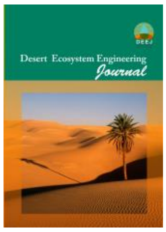
DEEJ (2023) 12 (8) 27-36

University of Kashan

Desert Ecosystem Engineering Journal

Journal homepage: http://deej.kashanu.ac.ir



Evaluating the Effectiveness of Ackerman's Algorithm in Monitoring Dust Storms: A Case Study of Ilam Province, Iran

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Received: 20/02/2021 Accepted: 24/01/
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Abstract

Determining the spatial distribution of dust storms in sedimentary areas is essential for forecasting and controlling these natural-manmade hazards. Therefore, this study sought to investigate the efficiency of Ackerman’s dust detection technique and the normalized difference dust index (NDDI) in identifying dust storms in Ilam province using the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor images taken on 12/08/2015 and 02/09/2015. To this end, the data regarding the dusty days in five meteorological stations were collected and analyzed to examine the status of dust in Ilam province using climate data and remote sensing. Moreover, an output dust map was used for the images based on numerical values. On the other hand, dust areas were identified by applying thresholds related to each algorithm. Finally, the accuracy of Ackerman’s technique and the NDDI was determined using PM_{10} pollution monitoring stations in the five stations mentioned above.

The results showed that the algorithms used in this study could detect particulate matter: the Ackerman algorithm was more efficient in detecting dust, while the NDDI algorithm was only applicable for separating clouds from the ground. Furthermore, a low correlation was found between the NDDI and the terrestrial data (0.15). In other words, it was found that from among the two techniques, Ackerman’s dust detection technique obtained a higher correlation (0.35) with terrestrial data than did the NDDI (0.15), indicating the high capability of the algorithm in detecting the dust phenomenon. Therefore, it could be argued that dust storms can be modeled and simulated with high accuracy via Ackerman's algorithm.

Keywords: Dust, NDDI, Ackerman’s Dust Detection Technique, Climate Data, MODIS, Ilam.

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1. Introduction

In recent years, the dust phenomenon has turned into one of the most important environmental challenges in Iran and the Middle East. Dust storm is a natural phenomenon that occurs in many areas worldwide. However, due to the increased risk of desertification at the expense of green cover and its impact on human health, the study of dust storms has recently gained much more significance. Moreover, as dust storms are more difficult to detect in desert areas than in other regions (Hoslett, John, et al, 2020), they are currently considered as one of the main problems in arid and semi-arid regions. On the other hand, dust storm occurs as a climatic phenomenon in all climatic conditions, bringing about adverse social, economic, environmental, and commercial consequences. Also, as a dominant phenomenon in desert areas, the storm disrupts human activities, agriculture, social infrastructure, transportation, and industry. Furthermore, a large volume of particles that are transported to the troposphere affects the energy balance, exerting a negative influence on an area's climate and climatic conditions (Eyring et al., 2010).

Occurring when the visibility is reduced to less than one kilometer (Shamsipoor et al., 2012), dust storms are geomorphologically important because of their role in erosion and sedimentation. On the other hand, one of the primary and effective factors involved in the occurrence of dust phenomenon is the geographical location and climatic conditions of the phenomenon's original regions and the areas affected by it. In this regard, the rise of dust in Ilam province could mainly be attributed to the following reasons: Iran is located in the arid and semi-arid belt of the world, neighboring countries with poor vegetation, low precipitation rate, and high temperature, including Saudi Arabia, Iraq, and Syria. Furthermore, due to intermittent droughts in such countries because of their prevailing desert conditions (causing air instability and strong winds, Iran's western and southwestern regions are periodically faced with dust events.

