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L-Moments and fuzzy cluster analysis of dust storm frequencies in Iran

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ABSTRACT

In this study, we use the *L*-moments and fuzzy-clustering techniques to analyze dust storm frequencies in Iran. A homogeneity test based on *H* statistics is first carried out using the dust-storm-frequency time series at 122 weather stations. The test shows that dust storms over the study area as a whole do not have the same probabilistic behavior. To identify homogeneous regions within the study area, a fuzzy c-means algorithm based on the *L*-moments of the dust-storm-frequency time series is employed. By use of the cluster validation index, partition coefficient and partition entropy, four clusters are identified, i.e., the first Zagros east cluster (Cluster 1A) and the second Zagros east cluster (Cluster 1B), related respectively to the Dashte Kevir and Dashte-Lout dust source regions, the Zagros west cluster (Cluster 2) and the Iran northwest cluster (Cluster 3). Based on the goodness-of-fit test, Z^{Dist}, the best regional distribution models for Clusters 1A, 1B, 2 and 3 are found to be Pearson III, generalized normal, generalized Pareto and generalized normal distributions, respectively. The different types of the distributions suggest that the dust storms in the different cluster regions are due to different generation mechanisms and are associated with different dust sources. The regional growth curves are then constructed using the regional distribution models. The sharp slope of the growth curve for Cluster 2 and 3 suggests that the dust storms in the northwestern and western parts of Iran are mainly due to dust transport from the Sahara, Rub al Khali and Arabian deserts.

1. Introduction

Dust storm is a major environmental phenomenon in arid and semi arid regions of the world, Iran included. A number of studies have been carried out on the mechanisms of local (Korcz et al., 2009; Liu et al., 2004) and global (Fan and Wang, 2004; Gong et al., 2007) dust storm generations. Korcz et al. (2009) used a mesoscale model to investigate dust emission in Europe and selected regions of North Africa and Southwest Asia. They showed that the spatial variability of dust emission depends on soil texture, land cover and meteorological conditions. Fan and Wang (2004) investigated the relationship between the Antarctic Oscillation (AAO) and the dust weather frequency in North China. Studies on the dust storm frequencies in North Africa and Northeast Asia have been studied in considerable detail (e.g., Klose et al., 2010; Kurosaki and Mikami, 2003; Shao and Wang, 2003). However, the climatic features of dust storms in the Middle East are less well understood (but see Middleton, 1986). To our best knowledge, there have been no comprehensive studies on the use of cluster analysis for the investigation of dust storm patterns. The advantage of applying the cluster analysis technique to dust observations is that it enables the grouping of the observations into clusters based on the similarity of probabilistic behavior of dust storms. In this way, each cluster contains the least variance of variables (smallest dissimilarity). Gottschalk (1985) applied the principal component analysis and cluster analysis techniques to hydrological regionalization of Sweden and found that cluster analysis is a suitable method to use on a national scale for a country with heterogeneous regions.

Dust storm histograms for individual locations are frequently used for dust climate analysis, but they are not sufficient for the characterization of dust activities in a region to answer questions such as the return period of a severe dust storm in a given region. Dust risk analysis and the implementation of dust mitigation measures also demand for investigations on the probabilities and the generation mechanisms of dust storm in different regions. The need to study dust storms from a regional perspective is readily understood. Dust storms, like many other atmospheric events, mostly occur on regional and even global scales. For example, dust over the Arabian Sea may be related to the dust emission from the deserts that stretch from Iran through Afghanistan and Pakistan (Pease et al., 1998a). Dust storms originating from the Gobi may influence the eastern parts of China, Korea and Japan and the dust particles be transported thousands of kilometers over the Pacific

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Ocean. Dust sources themselves may cover large parts of a continent, e.g., the Sahara. Hence, it is important in dust storm analysis to go beyond at-site frequency analysis to obtain a much broad perspective of dust climatology.

The use of the *L*-moments method for regional frequency analysis of large-scale phenomena, such as dust storms, is highlighted here. This method has been extended by Hosking and Wallis (1993) for regional frequency analysis and increasingly used by hydrologists in the studies of regional stream flows (Chen et al., 2006; Kroll and Vogel, 2002; Modarres, 2006; Peng et al., 2010), floods (Jaiswal et al., 2002; Kumar et al., 2003; Lim and Lye, 2003; Neslihan, 2009; Parida et al., 1998; Rao and Hamed, 1997), rainfall (Eslamian and Feizi, 2007; Modarres and Sarhadi, 2010) and wind speeds (Modarres, 2008). On the other hand, the results of regional estimates obtained by using this method are reasonable, only when there exist homogeneous regions. To deal with the homogeneity problem, cluster analysis techniques have been developed to classify the stations in an area into regions (or clusters) that are homogeneous according to certain statistical parameters. Modarres (2009) applied a hierarchical cluster analysis to find smaller homogeneous regions based on the annual maximum dry-spell-length time series in Iran. The cluster analysis can also be applied to studying spatial patterns and variability of a specific phenomenon and to identify the underlying causal mechanism. Romero et al. (1999) and Modarres and Sarhadi (2010) have used cluster analysis to classify rainfall patterns and their relationship to atmospheric circulations.

