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Bivariate trend assessment of dust storm frequency in relation to climate drivers

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Abstract

Climate variability and change in arid regions are important factors controlling emission, frequency and movement of dust storms. This study provides robust statistical methods to detect trends in dust storm frequency across arid regions of Iran in relation to climate variability and trend in recent decades. The univariate trend assessment based on block bootstrapping method and three bivariate trend assessment methods, Covariance Inversion Test, Covariance Sum Test and The Covariance Eigenvalue Test are applied in this study to find if change in dust storm frequency can be attributed to changes in climatic variables. In this regard, the annual number of dust storms from 25 stations in central arid and semi-arid regions of Iran were selected. In addition, five major climatic variables including annual rainfall, annual maximum and average wind speed, annual maximum and average temperature were also collected. The univariate trend test indicates both increasing and decreasing trend in dust storm frequency and climate variables. The bivariate trend test shows a strong and statistically significant relationship between trend of climate variables and dust storm frequency for most of the stations across the region. Among climate variables, rainfall change has an inverse impact on dust storm frequency while wind speed and temperature have direct covariance structure with dust storm frequency. The wind speed also seems to be the most effective climate driver on dust storm frequency in arid regions of Iran, followed by temperature. The results also shows that local conditions that are not considered in this study may also play significant role in dust storm emission in some parts of the region.

Key words: Climate drivers, Dust storm, Block bootstrapping, Multivariate trend, Arid regions, Iran

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1. Introduction

It is a long time that the relevance of dust storms in arid and semi-arid regions has been realized. Environmental impacts of dust storms range from soil degradation and soil loss to air pollution and health risks as well as climate modification from meso- to macroscale (Littmann, 1991).

Although many effective factors on dust storm generation have been discussed, climatic factors are considered to have a major contribution. Many studies have applied climate data and used simple statistical methods to establish the relationship between dust storm frequency (DSF) and climate variability.

For example, Spearman's rank correlation coefficient showed negative relationship between dust frequency and rainfall in Mildure, Australia (Yu et al., 1993). Seasonal wind speed and soil moisture were mentioned as controlling factors of dust storm in eastern Australia (Mc Tanish et. al., 1998). Gao et al., (2003) showed that dry and cold periods correspond with a high frequency of sandstorms, wet and warm periods with a low frequency. The analysis of spring dust storm frequency in northern China indicated a positive and negative relationship of wind velocity and rainfall with DSF, respectively (Liu et al., 2004). Surface wind speed from 6 to 20 ms^{-1} was highlighted by Natsagdotj et al (2003) as an effective factor on frequency of dust storms in Mongolia.

The 23 October 2002 dust storm in Australia was found to be highly related to long term drought condition and concurrent high temperature when soil moisture declined and evapotranspiration increased (Mc Tanish et al., 2005). Gao et al., (2010) suggested strong winds to be helpful in spring dust storm forecasts. They developed a multivariate regression model between predictors such as wind speed and sea surface temperature and dust frequency.

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The above literature review mention that the impact of climate variation and change on dust storm frequency of occurrence is a major issue in the arid regions. It is believed that there is complex interaction between climate variability and dust storm occurrence (Zhang et al., 2002). In other words, both climate variation and dust storms have feedback effects on each other (Yang et al., 2008). Although the potential of climate variability on dust activity has been recognized, advanced statistical techniques have not been developed for dust storm-climate relationships through climate change context. This states that in a changing climate when the climatic variables vary in time, the frequency of dust storms may change in time. This implies the joint behavior of climate drivers and dust storm occurrence. However, this issue has not been considered in literature of dust storm-climate relationship. This study aims to develop a new multivariate trend analysis in order to establish a dynamic relationship between dust storm occurrence and climate variability. In contrast to previous statistical methods such as correlation coefficient and regression analysis which present a rigid relationship between dust frequency and climate variables in time, multivariate trend analysis not only shows a secular trend for any single dust and climatic variables but also considers a change in dust storm frequency in relation to the change in climate variables in through time. The basic hypothesis to be tested by multivariate trend assessment is that the covariance structure between dust storm frequency and rainfall, as a source for soil moisture, is negative but this structure is positive for temperature and wind speed.

We provide details of study region and data in section 2. This section is followed by methodology of univariate and multivariate trend tests. Results and discussion on climate and dust storm multivariate relationship will be given in section 4. The conclusion and recommendation sections will be presented at the end of the paper.