Moreover, drought and the unfavorable use of the environment and natural resources by humans in Iran and its neighboring countries have aggravated the intensity of dust events (Miri, 2011), leaving Iran's southwestern habitats unprotected and exposed to the risks of wind erosion, which is gradually becoming more widespread and severe. On the other hand, low precipitation rate, dryness, and dehydration of ponds and reservoirs decreased the growth of desert plants, increased wind intensity, drought, and some human-related factors, including the alterations made in land use, have led to the increase in fine dust throughout the southern and southwestern Iran (Fayazi, 2014), creating many environmental, health, social, and economic problems for the residents of such areas, giving rise to public dissatisfaction, and making the politicians face political challenges.

Studies show that the dust phenomenon is a natural disaster that inflicts much damage annually on Iran's western and southwestern provinces. Therefore, understanding how this phenomenon occurs can effectively reduce its potential damage (Omidvar, 2009). In this regard, Azizi et al. (2012) have investigated the dust phenomenon in the western half of Iran using the remote sensing method and a combination of survey models, whose results revealed two main routes for dust transfer in the region: 1) northwest-southeast route 2) west-east route (together with limited cases of north and south route). Moreover, According to the results of their study obtained from processing images and outputs of the regional border model, Syria, Iraq, and the northwest-southeast route were identified as the main sources and routes of dust entry to the western half of Iran.

Moreover, Patel, Ahmed, et al. (2013) investigated and monitored the Iranian dust storm using remote sensing methods. They also compared the images reconstructed via infrared and visible wavelengths with the maps of Aerosol Optical Thickness (AOT), the output of the DREAM 8b model, and station reports, finding that the application of dust detection algorithms is a safer way to monitor dust than other methods (such as dust recovery with model output).

On the other hand, Qian et al. (2015) examined dust storms in China using meteorological maps at 850 and 1000 hPa levels, reporting that the global warming in the Mongolian deserts and the cooling of the earth in northern China were the contributing factors in the occurrence of dust events in northern China. Furthermore, Levy et al. (2015) conducted a study on the particulate matter recovery algorithm for 2012-2014 using the Moderate Resolution Imaging Spectroradiometer (MODIS) dark pixel algorithm at land and sea levels, finding that the difference between the AOD data extracted from images with ground stations was reduced (close to zero). Therefore, their studies indicated a high correlation between data extracted from the 0.555 and 0.855 μm bands and ground station data.

Bin et al. (2019) assessed the performance of five dust detection algorithms, including brightness temperature difference (BTD), parameter D, normalized dust index (NDDI), thermal infrared dust index (TDI), and Middle East Dust Index (MEDI), suggesting that all such algorithms significantly detected dust-contaminated pixels during three dust events with an average detection rate of 85%). However, significant differences were found in algorithms' ability to detect dust from clouds and the earth's surface, leading to substantial detection errors. In this regard, direct validation of the algorithms by observing seven aerosol robotic network stations (AERONET) in the region revealed an average incorrect detection rate of 89.6%. Therefore, while the algorithms performed well in detecting dust-contaminated pixels, their high level of misdiagnosis indicated that their application would be operationally challenging.

Jebali et al. (2020) evaluated the performance of dust storm detection algorithms in arid areas of Yazd province, reporting that the TDI and TIIDI algorithms performed better in detecting dust (at a 99% significance level) than the optical depth of dust particles, with their correlation coefficient being 0.65 and 0.49, respectively. In the case of a dust storm event on 11/21/2014, it was found that the correlations between the Roskovensky and Liu algorithms and the dust particles' optical depth and visibility were 0.68 and 0.76 at 99% and 95% significance levels. were significant. Generally, they concluded that none of the algorithms would be able to detect all dust events.

However, it appears that the inclusion of thermal bands or a combination of thermal and reflective bands in algorithms can perform more effectively in dust detection. Therefore, to better detect dust events in any area, it is necessary to use threshold limits commensurate with the spectral characteristics of the area (and even with each event) when using detection algorithms.

Considering the fact that no comprehensive research has so far been conducted on the effectiveness of Ackerman's algorithm in monitoring dust storms (as proved by the review of the related studies mentioned above), this study sought to do so by investigating the issue in Ilam, Iran, as the province (located at Iran's western borders with high natural and human potential) faces the challenges made by dust storms.

