

Determination of dust storms by Hoffman index in Tehran, Iran and compare with remote sensing, and responsible organizations from March 2014 through March 2015

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ABSTRACT:

Introduction: The occurrence of dust storms in recent years, has led to the use of data recorded in ground measurements stations to determine the sources and investigate the occurrence of these storms in the past; however, it is associated with the possibility of measurement errors or failures in some cases.

Materials and methods: In this study, using the data records by synoptically stations, dust storms that occurred in Tehran during March 21, 2014 to March 20, 2015 were determined.

To verify the detected cases of dust storms through the index, satellite imagery was collected and analyzed on the days. For remote sensing, Modis Level 1 images were processed using the ENVI 5.3. In order to show dust, NDDI, BTDD (32-31), and BTDD (20-31) indices were used. Finally, the sensitivity and specificity of all two items were compared with the weather data announced on these days; using R software.

Results: Results indicate, compared to actual observations, that the sensitivity of this method was 100% and its specificity was 98%.

Conclusion: Because the index used in this study consisted of three parameters of wind speed, PM₁₀ concentration, and horizontal visibility, it minimized the possibility of mistakes due to the simultaneous use of all three parameters to show dust storms.

Introduction

A dust storm is a natural phenomenon that occurs in arid and semi-arid areas. The occurrence of dust storms has recently increased in Iran, especially in the west and southwest areas, and has had adverse effects on the climate, environment, daily activities, and human health [1]. Determining the contamination caused by these events is

important to manage and reduce the risk of this phenomenon. For this reason, it is very important to choose an appropriate method for identifying the severity of this phenomenon.

One of the dust sources in Iran is located in the south of the Alborz Mountains, which extends from Tehran to 60° latitude.

There is a desert plain in this area, which includes

salt plains located in the western part of the region, an area that ends in Tehran. There are many drainage channels, temporary lakes and lagoons, and salt lakes in the area [2].

Over the past few years, suspended particulate pollutants have been introduced as a pollutant source in the city of Tehran. Tehran Air Quality Control Agency in its annual report in 2014 stated that all polluted days in this year were caused by an increase in the concentration of particulate matter less than 10 and 2.5 μm (PM_{10} and $\text{PM}_{2.5}$) [3].

Meteorological parameters have an effective role in the sustainability and diffusion of air pollutants. The wind is effective in translating and moving the particles, depending on their size and direction.

When strong winds rise in areas that are prone to dust, it raises and carries these particles, which has many adverse effects in these areas [4]. One of the most common effects of dust storms is reduced horizontal visibility. Horizontal visibility during dust storms is a decisive factor that can be used to estimate the dust concentration [5, 6].

Many studies have used horizontal visibility for reporting storms events. Based on horizontal visibility reports, there is a dust belt in Asia extending from the Arabian Peninsula to Mongolia in China [7]. In this belt, the main dust activity is in the Arabian Peninsula, the Middle East, and southwest and central Asia, including: Iran, Turkmenistan, Afghanistan, Pakistan, North India, and the Gobi Desert in Mongolia and Tarim plain in China [8].

Because other factors can also affect the horizontal view, these factors should also be included in the reports. What is clear is that dust concentration during these events is an important factor.

In dust storms, the concentration of PM_{10} will increase air quality stations in the same or farther locations. Thus, seasonal and regional differences

in dust phenomena can be determined through using the PM_{10} data recorded in the air quality stations [9, 10].

Many studies have shown a link between increased PM_{10} concentrations and the occurrence of dust storms.

In 2000, a study showed the difference in the concentration and the maximum and minimum concentration in different sites using hourly PM_{10} concentration data from 72 sampling stations in Taiwan [11].

In the southeast of Zahedan in Iran, were measured the airborne particles less than 1 μm , 2.5, and 10 μm between July 2008 and March 2010, and were examined the relationship between their values and their daily, seasonal, and annual differences. Results showed that the PM_{10} concentration peaked in the summer [10].

In Iran, a study was measured the average concentrations of PM_{10} , $\text{PM}_{2.5}$ and PM_1 in Ahwaz in April-September 2010. Ahwaz suffers from dust coming from southern Iraq. According to the results, the concentration of PM_{10} , $\text{PM}_{2.5}$, and PM_1 was 320-470, 70-83, and 35-37 $\mu\text{g}/\text{m}^3$, respectively [12]. In 2012, in Iran were measured the concentration of PM_{10} in several cities under the influence of sandstorms, and observed that the annual concentration of PM_{10} in most cities was above 75 $\mu\text{g}/\text{m}^3$ [13].