2. Region of Study and data

Arid and semi-arid regions of Iran cover more than 60% of the country covering the central parts of Iranian plateau. Our analysis is based on ground-based observation of the annual total number of dust storms and five climatic variables (annual maximum wind speed, annual average wind speed, annual maximum temperature, annual average temperature and annual total rainfall) from 25 stations launched by the Iran Meteorological Organization across desert regions of Iran. These regions cover more than 60 percent of the country and locate in the central parts of the Iranian plateau. This vast region receives between 250 to 50 mm rainfall in the year due to surrounding two major mountains in the north (e.g. Alborz Mountain) and in the west (e.g. Zagros Mountains). During decades of land use change, increasing abandoned agricultural fields and harsh dry conditions, dust storms have become a major phenomenon (Modarres and Sadeghi, 2017). In this vast region, climate variable such as rainfall, temperature and wind speed and their impacts on dust emission change in both time and space. In order to investigate tend in dust storm frequency in relation to climatic change, annual number of dust storms recorded at 25 stations were gathered. These data are recorded by the Iran Meteorological Organization. Dust storm is considered the events when horizontal visibility is less than 1 km. Along with dust data, climate variables, total annual rainfall, annual average wind speed, annual maximum wind speed, annual average temperature and annual maximum temperature were also collected. The location map of these stations is provided in Figure 1.

3. Methods for trend assessment

3.1. Univariate trend

In the univariate trend analysis, there exist several approaches to detect trends in hydro-climatic variables (Faucher et al., (1997), among which, a widely employed method is the

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non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975). However, a major issue regarding the use of MK test for hydro-climatic variables is the existence of the serial correlation which influences the relevance of MK trend test (Khaliq et al., 2009)

In order to overcome this problem, we employ block bootstrap (BBS) Mann-Kendall test (Onoz and Bayazit, 2012) to estimate monotonic trends for both annual climatic variables and dust frequency at selected stations across arid regions of Iran.

For a single time series of *n* random observations, the MK test statistics is calculated based the sign of the difference between two consecutive observations, $sgn(x_j - x_i)$. The sign function is

$$sgn(x) = 1\ if\ x > 0; = 0\ if\ x = 0; = -1\ if\ x < 0 \qquad (1)$$

And then

$$M = \sum_{1 \le i \le j \le n} sgn(x_j - x_i) \qquad (2)$$

Under the null hypothesis (H_0) of no monotonic trend, M has asymptotically normal distribution with mean zero and approximated variance:

$$Var(M) = n(n-1)(2n-5)/18 \qquad (3)$$

3.2.Multivariate trend

The multivariate MK test is a simple extension of univariate test (Chebana et al., 2013). Having d number of time series, and under the null hypothesis, $M = (M^{(1)}, \dots, M^{(d)})'$ is asymptotically d-dimension normal with zero mean and covariance matrix $C_M = (c_{u,v})_{u,v=1,\dots d}$ with $C_{u,v} = cov\left(M^{(u)}, M^{(v)}\right)$. The following equations are used to estimate the covariance between each pairs of time series:

$$C_{u,v} = \frac{t_{u,v} + r_{u,v}}{3} \quad \text{for } u \neq v \qquad (4)$$

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Where

$$t_{u,v} = \sum_{1 \le i < j \le n} sgn((x_j^{(u)} - x_i^{(u)})(x_j^{(v)} - x_i^{(v)})) \quad (5)$$

$$r_{u,v} = \sum_{i.j.k=1}^{n} sgn((x_k^{(u)} - x_j^{(u)})(x_k^{(v)} - x_i^{(v)})) \quad (6)$$

There are three tests for multivariate trend assessment which are based on the covariance structure between two time series (here the frequency of dust storms and climate variables), namely the Covariance Inversion Test (CIT), Covariance Sum Test (CST) and Covariance Eigenvalue Test (CET). The detail formulation of these test are provided by Chebana et al., 2013). To avoid repetition, here we provide the test statistics only.

The test statistic of the CIT test is

$$D = M' C_M^{-1} M \quad (7)$$

This statistic is asymptotically $\chi^2(q)$-distributed under H_0, where q is the rank of C_M with $1 \le q \le d$.