2. Materials and Methods

2.1. The geographical location of the region

Covering an area of 19086 square kilometers, Ilam province is located in western Iran between 31 degrees and 58 minutes to 34 degrees and 15 minutes north latitude of the equator and 45 degrees and 44 minutes to 48 degrees and 10 minutes east longitude of the Greenwich meridian. The province is also a mountainous region at high altitudes located in the west and southwest of Iran among the Kabirkuh mountain range of the Zagros Mountains. Moreover, the province is limited to Kermanshah province from the North, some parts of Khuzestan and Iraq from the South, Lorestan province from the East, and Iraq from the West. Figure (1) illustrates the geographical location map of the study area.

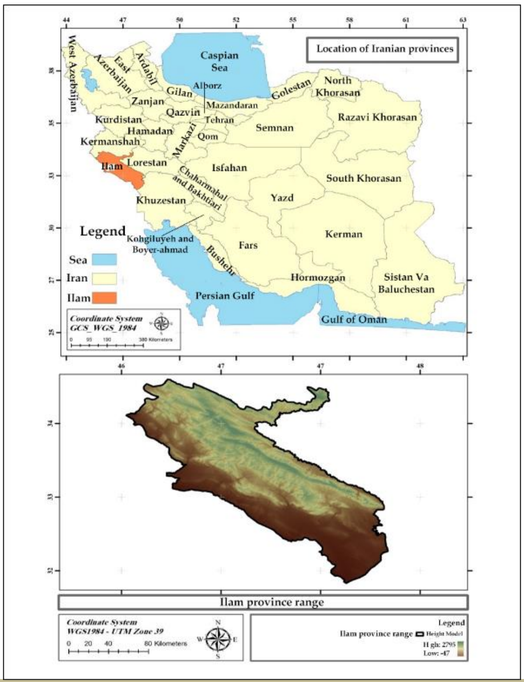


Figure (1): Map of the study area’s geographical location

2.2. Methods used to detect dust storms via MODIS images

Various methods and techniques have so far been developed for detecting dust storms via MODIS images, one of which is Ackerman’s dust detection technique (BTD of bands 31 and 32 in MODIS images (Terra & Aqua, MOD08 & MYD08)) which has widely been used in different studies. Moreover, the NDDI is another method used to detect dust storms. Therefore, the present study sought to apply these two techniques to investigate dust storms in the study area of Ilam province using the remote sensing method.

2.3. Ackerman’s dust detection technique

As the bands in the 11 and 12 μm spectra (bands 31 and 32 in MODIS) fall within the thermal infrared range (absorption by other atmospheric gases is negligible, and dust has a higher radiation power in the 12 spectra than in the 11 μm spectrum), the BTD of the bands can be used to detect dust storms (Huang et al., 2007). In this regard, Ackerman (1997) showed that the BTD of the 11 and 12-micrometer bands was negative for dust, considering the fact that the phenomenon revealed higher reflectance in the range of 12 microns than 11 micrometers, where the clouds were separated from the dust.

Ackerman’s dust detection technique did not set a precise threshold for dust separation. However, it found that the BTD of the 11 and 12-micrometer bands was negative for dust, thus, the global dust separation threshold could generally be set to zero, where negative values indicated a dust storm. This threshold can somewhat vary based on the variability of the dust’s emissivity and transmissivity (Baddock et al., 2009). Therefore, the value of this threshold varies slightly in different studies. Baddock et al. (2009) used 0.0, -1.2, and -0.35 Kelvin as the threshold in examing four dust storms that occurred in the Australian Lake Eyre. Moreover, Zhang et al. (2006) used a threshold of -0.5 to detect dust storms in northern China.

Considering the limitations and disadvantages of existing methods in detecting dust storms via MODIS images (which will be discussed later), this study sought to develop a model that can detect the dust phenomenon more accurately as one of its objectives, being able to distinguish dust from other phenomena, such as clouds, water levels, and land surfaces (bright and dark). To this end, after determining the dust days in the study period, the required satellite images were collected from http://ladsweb.nascom.nasa.gov. Table (1) shows the spectral band characteristics used in this study, where bands 1 to 19 are visible and near-infrared spectra, and bands 20 to 32 lie within the thermal infrared range.