Therefore, increased PM_{10} levels at air quality monitoring stations can be a sign of dust storm. However, but only high levels of PM_{10} cannot be a sign of a dust storm and This parameter can be considered by measuring other parameters such as wind speed and horizontal visibility. According to Hoffmann Theory, the concentration of PM_{10} , wind speed, and horizontal visibility are the main attributes of a dust storm.

In 2008, Hoffman ranked the dust storms severity according to these parameters. These features can be obtained from data recorded in ground mea-

surements. These three parameters are the main characteristics of dust storms. According to this system, five types of dust phenomena are defined. Hoffman sampling all the suspended particles and measured their diameter and found that the average particle diameter was 23 μm and that PM_{10} particles comprised 58 to 63% of the mass of the total accumulated particles [14].

Another instrument that is widely used, especially in areas where dust storms occur repeatedly, is satellite imagery. The use of satellite imagery to observe dust events and determine the aerosol character of the globe has become a common practice. Satellite imagery provides new information on the dust phenomena in different areas of the earth, especially areas that cannot be easily accessed by land-based information maps.

Dust phenomena can be seen by satellite images in different spectral channels. However, the accuracy of the results depends on different parameters such as the spatial resolution, radiometry, and spectral properties of the images, the method of using spectral bands, defined thresholds, atmospheric conditions, atmospheric states, clouds, etc [1].

Multiple sensors are used for this purpose on most satellites. The most commonly used sensor is the Modis, which is installed on the NASA's Earth Observing System (EOS), TERA and AQUA satellites. It allows observation by using 36 spectral bands at wavelengths of 0.41 to 14.4 μm and spatial resolution of 0.25, 0.5 and 1 km[5].

There has been an increase in the use of remote-sensing instruments to determine the sources and routes of these storms in recent years; however, it is not possible to solely rely on these images, especially in local storms that occur in a short time and lack momentary imagery, is not possible.

On the other hand, the use of data derived in ground measurements is also associated with the possibility of measurement errors or failures in

some cases.

In addition, because the index used in this study consisted of three parameters of wind speed, particle concentration, and horizontal visibility, it minimized the possibility of mistakes due to the simultaneous use of all three parameters to show dust storms.

Therefore, this index can eliminate errors in the recorded data of each of the parameters. Moreover, it can be used as an appropriate buffer for the recorded data of the three parameters.

In this study, the degree of agreement between these two methods was examined through comparing them with the reports of responsible organizations.

Materials and methods

In this fundamental-applied study, the concentrations of PM_{10} recorded in Tehran Air Pollution Sensor stations were investigated. To study the relationship between high concentrations of PM_{10} and the occurrence of dust storms, the Hoffman Index, which includes three main parameters of wind speed, PM_{10} concentration and horizontal visibility, was used and the concentrations were classified according to the definition of this index. The PM_{10} concentration data were obtained from Tehran Air Quality Control Company. The concentration of PM_{10} was monitored in 20 stations owned by the company, all of which were active in the year 2014. However, due to technical problems in all stations, the number of measured data was not equal to the number of days in the year. Hourly data related to wind speed and horizontal visibility parameters were obtained from the NOAA website. The data published by this website belongs to the World Meteorological Organization (WMO), which, in accordance with resolution 40 of this Organization, allows member states to release meteorological information free of charge for the purposes of research, education,

and other nonprofit activities [15].

To obtain the images of dusty days, the Modis sensor data, which is on board the Terra and Aqua satellites, were used.

First, the PM_{10} concentration was studied in all stations, data were entered into Excel and categorized in concentration groups of 50-200, 200-500, 500-2000, and above 2000.

The data of the wind speed and horizontal visibility were also studied in these days. All units were converted to the metric system. According to the Hoffman's index, dust storm was defined as a PM_{10} concentration above 500, horizontal visibility less than 0.6, and wind speed more than 17 m/s. Light dust storm was defined as a PM_{10} concentration of 200-500 $\mu\text{g}/\text{m}^3$ and horizontal visibility less than 1. PM_{10} concentrations over 2000 were categorized as severe dust storms, and concentrations ranging from 50 to 200 were considered as dusty days.

A combination of three indicators was used to compute and visualize the dust in the images.

To obtain an equation for each image, the data were first adapted to their ground coordinates using the ENVI (georeference). Then, using the Band Math tool, NDDI, BTM (32-31), BTM (20-31) values were calculated for each image.

Normalized dust difference index (NDDI)

Bands 3 and 7 are used in this equation. These bands have a resolution of 500 m, which separates the dust from the surface of the earth and the cloud.

