Mausam*, **64**, 3, 481-488.

Vauclin, M., Vieira, S. R., Vachaud, G. and Nielsen, D. R., 1983, "The use of cokriging with limited field soil observations", *Soil Science Society of America Journal*, **47**, 2, 175-184.

Wang, H. P., Zhang, B., Liu, Z. H., He, J. Y. and Luo, J., 2012, "Chaos theory-based comparative study on monthly rainfall characteristics in Wuhan and Yichang during recent 60 years", *Journal of Natural Disasters*, **21**, 6, 111-118.

Wang, J. L. and Li, Z. J., 2013, "Extreme-point symmetric mode decomposition method for data analysis", *Advances in Adaptive Data Analysis*, **5**, 3, 1350015(36 pages).

Wang, S. J., Jiao, S. T. and Xin, H. J., 2013, "Spatio-temporal characteristics of temperature and precipitation in Sichuan Province, Southwestern China, 1960-2009", *Quaternary International*, **286**, 103-115.

Webster, R. and Burgess, T. M., 1980, "Optimal interpolation and isarithmic mapping of soil properties III changing drift and universal kriging", *Journal of Soil Science,* **31**, 3, 505-524.

Webster, R., 1985, "Quantitative spatial analysis of soil in the field", *Advances in Soil Sciences*, Vol. 3. pp. 2-70. Edited by B.A. Stewart. Springer-Verlag, New York

Wu, C. S. and Murray, A.T., 2005, "A cokriging method for estimating population density in urban areas", *Computers, Environment and Urban Systems*, **29**, 5, 558-579.

Wu, Z. H. and Huang, N. E., 2004, "A study of the characteristics of white noise using the empirical mode decomposition method", *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, **460**, 2046, 1597-1611.

Wu, Z. H., Huang, N. E., Long, S. R. and Chung-Kang, P., 2007, "On the trend, detrending, and variability of nonlinear and nonstationary time series", *Proceedings of the National Academy of Sciences*, **104**, 38, 14889-14894.

Xue, C. F., Hou, W., Zhao, J. H. and Wang, S. G., 2013, "The application of ensemble empirical mode decomposition method in multiscale analysis of region precipitation and its response to the climate change", *Acta Physica Sinica*, **62**,10, 10923 (8pages).

Xu, J. H., Chen, Y. N., Li, W. H. and Wang, S. G., 2013, "Understanding the complexity of temperature dynamics in Xinjiang, China, from multitemporal scale and spatial perspectives", *The Scientific World Journal*, **Vol. 2013**, Article ID 259248, p9.

Xu, J. H., Chen, Y. N., Lu, F., Li, W. H., Zhang, L. J. and Hong, Y. L., 2011, "The Nonlinear trend of runoff and its response to climate change in the Aksu River, western China", *International Journal of Climatology*, **31**,5, 687-695.

Xu, L. G., Zhou, H. F., Liang, C. and Wu, A. Q., 2009, "Multi-time scale variability of precipitation in the desert region of North China", *Journal of Hydraulic Engineering*, **40**, 8, 1002-1011.

Xu, Y., 1991, "Southwest Climate", Meteorological Press, Beijing, p298.

Yu, Y. S. and Chen, X. W., 2008, "Chaotic characteristics on multi-time scales of precipitation series in Fuzhou urban region", *Journal of Fujian Normal University (Natural Science Edition)*, **24**, 5, 96-100.

Yan, H. S., Chen, L. L. and Cheng, J. G., 2006, "The nonlinear dynamical features of annual precipitation climate oscillation in China", *Plateau Meteorology*, **25**, 2, 203-208.

Zhang, H., Fraedrich, K., Blender, R. and Zhu, X., 2013, "Precipitation extremes in CMIP5 simulations on different time scales", *Journal of Hydrometeorology* **14**, 3, 923-928.

Zhao, X., Li, Y. H. and Qi, D. M., 2013, "Spatial-temporal variation characteristics of summer precipitation in Sichuan, 1961-2007", *Journal of Glaciology and Geocryology*, **35**, 4, 959-967.

Zhao, Z. and Xu HT., 2014, "The research of temperature variation trends over Xinjiang in China by extreme-point symmetric mode decomposition method", *Geographical Research*, **33**, 12, 2358-2366.

Zhou, C. Y., Cen, S. X., Li, Y. Q., Peng, G. Z., Yang, S. Q. and Peng, J., 2011, "Precipitation variation and its impacts in Sichuan in the last 50 years", *Acta Geographica Sinica*, **66**, 5, 619-626.

Zhu, L. K. and Meng, J. J., 2010, "Study on rainfall variations in the middle part of Inner Mongolia, China during the past 43 years", *Environmental Earth Sciences*, **60**, 8, 1661-1671.

Zhu, Y. F. and Yu, R. C., 2003, "Interannual variation of summer precipitation in the west of Sichuan basin and its relationship with large-scale circulation", *Chinese Journal of Atmospheric Sciences*, **27**, 6, 1045-1055.

Zuo, H. C., Lu, S. H. and Hu, Y. Q., 2004, "Variations trend of yearly mean air temperature and precipitation in China in the last 50 years", *Plateau Meteorology*, **23**, 5, 239-244.