The test statistic for CST test is

$$H = l' M = \sum_{u}^{d} M^{(u)} \quad (8)$$

With $l = (1, \ldots, l) \epsilon R^d$. The statistic H is asymptotically normal under the null hypothesis.

The test statistic of CET test is a

$$L = M' M = \sum_{u=1}^{d} (M^{(u)})^2 \quad (9)$$

This statistic is asymptotically $\sigma^2 \chi^2(q)$-distributed where q is the rank of C_M as given in (4).

The null hypothesis is rejected if the value of the above test statistics exceeds the critical thresholds determined according to the related distribution quantile.

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According to Chebana et all (2013) who provided the literature review on the performance of CIT, CST and CET tests, CIT test does not performance is poor for small data set (n=10) and its power is equal to other tests. The CST performs better even for small sample size. However its performance is not powerful enough if the univariate MK statistics have different signs. The CET displays an overall relatively good power and therefore represents the best method. It should also be noted that the results of CIT and CET are almost identical for large samples.

4. Results and discussion

4.1. Univariate trend test

In this section the univariate BBS Mann-Kendall test is applied to climate and dust frequency time series. The Z statistics and corresponding *p*-values are shown in Table 1. We can see that the northern and eastern margins of the Iranian deserts show negative trend while increasing frequency of dust storms are observed in the middle, south and western parts of the region. In general, 12 stations shows positive dust storm frequency trend and 13 stations shows negative dust storm frequency trends across region.

The stations with positive statistically significant dust storm frequency trend are called "Group A". This group includes Zahedan, Iranshahr, Bandarabbas, Fasa and Tabas stations. The stations with negative significant trend are called "Group B" which includes Kerman, Sharood and Sirjan. Other stations with no significant dust storm trends are called "Group C", henceforth.

The annual rainfall trend assessment shows a decreasing trend for most of the stations across arid region (all groups). However these negative trends are not statistically significant except for Zahedan station, from group A, and Kerman station, from group B, which are located in the southeastern regions.

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In the case of average temperature, results show both negative and positive trends where positive temperature trend is mostly observed for stations located in the western margins or the middle south to southeastern regions. It is interesting to note that the average temperature trend is showing different and similar sign to the sign of dust frequency trend for many stations. In group A, Zahedan and Tabas stations show positive, but not statistically significant, trend in average temperature. In Group B, all stations show positive and non-significant trend in average temperature. In contrast, maximum temperature shows increasing trend in most of the stations. This increasing trend is observed for all stations in Group A, except for Iranshahr station. In group B, maximum temperature also shows increasing trend which are also statistically significant for Kerman and Fasa stations.

The univariate trend test indicates that average wind speed has increased in half of the stations around arid regions of Iran. In group A, only Iranshahr and Sirjan stations show positive trend where Iranshahr trend is statistically significant. In group B, Tabas and Kerman stations show positive and Fasa station shows negative trend in average wind speed, all of which are not statistically significant. The maximum wind speed, however show increasing trend in most if the stations. In group A, Only Zahedan station shows negative trend. The statistically increasing trend in maximum wind speed, however, can only be observed for Iranshahr and Bandarabbas stations. In group B, maximum wind speed has increased but only for Fasa station shows significant trend.

4.2.Multivariate trend test

The multivariate test assessment using three procedures, CST, CIT and CET, is described here for each climate variable separately.

4.2.1. Rainfall

Rainfall and dust storm frequency relationship shows both positive and negative sign for CST, CIT and CET results (Table 2) when negative signs are dominant cross the region. This may imply that dust storm has an increasing covariance relationship with rainfall reduction as a climate driving factor. These stations are observed in the north and western parts. The stations located in the south and southeastern parts have usually positive sign in multivariate trend statistics. Looking at stations in Group A shows positive and significant signs for all stations where rainfall trend is negative. In group B, the sign of multivariate trend test's statistics is negative while rainfall trend is positive, except for Sharood station.

Generally we can see that rainfall as the driving factor has an inverse covariance structure with temporal trend in dust storm frequency for most of the stations. Although a few bivariate trend statistics are statistically significant but the opposite sign of dust storm frequency and rainfall trend is dominant in the region (Group C).

4.2.2. Maximum wind speed

Gusty winds in the study regions show increasing trend for most of the stations among which one third of them are statistically significant According to multivariate trends statistics' sign, most of the stations have positive sign; though a few of them show decreasing trend in maximum wind speed (Table 3). Among 12 stations with positive wind speed trend, there are 10 stations with the same multivariate trend sign. For 13 stations with negative trend of wind speed, 9 stations have the same sign of multivariate test.