Another indicator that separates dust from the cloud and can also be used to observe the storms at night due to its infrared bands is the brightness temperature difference between bands 31 and 32 (BTM (32-31)).

The third equation was applied to separate glowing levels of sand from dust, using the brightness temperature difference of infrared bands 20

and 31.

Since the NDDI values were above zero for dusty parts, these sections became visible. The threshold used for the BTM (32-31) and the BTM (20-31) was 0 and 25 °K, respectively. All images underwent this process individually and the dust masses became visible [16].

The results of the Hoffman Index were compared to actual storm observations and meteorological reports, and the sensitivity and specificity of this method were compared with the sensitivity and specificity of the actual observations and meteorological reports using the R.

After considering the PM_{10} concentration, the highest frequency was observed for the 50-200 batches, which was uniformly seen at different hours of the day. A batch of concentrations ranging from 200 - 500 $\mu\text{g}/\text{m}^3$ was in the next category, which was most likely to be seen in the late hours of the day until the early hours of the next day. The third group, which included concentrations of 500-2000 $\mu\text{g}/\text{m}^3$, also had a clock distribution similar to the previous one. Data analysis showed no concentrations higher than 2000 $\mu\text{g}/\text{m}^3$.

Results and discussion

After classifying horizontal visibility and wind speed and using the PM_{10} data according to the thresholds defined in the Hoffman Index, the number of storm days according to this index was determined to be 12 days (Table 1). The findings of the study showed that during 12 h when the PM_{10} concentration was above 200, storms occurred according to the Hoffmann Index (Table 1). Meanwhile, there was a moderate dust storm (as of June 12, 2014) and 11 light dust storms.

This study was based on PM_{10} concentrations recorded at Tehran Air Quality Control Company stations. Investigation of the changes in the monthly concentration of these particles shows that May and June had the highest amount of pol-

lutants, which was due to the occurrence of dusty phenomena in the summer.

In many studies, dust storms and dust phenomena have assessed based on the reports of ground measurements of dust-related parameters- i.e., PM₁₀ concentrations, horizontal visibility and wind speed. The simultaneous use of these three parameters not only minimizes measurement errors, but also makes it possible to classify storms in terms of severity.

The frequency of storms according to Hoffman's index (Fig. 1) showed that the highest frequency occurred in May, June. The results of this study showed that according to Fig. 2, the distribution

of the PM₁₀ concentrations of 50-200 µg/m³ was the same at different hours of the day, but concentrations above 200 µg/m³ were more frequent at the end of the day and in the early hours of the next day.

The reference method used in this study was the use of the Normalized Difference Dust Index (NDDI), which separates dust from the surface of the earth and the cloud by using the ratio of visible bands 3 and 7. Another indicator used in this study was the brightness temperature difference of MODIS 31 and 32, which separates the clouds from dust. It is also suitable for observing storms at night. Finally, using the difference

Table 1. Dust storms according to Hoffman index

Date	PM ₁₀ concentrations (µg/m ³)	Horizontal visibility (m)	Wind speed (m/sec)	Light dust storm	Moderate dust storm
13-05-2014	500-2000	2	17	+	
14-05-2014	500-2000	1	17	+	
24-05-2014	200-500	2	19.5	+	
27-05-2014	200-500	0	24.5	+	
02-06-2014	500-2000	0	27.5		+
06-06-2014	500-2000	2	22.5	+	
30-06-2014	500-2000	0.5	15	+	
02-10-2014	500-2000	1.8	5.5	+	
03-10-2014	500-2000	1.8	11.5	+	
21-10-2014	200-500	1	14	+	
09-03-2015	500-2000	1	11.5	+	
10-03-2015	500-2000	1.8	9	+	

