Investigation of South Korea Precipitation Variation using Empirical Orthogonal Function (EOF) and Cyclostationary EOF

Mingdong Sun¹, Gwangseob Kim², Xiangxin Xu¹, Yan Wang*¹

¹ Institute of Water Ecology and Environment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
² Department of Civil Engineering, Kyungpook National University, Daegu 702701, South Korea
*Corresponding author’s e-mail: wang.yan@craes.org.cn

Abstract. The monthly precipitation data of 56 stations during 47 years (1973-2019) in South Korea are comprehensively analysed using the EOF technique and CSEOF technique respectively. The main motivation for employing this technique in the present study is to investigate the physical processes associated with the evolution of the precipitation from observation data. The first mode account for 77.07% of the total variance and exhibits annual cycle of corresponding PC time series with traditional spatial pattern, and the second mode spatial patterns account for 8.13% of the total variance and show strong north to south gradient. In CSEOF analysis, two leading modes temporal pattern of PC time series reveals the annual cycle on a monthly time scale and long-term fluctuation, the first mode temporal pattern of PC time series account for 73.55% of the total variance and shows an increasing linear trend which represents that temporal variability of first mode pattern has been strengthened. The spatial distribution corresponding to two leading modes show monthly spatial variation. Compared with the EOF analysis, the CSEOF analysis preferably exhibits the spatial distribution and temporal evolution characteristics and variability of South Korea historical precipitation.

1. Introduction

In East Asia, the monsoon seasons are mainly driven by the interactions between the rapidly changing atmosphere and the tardily changing oceans. Periodically meteorological variation phenomena have attracted the attention of a lot of meteorologists as the main freshwater resource is the precipitation in East Asia. The results of precipitation variations in the timing and amount in a time could bring about some serious disaster, like flooding and droughts. Thus, there have been a lot of research about investigating long-term trends of precipitation and the relationship with global climate change accelerates the water cycle [1, 2]. Some organizations and researchers have indicated that there is more and more interest in the precipitation significantly increases in amount and intensity among the scientific community[3, 4].

Many climatic variable indices, such as surface temperature, precipitation, present obvious periodic (annual, monthly, etc) variations in their statistics fluctuations, which because the cyclic characteristic of weather and climate processes deliver the correlation feature into these variables. While analysis of such datasets it would normally obtain the poor and anamorphic statistical characteristic with the stationary approaches. So, it is evidential that more appropriate and advantageous to adopt a
cyclostationary methodology than a stationary on the statistical analysis of climatic phenomena with some strong cyclic phase.

The precipitation variable is the representative cyclic variations whose statistic fluctuation is recurrent along with seasonal variety. Especially when precipitation is analysed across more stations or spanned over a long different seasons or months, the poor statistical trend and analysis result might be obtained with normal stationary methods. Thus, the spatially distribution and temporal trends of precipitation is still an ongoing research. By adequately using and analysing the most comprehensive datum set, a cyclostationary EOF (CSEOF) analysis technique is employed, which is useful in extracting physical evolving spatial pattern. This study primarily focuses on the most conspicuous component of seasonal cycle and evolution of the South Korea precipitation variable. And will uncover the spatial patterns and temporal patterns of South Korea precipitation variables trends and investigate the corresponding to particular characteristics. In the present study, observational data of precipitation in South Korea with a 47-yr time scale are decomposed via EOF and cyclostationary EOF analysis respectively into the temporal and spatial evolution of individual synoptic fields in the dataset.

2. Methodology and Data

2.1. Methodology

The techniques employed in this study are empirical orthogonal function (EOF) and cyclostationary empirical orthogonal function (CSEOF). These two techniques are particularly useful for extracting time-dependant spatial modes. Empirical orthogonal function (EOF) analysis is among the most extensively applied techniques in oceanographic and atmospheric science[5]. The method can generate the decomposition from a signal or data set base on orthogonal basis functions; it is the same as employing a principal components analysis on the data besides that the EOF analysis method obtains both temporal patterns and corresponding spatial patterns.

In the EOF analysis, space-time data $D(r,t)$ are represented in terms of the loading vectors ($L$) and their principal component ($PC$) time series:

$$D(r,t) = \sum_n PC_n(t)L_n(r)$$

(1)

where $L_n(r)$ and $PC_n(t)$ are specific spatial patterns and their temporal evolutions respectively. The equation indicates that the research data are decomposed into a series of spatial patterns and their evolution of temporal patterns. These loading vectors are usually explained as the physical modes of the data structures and depict the independent spatial patterns of variability in the dataset. These temporal patterns are ordered in the sequence of their magnitudes, they present the oscillations in time evolutions and the related spatial patterns are obtained such that they are orthogonal to one another, and are ordered in the sequence of their magnitudes. EOF analysis has been used in many research and different works[6].

The cyclostationary EOF (CSEOF) is the cyclostationary processes and cyclostationary arithmetic base on the function of EOF in stationary approaches[7, 8]. In the CSEOF analysis, a space-time datum is represented as

$$D(r,t) = \sum_{k=0}^{p-1} c_k(r,t)e^{2\pi ikt/p} = \sum_{k=0}^{p-1} \sum_{m} c_{km}(t)F_k(r)e^{2\pi ikt/p}$$

(2)

where $F_k(r)$ is any basis function, $p$ is the nested period representing the inherent periodicity in the statistics. Through calculation of the covariance function and Bloch function, space-time CSEOF are given by

$$D(r,t) = \sum_n PC_n(t)CL_n(r,t)$$

(3)

where $CL_n(r,t)$ are cyclostationary loading vectors ($CSLV$) and $PC_n(t)$ are their corresponding principal component ($PC$) time series. Different from the conventional EOF analysis, the $CSLV$ are also time-
dependent. The temporal evolution of spatial patterns is further due to the periodic data with a period $p$, that is:

$$CL_n(r,t) = CL_n(r+t+p)$$

Therefor the CSLV are also periodic and time-dependent eigenfunctions of covariance statistics. There is an important key when employing a CSEOF analysis is to decide the nested period $p$, which is the intrinsic period of covariance statistics corresponding to the physical processes. A proper option of the nested period depends on the physical information of the researched datasets[9].