In group A, all stations have both positive trend in dust frequency and positive statistically significant multivariate trend sign, except Zahedan station. In group B, the sign of multivariate trend is negative and statistically significant while the maximum wind speed has positive trend.

For other stations (group C) the sign of dust storm bivariate trend and maximum wind speed have almost the same direction. In other words, the increasing/decreasing trend in wind speed seems to make effective influence on increasing/decreasing change in dust storm frequency. The effectiveness of wind speed change on temporal variation of dust storm frequency can also be seen through the test statistics of CIT and CET method which are statistically significant for many stations.

4.2.3. Average wind speed

Regarding CIT and CET, average wind speed has significant influence on dust storm frequency trend. This significant influence can be observed for most of the stations except four stations, namely Abadeh, Mashad, Konarak and Minab (Table 4). Among 12 stations with positive dust storm frequency trend, there are 7 stations with positive signs of multivariate test while for 13 stations with negative dust storm frequency trend, there are 11 stations with the same covariance suture with average wins speed change.

In group A, the sign of multivariate trend statistic is positive for all stations while two stations have different signs of univariate trend in dust frequency and wind speed, e.g. Bandarabbas and Fasa stations. In group B, multivariate trend sign is negative and significant. While only at Sirjan station average wind speed has positive trend, at other stations univariate and multivariate trend statistics have the same sign.

Similar to gusty wind trend, the bivariate trend sign is the same as average wind speed for large number of stations (Group C), however, this is not true for a few stations. It is also observed that the bivariate trends are statistically significant according to CIT and CET tests.

4.2.4. Maximum temperature

The results of multivariate trend for maximum temperature are given in Table 5. Both positive and negative signs of multivariate trend are observed and a number of stations show significant CIT and CET results while they are less than those significant CIT and CET for maximum wind speed. Among 12 stations with positive maximum temperature trend sign, only 7 stations have the same covariance structure. For the stations with decreasing trend of dust storm frequency, 11 stations show the same multivariate sign as the sign of univariate test. For group A, the sign of multivariate and univariate statistics are the same, implying direct association between maximum temperature and dust storm increasing trend. In group B, the sign of multivariate trend is negative and the maximum temperature is showing increasing trend. This may indicate that for these stations maximum temperature has inverse effect of dust storm frequency.

Similar to other variables, there are some stations where the sign of dust storm and maximum temperature are not the same which are for negative dust storm frequency trends only.

4.2.5. Average temperature

The multivariate trend results for average temperature are presented in Table 6. The number of significant statistics is higher than those for maximum temperature in Table 5. However, for maximum temperature the number of positive and negative signs are almost the same.

In group A, all multivariate trend signs are positive while only two out of 5 stations show positive trend in average temperature. However, in Group B, negative multivariate signs are observed while average temperature shows an increasing trend. This is the same as the results for maximum temperature for this group.

For other stations, the number of stations with the same signs of bivariate and univariate test is high but less than those for maximum temperature. The number of stations with positive univariate test, 11 stations have the same multivariate sign. Among stations with negative univariate trend, 7 stations show the same covariance structure with temporal change of the

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average temperature. It is also observed that the results of CIT and CET test give more significant results than the CST test which is the same as other climatic variables.

5. Conclusions

Climate changes and variability are effective factors on dust storm emissions. In arid regions of Iran where dust storms are frequent phenomenon, we show that the monotonic trend of dust storm frequency can be related to change in climate variables. Based on the univariate test, trends of the dust storm frequency and climate variables are showing both negative and positive trend but not statistically significant for most of the stations.

However, the bivariate trend methods indicate the significant role of changing climate in temporal change of dust storms frequencies. For most parts of the region, the dependence structure between climate variables and dust storm frequency is significant.

Among climate drivers in this study, the maximum wind speed and temperature are potential drivers on changing dust storm frequency with the same direction of changes. Their potential effects are usually observed for stations with positive trends. The effect of wind and pressure on dust storm occurrence was also shown by Hermida et al., (2018) across Arabian Peninsular. Though in an indirect effect and for western regions of Iran, Amanollahi et al., (2015) showed the effect of the temperature difference between Mediterranean Sea and Syrian deserts can cause dust storms in the western regions of Iran.