The model, which was developed via MODIS reflective and thermal bands, was tested using several cases of dust storms in the study area. Finally, the results were evaluated through the true color combination image of MODIS and the data collected from field studies. The study also applied a correlation coefficient to the data recorded by the dust measuring stations of the Department of Environment and the data obtained from each algorithm to evaluate the accuracy of the algorithms.

The correlation coefficient is a statistical measure applied to two quantitative variables, indicating the strength and type of the correlation (direct or inverse) that ranges from 1 and -1. If no correlation is found between the two variables, the coefficient would be zero. The correlation between two random variables X and Y is obtained via Equation (1):

Equation (1):

$$\mathrm{corr}(X,Y)=\frac{\mathrm{cov}(x,y)}{\sigma_X\sigma_Y}=\frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X\sigma_Y}$$

Where E stands for the mathematical expectancy operator, “cov” represents covariance, “corr” is the Pearson correlation, and Sigma (σ) shows the symbol of standard deviation.

Generally, the steps taken in the current study are as follows:

1. Data collection
2. Atmospheric correction
3. Geometric correction
4. Radiometric correction
5. Data processing and index extraction
6. Applying Ackerman's algorithm
7. Measuring the efficiency of Ackerman's algorithm
8. Validation
9. Conclusion

3. Results

3.1. Detection algorithms

This section presents the results of Ackerman’s dust detection technique, which were obtained by applying a threshold of -0.5 and NDDI to distinguish dust from the surface of the desert.

3.2. Ackerman’s dust detection technique results

Brightness Temperature (BT) forms the basis of most detection algorithms. On the other hand, as the 11- and 12-micrometer spectra (bands 31 and 32 in MODIS) fall within the thermal infrared range, the BTD of these two spectra can be used to detect dust storms. Ackerman used this method in 1997 to detect dust, finding that the index’s negative values indicated the dust phenomenon due to the phenomenon’s high reflectivity in the 12-micrometer spectrum compared to the 11-micrometer one, making the index highly effective in detecting dust storms and determining their origin. Moreover, as the difference in radiance temperature is negative for the 11 and 12 μm bands of dust, the global dust separation threshold can be set to zero, where negative values indicate a dust storm.

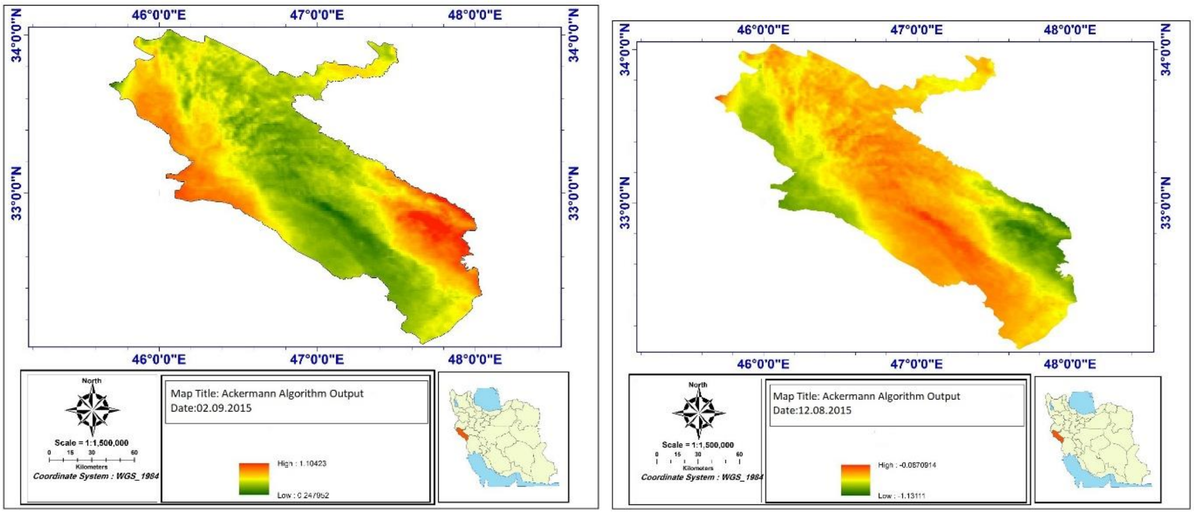
The Ackerman index is derived from a BTD between the thermal bands 32 and 31 (11 and 12 μm) of the MODIS sensor. The thermal band 32 has a low temperature in the clouds, a very high temperature on the surface of the earth, and the dust temperature when falls between the clouds and the earth's surface. Band 31 is similar to Band 32 in terms of distinguishable temperature rates between cloud, dust, and earth phenomena. On the other hand, as low-concentration dust and desert lands have the same numerical values, clouds, water, and parts of the earth can numerically be distinguished from dust via BTD. Table (2) shows the numerical values of the Ackerman index in distinguishing the dust phenomenon. However, the index is unable to identify and distinguish the possible dust existing in the water.