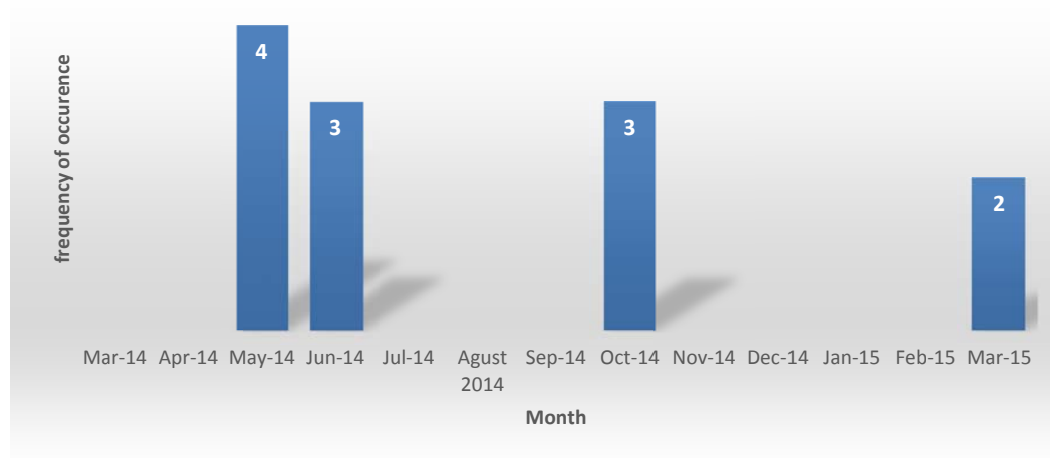


Fig. 1. The frequency of storms occurring in different months of the year according to Hoffman index

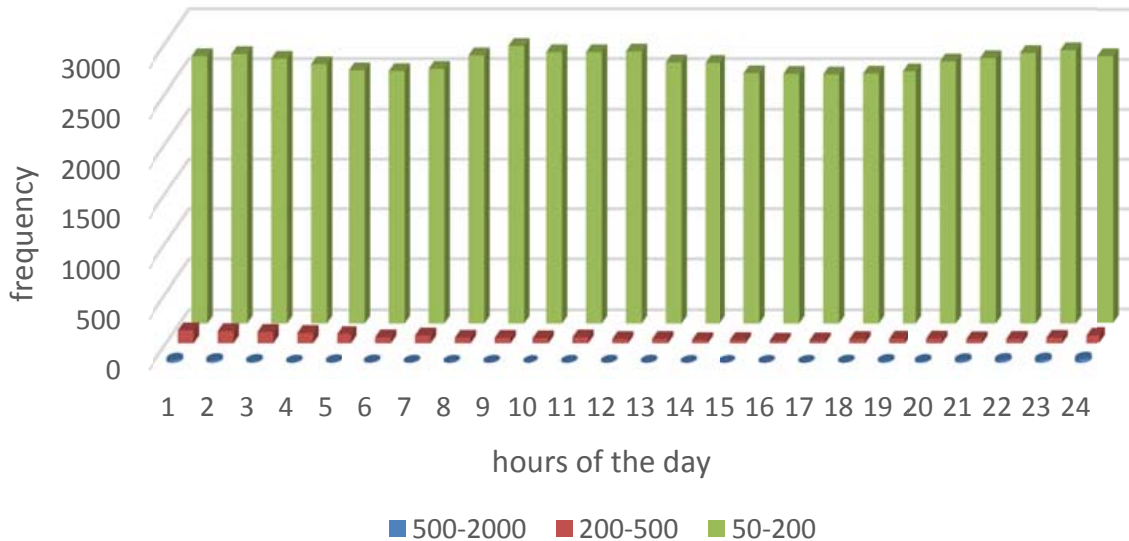


Fig. 2. The distribution of the PM₁₀ concentrations at different hours of the day

between bands 20 and 31, the brightness of the sand surfaces was also isolated. Many studies using these indices have shown dust and produced good results.

In Iran, were used these two indicators to disassemble the dust from the cloud and obtained good results in all sand storm incidents [1, 17]. The threshold used in these two studies and for both indicators was zero for the separation of dust. In the next step, the brightness of the ground surface was eliminated using the brightness difference of bands 20 and 31.

After overlapping of the three indicators, a dust distribution map was prepared at the moment of imaging; in this image, dust with a red color in west of Tehran has been detected (Fig.3).

The false color image is a combination of multi-bands together that shows each phenomenon with a specific color. In this image, dust in white color is seen in the west of Tehran (Fig. 4).

A survey of satellite images on these days showed that the results of the two methods had agreement in 5 incidents. In these five incidents, the time of satellite imaging was close to ground data (Table 2).

A limitation that makes it impossible to comment on satellite imagery accurately is that the time of the incident is not concurrent with the shooting time.

Terra and Aqua satellites optimally send 4 times from each image area per day. A review of the archive of images showed that of the 4 times, only the morning images have the resolutions of 250 m, 500 m, and 1 km resolutions. Also, there are only one or two images of the area in some days. Comparison of the accuracy of the two methods was done by analyzing the sensitivity and specificity of the satellite images to the Hoffman index, which showed a sensitivity of 0.5 and a specificity of 1. Moreover, comparison of the sensitivity and specificity of the two methods with the reports of responsible organizations showed both methods were highly accurate for correct identification of all storms.