Rainfall, in contrast, has inverse effect on temporal change of dust storm frequency in many stations. For many stations, rainfall temporal increase has negative impact on dust storm change regarding bivariate trend sign. However, the effectiveness of rainfall is less than those for wind speed and temperature. Wang Et al., (2017) also indicated the importance of increasing wind and precipitation reduction on dust storm frequency in Northern China.

There are few stations where dust frequency show insignificant relation to climate variability or the hypothesis of this study (see last paragraph of the section 1) is rejected. This may be due to local conditions that are not considered in this study which cause local influence on the effect of gusty winds, high temperature and rainfall reduction on dust storm occurrence. This may arise from three facts. First of all, the temporal land use/land cover changes have not been considered in this study due to unavailable data. Secondly, the temporal scale of this study is annual and some potential seasonal effects have been merged with other seasons so that the seasonal effects are not taken into account. Another reason may reflect the development of green space and rehabilitation of desert regions by plantation, mulching, etc, in recent decades that may reduce the effective of climate variables on dust storm emission.

The last important point to be noted is the performance of bivariate tests applied in this study. As mentioned before, the CET and CIT test are relatively stronger to detect bivariate trend. The results of this study also show more significant bivariate trend statistics for these two tests than those belong to CST test. This may show that the dependence between climatic variables and dust storm frequency is relevant. In other words, the covariance structure between dust storm occurrence climate drivers is very strong. General, the hypothesis of this study is strongly accepted in arid and semi-arid regions of Iran, in spite of the existence of a few stations which do not support our hypothesis.

6. Future research

This study applied dust storm frequency multivariate trend assessment due to climate variables in the annual time scale. It is highly recommended to use seasonal or monthly time scale data for multivariate trend assessment. One of the main factors affecting dust storm is the land cove change which was not considered in this study. It is therefore important to apply land cover indices time series, such as NDVI, in future studies.

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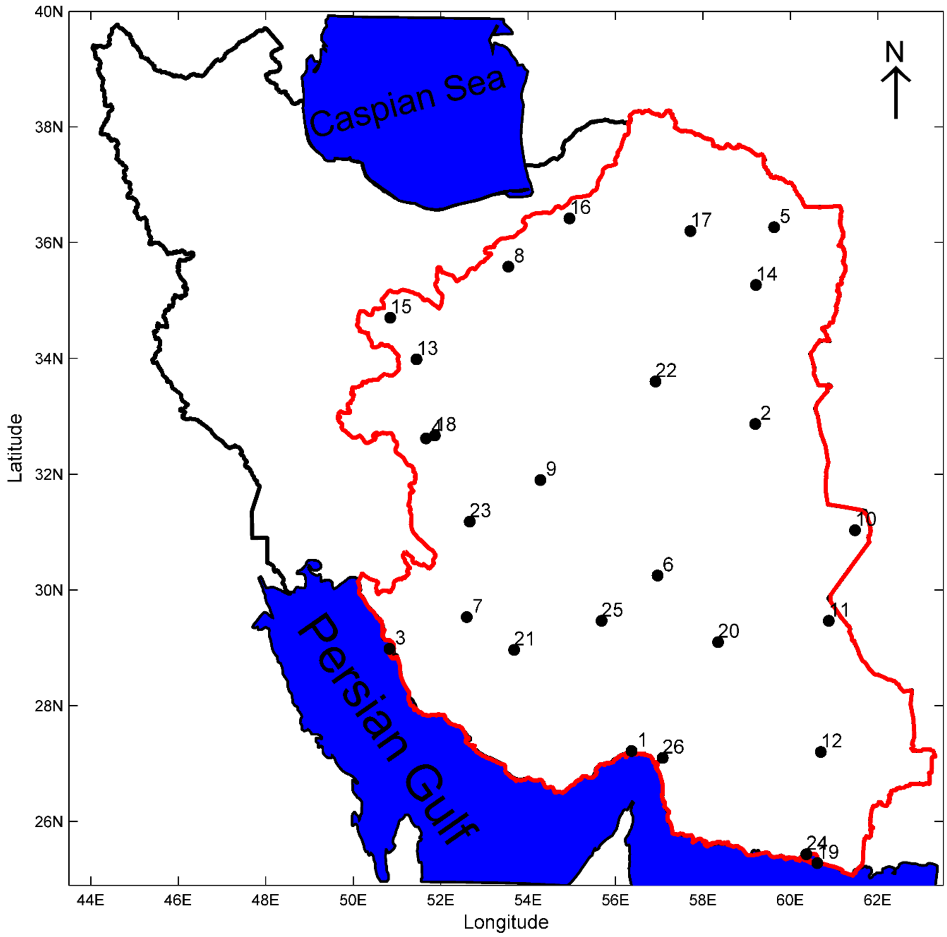