Table (2): Normal values obtained from the BTD index

Phenomenon	Normal values
Earth and other phenomena	-1.2<
Dust	–0.4 -0.5

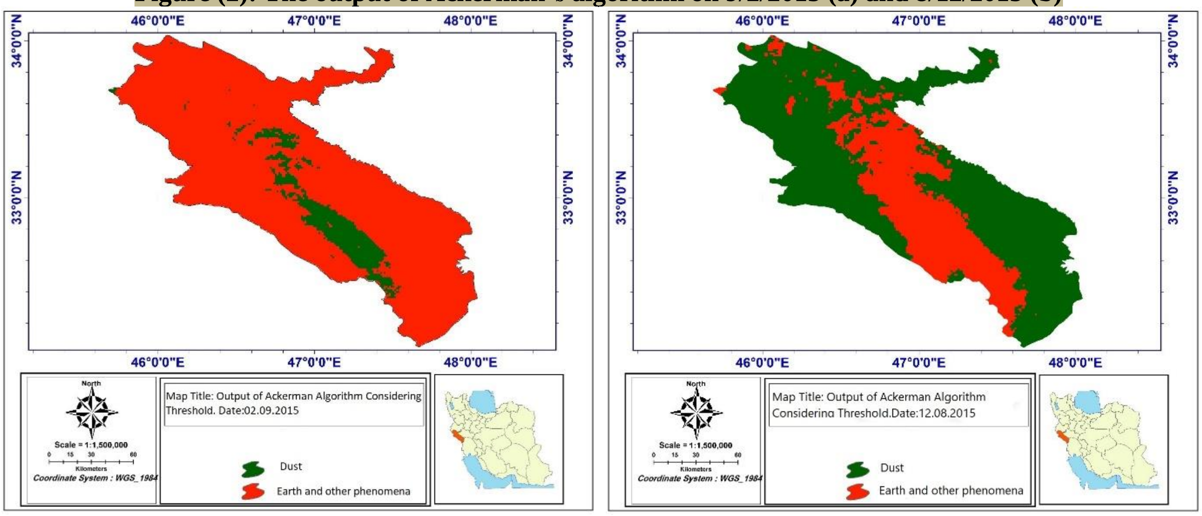
Since the phenomena in band 31 of MODIS sensors (range 11 μm) make more emissions than do band 32 (12 μm range), the most significant difference belongs to the ground. Therefore, the application of Ackerman's dust detection technique makes the earth more visible than other phenomena. However, while the Ackerman index can easily separate earth and dust, it cannot do so for dust and cloud.