The CSEOF technique is conceptually similar to the EOF techniques and that both techniques extract a time sequence of spatial patterns as an eigenfunction based on the space-time structure of covariance function. However, the crucial difference between EOF and CSEOF is that each CSLV represents a group of spatial patterns that are an independent mode evolves in period time. The vital motivation for the CSEOF is that the spatial patterns of many proverbial phenomena in climate and geophysics evolve in time with clear periods as well as with slow fluctuations on longer time scales. There are some typical applications with CSEOF in this regard. Comparison and assess research works of EOF and CSEOF techniques can be found in the research [10].

2.2. Data
The data of monthly precipitation over South Korea came from the Korea Meteorological Administration (KMA). The 56 weather stations are generally well-distributed across the country, as shown in figure. 1, where some islands were excluded from the analysis. The dataset represents the longest and most consistent precipitation observations, spanning 47 years (1973-2019).

![Figure 1. Location of 56 precipitation stations in South Korea.](image1.png)

![Figure 2. The scree plot of the Accumulated Percent of EOF and CSEOF analysis](image2.png)

3. Result and Discussions
The EOF technique and CSEOF technique have been applied to the monthly precipitation data of 56 stations during 47 years in South Korea. The scree plot of the accumulated percent of EOF and CSEOF analysis are showed in figure 2. The main motivation for employing this technique in the present study is to investigate the physical processes associated with the evolution of the precipitation from the observation data.
An EOF analysis was performed on the unnormalized monthly precipitation data, the two leading EOF modes account for 85.20% of the total variance. Individually, they explain 77.07% and 8.13% of the variance. According to North’s rule of thumb[11], these two leading modes are the magnitude of the total eigenvalues properly, and mostly decomposed the time-space data structure. The temporal and spatial patterns associated with the two leading precipitation modes variability of each EOF represented by the expansion coefficients are described in figure 3, as homogeneous correlation maps.

Figure 3. First and second EOF modes of precipitation: (a) principal component time series of 1st EOF mode, (b) principal component time series of 2nd EOF mode, (c) loading vectors of 1st EOF mode, (d) loading vectors of 2nd EOF mode.

The temporal patterns of PC time series corresponding to first mode, as shown in figure 3a, present an unsymmetrical oscillation with 1-yr period and a slight fluctuation at a longer timescale. And the spatial patterns are shown in figure 3c exhibits an evident northern and southern symmetrical trend. Similar to the first mode temporal patterns in figure 3b, the corresponding second mode PC time series also shows an oscillation with 1-yr period around value of zero. But different from the first mode, shown in figure 3d, the second mode’s spatial patterns display an obviously increasing trend from the north to south.

In applying the CSEOF technique, $d$ (nested period) is set to 12 months since the annual cycle is to be extracted in this study. Based on the monthly precipitation data, the two leading CSEOF modes account for 78.83% of the total variance, individually they explain 73.55% and 5.28% of the variance. As shown in figure 4 and figure 5, the monthly spatial patterns and temporal patterns associated with the two precipitation modes of CSEOF are depicted respectively.

The advantage of CSEOF analysis is well demonstrated in the temporal patterns of PC time series, as shown in figure 4a, the first mode PC time series reveals the evolution of the annual cycle on a monthly time scale, The PC fluctuates around zero and a value smaller or larger than average, which means a weaker or stronger than normal annual cycle.

The first mode spatial patterns of CSEOF in figure 4b mainly describes the annual cycle since it is the representation in all of the modes. These cyclostationary loading patterns are nearly identical with the composite annual cycle. This set of spatial patterns reflects some familiar observations; the most pronounced feature is that the patterns’ spatial distribution are varying along with the seasons.

As shown in figure 5a, resemble to the first mode, the second mode temporal patterns of PC time series also reveal the similar evolution of the annual cycle on a monthly time scale and the PC fluctuates around zero. At the second mode spatial patterns of CSEOF in figure 5b, the spatial distribution are also varying along with the seasons, specially highest in July and lowest in August.
4. Conclusions

The variability of precipitation and the associated temporal and spatial evolution of synoptic fields have been investigated by using EOF and CSEOF analysis respectively in South Korea.

The spatial patterns of two leading EOF modes exhibit then symmetrical trend and increasing trend towards. Corresponding PC time series show an unsymmetrical oscillation with 1-yr period. Hence, the two leading EOF modes commendably described the spatial distribution and temporal evolution characteristic of South Korea historical precipitation.

In CSEOF analysis, the spatial patterns of two leading CSEOF modes varying along with the seasons are the most pronounced feature, these patterns clearly reflect some familiar observations, especially the first mode, where the spatial patterns’ regional distribution regularly transform from winter to summer then to winter. In the second mode, the spatial patterns also show the rainy and rainless regional distribution with recurrent seasons. Corresponding temporal patterns reveals the evolution of the annual cycle on a monthly time scale, both PC fluctuates means a weaker or stronger than normal annual cycle.

Compared with EOF technique analysis, the CSEOF technique analysis more comprehensively displays the spatial distribution and temporal evolution characteristics of South Korea historical precipitation and variability along with recurrent seasons. The CSEOF technique is effective proved that it can facilitate an understanding of the physical interactions among the different component involved in the precipitation evolution.
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