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Zohre Ebrahimi-Khusfi (zohreebrahimi2018@ujiroft.ac.ir)
University of Jiroft https://orcid.org/0000-0002-1036-6386
Fatemeh Roustaei
Ardakan University

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Dust Storm Index Anomaly for Sand-Dust Events Monitoring in Western Iran and its Association with the NDVI and LST Anomalies

Zohre Ebrahimi-Khusfi*[a], Fatemeh Roustaei[b]

[*a] Department of Ecological Engineering, Faculty of Natural Resources, University of Jiroft, Jiroft, Iran. Email: Zohreebrahimi2018@ujiroft.ac.ir

[b] Assistant Professor, Faculty of Natural Resources, Department of Nature Engineering, Ardakan University, Ardakan, Iran. Email: froustaei@ardakan.ac.ir; Telephone number: +989132539554

*** Corresponding author:**

Zohre Ebrahimi-Khusfi

Department of Ecological Engineering, Faculty of Natural Resources, University of Jiroft, Jiroft, Iran.

Email address: Zohreebrahimi2018@ujiroft.ac.ir

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Abstract

Sand-dust events (SDE) are an increasing concern in many arid and semi-arid regions of the world, which have severely damaged air quality and human health in recent years. This study was conducted to monitor the SDE in western Iran using the dust storm index anomaly (DSIA) during 2000-2018. The spatiot-emporal change detection and statistical analysis were used to understand the impacts of normalized difference vegetation cover anomaly (NDVIA) and land surface temperature anomaly (LSTA) on the SDE activities. The area has suffered from the highest dust pollution in 2004, 2009, and 2012 (DSIA>+40) while it experienced the lowest dust pollution in 2002 and 2017 (DSIA<-40). Approximately 48% of western Iran experienced decreasing changes and 52 % of the total area experienced increasing changes in dust pollution during 2010-2018 compared to the previous years. Incremental changes in NDVIA and LSTA were observed in 73.2% and 7.5% of the study area while their decreasing changes were observed in 26.8% and 92.5% of the total area, respectively. Spatially, regions affected by the increase in dust pollution are mainly distributed in the eastern and southern regions of the study area. Significant effects of changes in anomalies of both terrestrial parameters on DSIA were observed throughout the study period ($R_{LSTA\text{-}DSIA}$= +0.52; $R_{NDVIA\text{-}DSIA}$= -0.41); P<0.05). It was also found that spatial correlation between LSTA and DSIA as well as NDVIA and DSIA in many parts of the study area were significant at the 95% confidence level ($\left|R\right| > 0.45$). These findings can be useful for decision-makers to assess the risks of dust pollution and reduce its negative consequences in western Iran.

Keywords: air quality, dust pollution, vegetation cover, land surface temperature, remote sensing.

1. Introduction

Sand-dust events (SDE) are one of the most destructive processes of land degradation that can lead to desertification and air quality degradation. This phenomenon usually occurs when the surface winds speed exceeds the wind erosion threshold velocity (Shao 2008). During this process, particle matters from ultra-fine (less than 0.1 µm in diameter) to large coarse particles (greater than 10 µm in diameter) enter the earth's atmosphere and results in increased air pollution in different areas, especially desert regions. It has also caused serious damages to infrastructure, urban and rural settlements, photovoltaic panels, public health, as well as to plant, animal, and human communities (Atafar et al.

2019; Bao et al. 2019; Cao et al. 2015a; Faraji et al. 2019; Jaszczur et al. 2020; Powell et al. 2015; Tam et al. 2012). The level of air pollution caused by SDE in different parts of the world varied at different space and time scales, depending on climatic conditions, terrestrial factors, and human activities (Chen et al. 2020; Ebrahimi-Khusfi et al. 2020b; Ebrahimi-Khusfi et al. 2020c; Guo et al. 2018). Therefore, identifying the associated drivers is essential to reduce SDE hazards.

The dependence of sand-dust events (SDE) on climatic factors including, wind velocity, precipitation, and temperature have been shown in various studies (Achakulwisut et al. 2018; Bolles et al. 2019; Mashat et al. 2018; Middleton 2019; N'Datchoh et al. 2018; Tan 2016; Xu et al. 2020). Higher air temperature, less precipitation, and erosive winds resulted in SDE intensification and air quality destruction. The normalized difference vegetation index (NDVI), as a proxy of vegetation cover, affects the air quality by changing the surface roughness, soil moisture, storage capacity, and wind erosion threshold velocity (Meng et al. 2018). Land surface temprature (LST) has also a key role in energy balance over the earth's surface on the regional and global scales (Orhan et al. 2014). The LST can affect air quality through changes in soil moisture content. As temperature increases, the evapotranspiration from the land surface increases and the soil moisture content decreases. As a result, the adhesion between the soil particles is reduced and the soil particles are more easily separated from the soil, thereby increasing the concentration of the particles in the atmosphere (Ebrahimi-Khusfi et al. 2020c). On the other hand, the concentration of suspended particles and the type of particles can affect the earth's surface temperature (Alseroury 2015; Kahya et al. 2016). Overall, these reports show the complex relationships between various climatic parameters, terrain factors, and air quality. In total, finding the relationships between dust pollution and its controllong factors can be useful for decision-makers to assess the risks of dust pollution and mitigate its negative consequences in arid and semi-arid regions of the world.