First, the BTD between bands 31 and 32 of the MODIS sensor is calculated. For each satellite image studied, the Ackerman index is calculated and examined to see whether the dusty areas had a negative brightness temperature difference,-. In this regard, Ackerman recommends a -0.5 threshold for dust detection. It should be noted that in non-dusty areas, the BTD was more significant than the threshold mentioned above. Figures 2 (a) and 3 (a) show the difference in BT of MODIS thermal bands 31 and 32. Moreover, Figures 2 (b) and 3 (b) display dust output on the image as the BTD of the study area on September 2 and August 12, 2015, taking the threshold as -0.5. The image clearly shows that the threshold was set at -0.5 for the BTD of dusty regions. Areas with values below the threshold are considered dusty areas, as shown in Figures 2 and 3 in green. The results obtained for such dusty areas are consistent with the ones found via visual observations. However, Ackerman's method can be assumed to be more accurate than the visual one.



B A

Figure (2): The output of Ackerman's algorithm on 9/2/2015 (a) and 8/12/2015 (b)



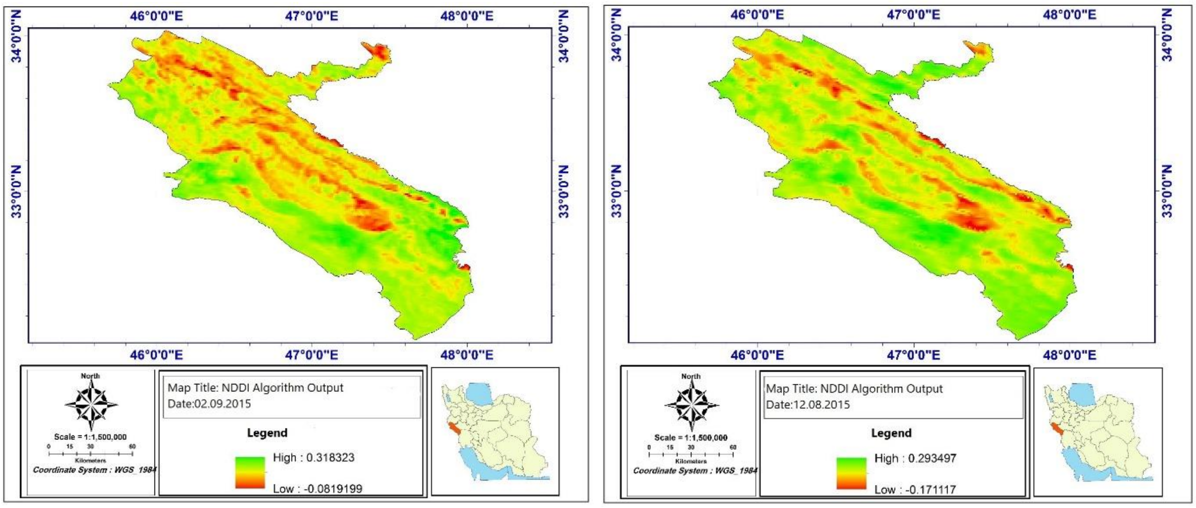
B A

Figure (3): The output of Ackerman's algorithm with threshold application on 9/2/2015 (a) and 12/08/2015 (b)