The sensitivity and specificity of this method, compared to actual observations, indicated that this technique was highly sensitive. The sensitivity of this method was 1 and its specificity was 0.98.

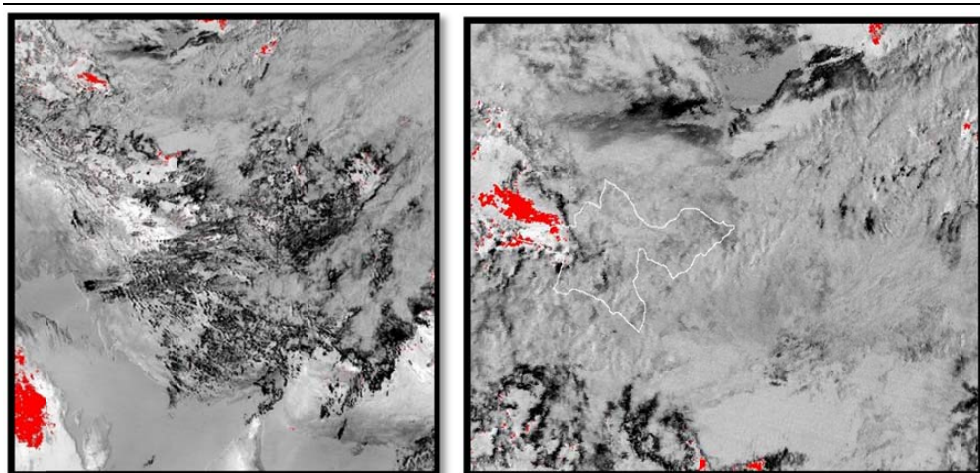


Fig. 3. Detected dust from MODIS image on 10 March 2015

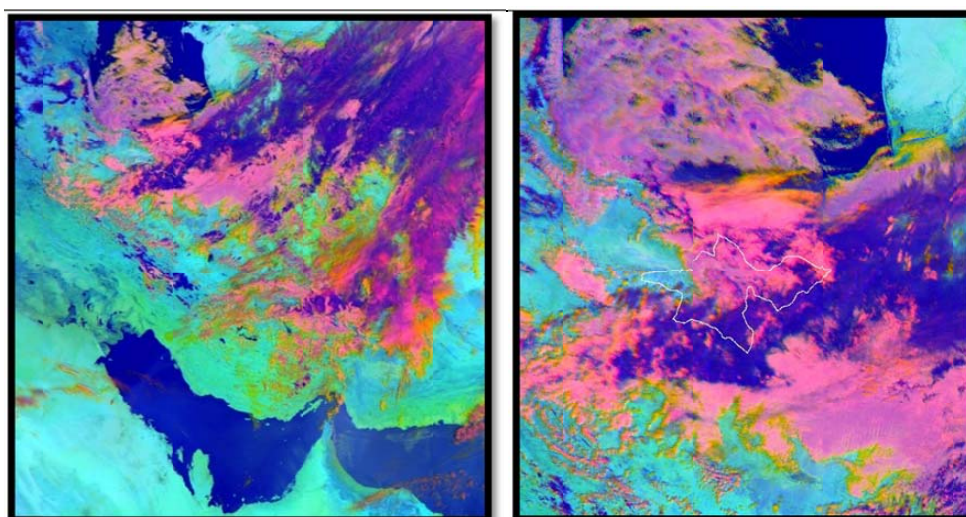


Fig. 4. False-color image extracted from MODIS image in 5 bands

Table 2. Comparison of the results of methods

Date	Reports of responsible organizations	Satellite images	Hoffmann Index
13-05-2014	-	-	+
14-05-2014	-	-	+
24-05-2014	-	-	+
27-05-2014	-	+	+
02-06-2014	+	+	+
06-06-2014	+	+	+
30-06-2014	+	-	+
02-10-2014	-	-	+
03-10-2014	-	N	+
21-10-2014	-	-	+
09-03-2015	+	+	+
10-03-2015	+	+	+

Conclusion

Since the data of three storm-related parameters were simultaneously used to calculate this index, it has a very low error rate and can classify dust storms very well; therefore, it can be used to study the trend of dust storms and their severity. Moreover, sensitivity analysis of the Hoffman's method in comparison with the reports of responsible organizations showed that the sensitivity of this method was 100% and its Specificity was 98%, indicating that the Hoffman's approach to storm detection was consistent with the reports of responsible organizations in 100% of the cases.

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Competing interests

The authors declare no competing interests.

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Ethical considerations

This research is in accordance with reality and is based on scientific criteria.

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