Figure 1. Location map of meteorological stations in arid and semi-arid regions of Iran

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Table 1. MK Test statistic, Z, and related *p*-values for univariate trend test. Bold values are statistically significant at 5% level and less. Numbers are corresponding the stations in Figure 1.

Station Name	Dust Frequency		Maximum wind speed		Average wind Speed		Maximum Temperature		Average temperature		Annual rainfall	
	Z	P-value	Z	P-value	Z	P-value	Z	P-value	Z	P-value	Z	P-value
1. Abadeh	-0.03	0.88	0.15	0.33	0.08	0.68	0.02	0.81	-0.08	0.55	0.02	0.89
2. Isfahan	-0.02	0.93	***-0.22***	***0.02***	***-0.56***	***0.01***	0.17	0.26	***0.49***	***0.00***	0.14	0.10
3. Iranshahr	***0.40***	***0.04***	***0.46***	***0.00***	***0.38***	***0.04***	-0.15	0.19	-0.33	0.08	-0.07	0.59
4. Bam	0.27	0.11	0.14	0.19	-0.02	0.93	***0.32***	***0.00***	***0.36***	***0.00***	-0.07	0.42
5. Bandarabbas	***0.44***	***0.01***	***0.26***	***0.02***	-0.02	0.93	***0.26***	***0.02***	-0.28	0.13	-0.04	0.69
6. Birjand	-0.20	0.17	-0.10	0.32	-0.07	0.66	-0.10	0.32	-0.07	0.70	-0.15	0.10
7. Torbat	-0.29	0.08	***0.32***	***0.02***	0.27	0.17	-0.22	0.05	-0.30	0.13	-0.06	0.58
8. Chabahar	0.23	0.17	-0.21	0.12	0.02	0.91	-0.21	0.13	-0.16	0.39	0.07	0.45
9. Zabol	0.13	0.46	***0.41***	***0.02***	***0.45***	***0.02***	0.11	0.39	-0.09	0.46	-0.11	0.27
10. Zahedan	***0.33***	***0.02***	-0.14	0.18	-0.23	0.15	0.09	0.30	0.33	0.05	***-0.23***	***0.02***
11. Sabzevar	-0.25	0.20	-0.06	0.77	-0.11	0.65	0.11	0.21	0.18	0.08	0.07	0.37
12.Semnan	-0.09	0.56	0.26	0.05	0.16	0.46	0.09	0.38	-0.02	0.88	0.01	0.89
13. Sirjan	***-0.44***	***0.04***	0.10	0.47	0.27	0.08	0.12	0.17	0.28	0.15	-0.14	0.30
14. Sharood	***-0.39***	***0.00***	0.31	0.08	-0.34	0.10	***0.30***	***0.00***	0.22	0.12	0.07	0.44
15. East Isfahan	-0.34	0.06	***-0.31***	***0.04***	0.12	0.50	0.13	0.27	***0.47***	***0.02***	0.08	0.30
16. Shiraz	0.32	0.10	0.18	0.05	***-0.42***	***0.01***	***0.36***	***0.00***	***0.50***	***0.01***	-0.06	0.53
17. Tabas	***0.37***	***0.01***	***0.42***	***0.03***	0.21	0.30	0.15	0.14	0.17	0.12	-0.03	0.71
18. Fasa	***0.58***	***0.00***	0.33	0.12	-0.12	0.56	***0.32***	***0.00***	-0.12	0.28	-0.12	0.23
19. Ghom	0.21	0.11	0.23	0.05	0.20	0.32	***0.42***	***0.00***	0.12	0.49	0.06	0.60
20. Kashan	-0.06	0.62	***0.39***	***0.01***	0.29	0.13	0.00	0.97	***-0.25***	***0.04***	-0.10	0.18
21. Kerman	***-0.43***	***0.00***	0.18	0.19	-0.36	0.08	***0.30***	***0.00***	0.00	0.99	***-0.23***	***0.01***
22. Konarak	0.16	0.41	0.09	0.51	0.16	0.44	***-0.34***	***0.02***	0.05	0.82	0.03	0.80
23. Mashad	-0.06	0.66	***0.22***	***0.01***	0.07	0.71	***0.25***	***0.02***	***0.53***	***0.00***	-0.07	0.41
24. Minab	-0.22	0.31	-0.03	0.81	-0.08	0.65	0.19	0.15	0.04	0.76	-0.11	0.41
25. Yazd	0.01	0.97	***-0.24***	***0.02***	-0.16	0.42	0.11	0.28	***0.41***	***0.00***	-0.05	0.53