3.3. The NDDI results

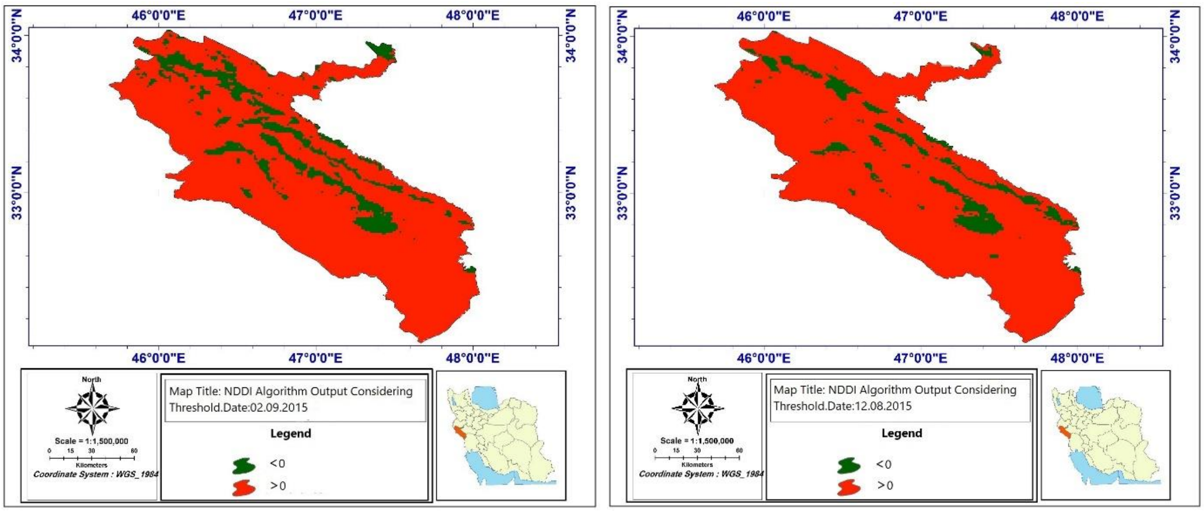
The NDDI uses bands 3 and 7 of MODIS images, being able to detect dust on bright surfaces. Accordingly, the dust was found to have a high reflectivity in the 2.13-micrometer spectrum and a low reflectivity in the 0.469-micrometer spectrum. However, as for distinguishing the cloud phenomenon, the results are reversed. Therefore, negative values of the NDDI indicate a cloud. However, as shown in the figures above, since there is no threshold for separating dust from the earth's surface, the NDDI can only be used to separate the dust from the cloudy and water areas. As mentioned earlier, the minus zero NDDI values indicate cloudy and water areas, and above zero NDDI values show the dust over the surface of the earth. The purpose of using this index is to distinguish desert areas, whose spectral reflection in the image is similar to dust. In this regard, only areas with an NDDI below the zero thresholds are taken into account. The images taken on September 2 and August 12, 2015, were used to show the influence of the index.

Figures 4 (a) and (b) show the outputs of the NDDI algorithm. Moreover, Figures 5 (a) and (b) display the output of the algorithm with a zero threshold on the NDDI images taken from the study area on September 2 and August 12, 2015, showing how other phenomena are separated from the dust.



B A

Figure (4): NDDI algorithm output on 9/2/2015 and 8/12/2015



B A

Figure (5): Output of NDDI algorithm with threshold application on 9/2/2015 (a) and 12/8/2015 (b)

Table (3) and Figure (1) shows the results obtained for each algorithm, suggesting that both algorithms could detect fine dust. However, while the Ackerman algorithm was more efficient at detecting dust, the NDDI algorithm was only suitable for separating clouds from the earth. However, the NDDI had a low correlation with terrestrial data (0.15). In other words, the Ackerman algorithm was found to have a higher correlation (0.35) with the earth-related data than the NDDI (0.15), indicating the high capability of the Ackerman algorithm in detecting the dust phenomenon.