In traditional methods (the hard partition methods) of clustering, feature vectors can be divided into non-overlapping clusters with well defined boundaries between them. Each feature vector is assigned to one of the clusters with a degree of membership equal to unity. In other words, a site is classified as belonging to a cluster on the basis of distance (or dissimilarity) between the sites and the cluster centroid in the multi-dimensional space of attributes (Srinivas et al., 2002). It is reasonable to suppose that most stations partially resemble several stations and therefore assigning one station to one region (cluster) or another may not be justified. Consequently, identification of regions with vague boundaries between them is preferable compared to crisp regions with well defined boundaries as in the case of hard clustering. Zadeh (1965) introduced fuzzy set theory, Ruspini (1969) introduced the idea of fuzzy clustering and it was used by Dunn (1974) to construct a fuzzy partition clustering method. Fuzzy partition clustering allows a site to belong to all the regions simultaneously with a certain degree of membership. The distribution of membership of a site among the fuzzy clusters specifies the strength with which the site belongs to each region. In recent years, advances in fuzzy set literature have spurred the development and utility of fuzzy clustering methods for a variety of applications in different disciplines.

Despite the importance of the dust-storm-frequency analysis in environmental risk management for air pollution by dust and other contaminants which caused local and regional air quality hazards in Iran, a systematic study of dust storms in Iran has not been done to our best knowledge and there does not seem to exist in the published literature detailed studies on regional dust-storm-frequency analysis.

The aim of this study is to identify the main regional dust storm groups in Iran by coupling *L*-moments and fuzzy cluster analyses. These analyses are used (i) to identify homogeneous regions based on the probabilistic behavior of dust storm events; (ii) to fit the best regional distribution models to the homogeneous regions; and (iii) to estimate regional quantiles (growth curves) of dust storm frequencies for each given region based on the selected distributions. The spatial pattern of the dust storm frequencies and their environmental causal mechanisms are also investigated.

2. Study area and data set

Iran is located between (45°E, 25°N) and (64°E, 40°N) and is surrounded by two mountain ranges, namely, the Elburz to the north and the Zagros to the west. These mountain ranges prohibit the Mediterranean moisture bearing systems to cross through the region in the eastern parts of Iran (Modarres and Silva, 2009) and lead to the different climatic conditions between the west and east flanks of the Zagros and between the north and south flanks of the Elburz.

Several major dust sources exist in Iran. To the east of the Zagros, the deserts stretching from Iran through Afghanistan and Pakistan to northwest India are the main sources of dust, which contribute to the high dust load over the Arabian Sea in winter and spring (Pease et al., 1998b). The great salt desert (Dasht-e Kavir) with an area of 48,000 km^2 is located in a basin situated to the south of the Elburz and the east of the Zagros. The Dasht-e Kavir largely consists of salt flats (Shao, 2008). The western part

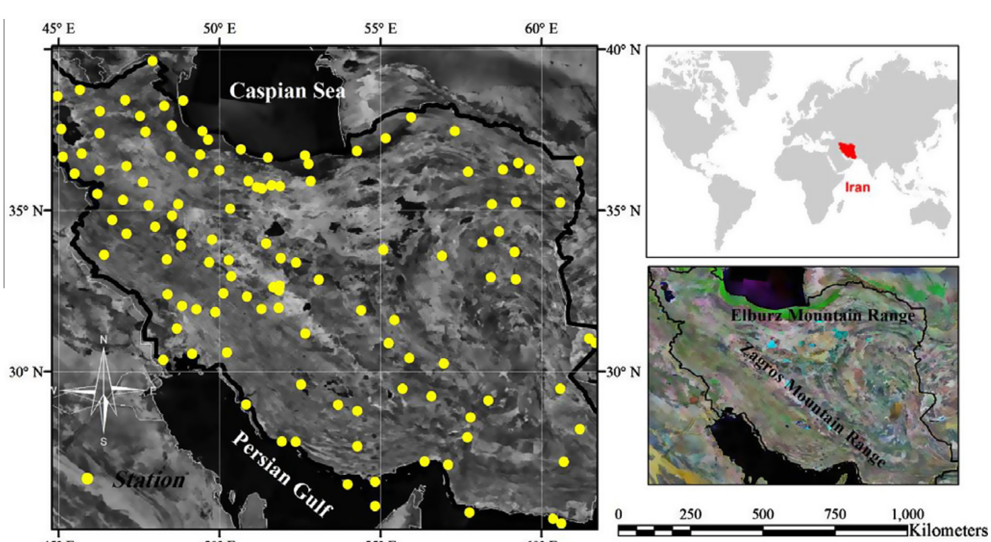

Fig. 1. Spatial distribution of the selected weather stations in the study domain.