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Table 2. Multivariate Mann-Kendall trend test and related *p*-values between dust frequency and total rainfall

Station Name	CST	CIT	CET	Sign
Abadeh	0.925	0.976	0.975	-
Isfahan	0.501	0.220	0.212	+
Iranshahr	0.109	***0.000***	***0.000***	+
Bam	0.388	***0.013***	***0.010***	+
Bandarabbas	0.081	***0.000***	***0.000***	+
Birjand	0.100	***0.009***	***0.033***	-
Torbat	0.112	**0.004**	**0.004**	-
Chabahar	0.169	**0.034**	**0.047**	+
Zabol	0.980	0.224	0.148	-
Zahedan	0.700	***0.000***	***0.000***	+
Sabzevar	0.399	***0.017***	***0.014***	-
Semnan	0.639	0.304	0.254	-
Sirjan	0.098	***0.003***	***0.003***	-
Sharood	0.245	***0.000***	***0.000***	-
East isfahan	0.332	***0.012***	***0.010***	-
Shiraz	0.256	***0.003***	***0.003***	+
Tabas	0.146	***0.001***	***0.001***	+
Fasa	***0.045***	***0.000***	***0.000***	+
Ghom	0.212	**0.043**	0.078	+
Kashan	0.990	0.980	0.943	-
Kerman	***0.003***	***0.000***	***0.000***	-
Konarak	0.452	0.346	0.384	+
Mashad	0.626	0.672	0.691	-
Minab	0.399	0.220	0.230	-
Yazd	0.828	0.886	0.884	-

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Table 3. Multivariate Mann-Kendall trend testing *p*-values between dust frequency and maximum wind speed

Station Name	CST	CIT	CET	Sign
Abadeh	0.672	0.419	0.426	+
Isfahan	0.245	***0.032***	***0.034***	-
Iranshahr	**0.002**	**0.000**	**0.000**	+
Bam	0.105	***0.011***	***0.006***	+
Bandarabbas	**0.005**	***0.000***	***0.000***	+
Birjand	0.146	**0.037**	**0.033**	-
Torbat	0.974	**0.000**	**0.000**	+
Chabahar	0.786	**0.009**	**0.022**	+
Zabol	0.062	**0.000**	**0.001**	+
Zahedan	0.343	***0.000***	***0.000***	+
Sabzevar	0.198	***0.012***	***0.020***	-
Semnan	0.738	***0.010***	***0.018***	+
Sirjan	0.375	***0.002***	***0.002***	-
Sharood	0.480	***0.000***	***0.000***	-
East Isfahan	***0.041***	***0.002***	***0.001***	-
Shiraz	***0.028***	***0.000***	***0.000***	+
Tabas	***0.006***	***0.000***	***0.000***	+
Fasa	***0.002***	***0.000***	***0.000***	+
Ghom	0.165	0.073	***0.031***	+
Kashan	0.353	***0.013***	***0.030***	+
Kerman	0.290	***0.000***	***0.000***	-
Konarak	0.332	0.238	0.248	+
Mashad	0.582	0.085	0.091	+
Minab	0.456	0.241	0.214	-
Yazd	0.309	***0.048***	***0.048***	-

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Table 4. Multivariate Mann-Kendall trend testing *p*-values between dust frequency and average wind speed