Table (3): Correlation coefficients of the data obtained from algorithms

NDDI	Ackermann	Algorithm
0.15	0.35	Significance coefficient

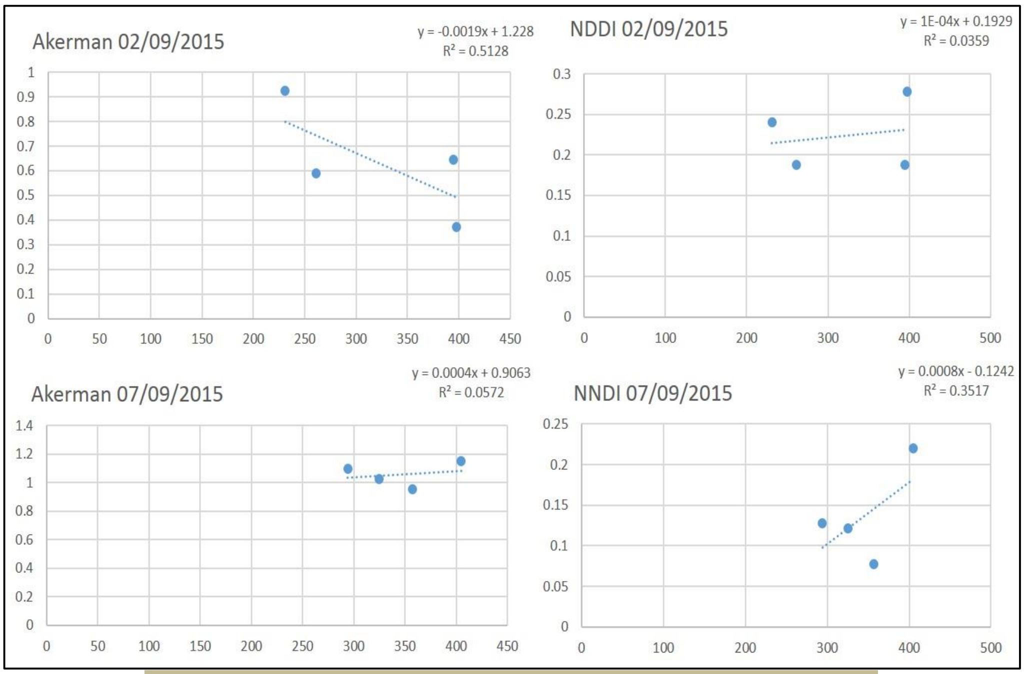


Figure (6): Correlation of algorithms with the earth-related data

4. Discussion and conclusion

Numerous algorithms have already been proposed to detect dust storms. On the other hand, various methods have been developed to determine the radiation and reflection signals affecting atmospheric dust detection, including the NDDI and Ackerman's dust detection technique (based on the BTD). Ackerman's dust detection technique is an index that can be used to detect dust in thermal bands. Therefore this study used two indices, i.e., BTD (Ackerman's dust detection technique) and the NDDI to detect dust.

Figures 2 (a) and (b) show the application of Ackerman's dust detection technique to dust detection using a (-0.05) threshold. Furthermore, as shown in the above-mentioned figures, the NDDI isolates dust-like desert areas, using zero thresholds to detect dust. Therefore, this study suggested that the simultaneous application of the NDDI and Ackerman algorithm can improve the dust classification process and minimize many classification weaknesses of dust detection (which occurs when the indices are used individually), which is consistent with the results found by Karimi et al. (2018).

In general, considering the dust events that occurred in Ilam province and the monitoring of satellite images, the results of this study can be applied to monitoring and managing dust in the province. Moreover, the Ackerman and the NDDI algorithms performed well in identifying fine dust in the province on the dates mentioned. It was also found that the Ackerman algorithm had a higher correlation than the NDDI algorithm, which is consistent with the study of (Zeng, Dongqiang, et al. 2019; Abdelwaheb, Mohamed, et al.. 2019).

5. Suggestions

Considering the adverse effects of particulate matter on many aspects of human life, the following suggestions are offered for further research:

1. The results of the dust phenomenon, which has led to the relatively accurate identification of particulate matter, should be used to manage and eliminate pollution and reduce the effect of this harmful phenomenon.
2. Examining fine dust in the identified areas in terms of their occurrence time can help better identify the causes and the way of their spreading, facilitating their control.
3. Combining the results of this study with other climatic phenomena, such as wind intensity and direction, precipitation, etc., can reveal new aspects of the factors causing dust in the study area.
4. A more comprehensive study should be conducted with the participation of neighboring countries on dust-generating centers by the earth-related data and satellite images with the should be done.
5. The emission velocity, volume, and concentration of dust particles in dust phenomena should be determined using modeling and satellite processing results in the calibration and validation of models.
6. The amount of damage caused by dust pollution and methods of reducing damage should be investigated.

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