Station Name	CST	CIT	CET	Sign
Abadeh	0.672	0.419	0.426	+
Isfahan	0.245	***0.032***	***0.034***	-
Iranshahr	***0.002***	***0.000***	***0.000***	+
Bam	0.105	***0.011***	***0.006***	+
Bandarabbas	***0.005***	***0.000***	***0.000***	+
Birjand	0.146	***0.037***	***0.033***	-
Torbat	0.974	***0.000***	***0.000***	+
Chabahar	0.786	***0.009***	***0.022***	+
Zabol	0.062	***0.000***	***0.001***	+
Zahedan	0.343	***0.000***	***0.000***	+
Sabzevar	0.198	***0.012***	***0.020***	-
Semnan	0.738	***0.010***	***0.018***	+
Sirjan	0.375	***0.002***	***0.002***	-
Sharood	0.480	***0.000***	***0.000***	-
East isfahan	**0.041**	***0.002***	***0.001***	-
Shiraz	**0.028**	***0.000***	***0.000***	+
Tabas	**0.006**	***0.000***	***0.000***	+
Fasa	**0.002**	***0.000***	***0.000***	+
Ghom	0.165	0.073	***0.031***	+
Kashan	0.353	***0.013***	***0.030***	+
Kerman	0.290	***0.000***	***0.000***	-
Konarak	0.332	0.238	0.248	+
Mashad	0.582	0.085	0.091	+
Minab	0.456	0.241	0.214	-
Yazd	0.309	***0.048***	***0.048***	-

Table 5. Multivariate Mann-Kendall trend testing *p*-values between dust frequency and maximum temperature

Station name	CST	CIT	CET	Sign
Abadeh	0.833	0.933	0.934	-
Isfahan	0.515	0.256	0.243	+
Iranshahr	0.286	***0.000***	***0.000***	+
Bam	***0.016***	***0.000***	***0.000***	+
Bandarabbas	***0.005***	***0.000***	***0.000***	+
Birjand	0.146	***0.037***	***0.033***	-
Torbat	***0.041***	***0.002***	***0.001***	-
Chabahar	0.786	***0.009***	***0.022***	+
Zabol	0.266	0.152	0.165	+
Zahedan	0.073	***0.001***	***0.001***	+
Sabzevar	0.483	***0.010***	***0.009***	-
Semnan	0.997	***0.047***	0.091	+
Sirjan	0.397	***0.001***	***0.002***	-
Sharood	0.537	***0.000***	***0.000***	-
East isfahan	0.437	***0.006***	***0.007***	-
Shiraz	***0.006***	***0.000***	***0.000***	+
Tabas	***0.033***	***0.000***	***0.000***	+
Fasa	***0.002***	***0.000***	***0.000***	+
Ghom	***0.044***	***0.001***	***0.001***	+
Kashan	0.825	0.916	0.892	-
Kerman	0.466	***0.000***	***0.000***	-
Konarak	0.786	0.090	0.072	-
Mashad	0.376	***0.007***	***0.010***	+
Minab	0.988	0.094	0.064	-
Yazd	0.683	0.583	0.582	+

Table 6. Multivariate Mann-Kendall trend testing *p*-values between dust frequency and average temperature

Stations	CST	CIT	CET	Sign
Abadeh	0.715	0.780	0.785	-
Isfahan	***0.024***	***0.000***	***0.000***	+
Iranshahr	0.791	***0.000***	***0.000***	+
Bam	***0.006***	***0.000***	***0.000***	+
Bandarabbas	0.441	***0.000***	***0.000***	+
Birjand	0.221	0.070	0.058	-
Torbat	***0.012***	***0.000***	***0.000***	-
Chabahar	0.704	***0.047***	***0.028***	+
Zabol	0.983	0.109	0.161	+
Zahedan	***0.005***	***0.000***	***0.000***	+
Sabzevar	0.645	***0.007***	***0.004***	-
Semnan	0.433	0.305	0.235	-
Sirjan	0.411	***0.003***	***0.002***	-
Sharood	0.363	***0.000***	***0.000***	-
East isfahan	0.607	***0.000***	***0.000***	+
Shiraz	***0.000***	***0.000***	***0.000***	+
Tabas	***0.032***	***0.000***	***0.000***	+
Fasa	***0.045***	***0.000***	***0.000***	+
Ghom	0.263	***0.115***	***0.107***	+
Kashan	0.283	***0.023***	***0.028***	-
Kerman	***0.031***	***0.000***	***0.000***	-
Konarak	0.443	0.417	0.275	+
Mashad	***0.025***	***0.000***	***0.000***	+
Minab	0.482	0.239	0.236	-
Yazd	*0.052*	***0.000***	***0.000***	+