Iran is located in the arid belt of the eastern hemisphere and SDE are serious environmental problems that have increased in this country and affected the concentration of suspended particulate matter over the past decades (Maghsudi et al. 2017; Meng et al. 2018; Norouzi et al. 2017; Nouri 2019). The extent of desert lands in Iran is about 907,300 km^2 (Khosroshahi et al. 2009), 5% of which is covered by sand dunes (Abbasi et al. 2019). The most important sources of dust generation in Iran are sand dunes, dune fields, shrinkage wetlands, and abandoned agricultural lands. According to the dust storm index (DSI), SDE activities in arid and semi-arid regions of eastern Iran had a weak increasing trend between the years 2000-2014 and 2000-2016, respectively. Wind speed, rainfall, temperature, and vegetation were known as the most important factors controlling dust pollution in these regions (Ebrahimi Khusfi et al. 2020; Khusfi et al. 2020).

In many previous studies, vegetation cover has been considered as the main terrestrial factor affecting SDE activities. However, according to the research background, land surface temperature (LST) has also affected dust events and air quality. The effect of climatic factors, soil moisture, vegetation cover, and human activity on SDE in some areas of western Iran have been investigated in some past works (Akhzari and Haghighi 2015; Akhzari et al. 2014; Kamal et al. 2019) but no attempt has been made to investigate the effect of NDVI anomaly (NDVIA) and LST anomaly (LSTA) on the DSI anomaly (DSIA) across western Iran. This study has therefore attempted to address this issue. Moreover, no attempt has been conducted to investigate the trend of spatiot-emporal variations in NDVIA, LSTA, and DSIA over the past decades in the western regions of Iran. The DSI is the most suitable index for monitoring SDE during the long-term period using the meteorological data (O'Loingsigh et al. 2014), which has been widely used in some previous studies (Khusfi et al. 2020; McTainsh et al. 2007; O'Loingsigh et al. 2014). Therefore, in this study, it was used to monitor the SDE from northwest to southwest of Iran.

The assumptions considered in this study are: (1) upward trend of dust pollution due to exacerbation of SDE in western Iran, (2) decrease in NDVIA and increase in LSTA across the study region, and (3) their significant effect on changes in air pollution caused by SDE throughout the whole monitoring period (2000-2018). Accordingly, the main objectives of this study are to monitor SDE using the DSIA and to identify changes in NDVIA and LSTA, both temporally and spatially. The ultimate goal of this study is to understand the spatiot-emporal relationships between the DSIA-NDVIA and DSIA-LSTA in western Iran.

2. Materials and methods

2.1. Study Region

Our study area covers the northwest to the southwest of Iran, comprising about one-third of the whole of Iran. The area is situated between the latitudes of 25°35' 30″N to 36°60'00″ N and the longitudes of 45°55'45″ E to 56°26'15″E (Fig.1a). More than 75% of the study area is covered by dry and semi-dry lands (Fig.1b) and there exist various land covers, temporal lakes, and wetlands in this region of Iran (Fig.1c). Most of the SDE in the area occurs in spring and summer (Kamal et al. 2019) when "Shamal" wind speeds is maximized and the rainfall is minimized (Alizadeh-Choobari et al. 2016). Al-Howizeh and Al-Azim marshes are important sources of dust generation in southwestern Iran (Cao et al. 2015b). Base on the digital elevation model (DEM) map, the average elevation in the area is 1000 meters above sea level (Fig. 1a). Figure (1a) also shows the geographical location of the study area and selected synoptic stations in western Iran.

2.2. DSIA Estimation

The SDE is one of the most important factors affecting air quality degradation, especially in arid and semi-arid regions of the world (Parajuli and Zender 2018). Understanding how air quality is affected by these events requires long-term data and analysis of variations trends. In the current study, the DSIA was used to monitor the SDE in western Iran. To calculate it, the long-term data on dusty days and the codes recorded for the SDE in synoptic stations are needed, which were obtained from the Meteorological Organization of Iran for the stations located in western Iran. The dust codes were used to detect the type of SDE, including local, moderate, and severe events. The total number of dusty days for some synoptic stations located in western Iran during the study period is shown in the supplementary section. The spatial distribution maps of dusty days and the average speed of dusty winds in the study period are shown in Fig.2a and Fig.2 b, respectively. Also, the direction of dusty winds that are drawn based on hourly wind speed and wind direction data using WRPLOT8.0.2 software, is shown in Fig. 2c.

The DSIA calculation steps are summarized below:

(i) Calculation of the monthly DSI (DSI $_{monthly}$) for each station over the study period using equation (1): (O'Loingsigh et al. 2014)

(ii) Estimation of the annual DSI (DSI $_{annual}$) and the long-term DSI (DSI_{lt}) using equations 2 to 3, respectively.

(iii) Calculation of the DSIA using the relation (4).

(1) $$DSI_{monthly} = \sum_{i=1}^{n} \left[(0.05 \times LDE) + MDE + (5 \times SDS) \right]_i$$

(2) $$DSI_{annual} = \sum_{1}^{12} DSI_{monthly}$$

(3) $$DSI_{lt} = \sum_{1}^{19} \frac{DSI_{annual}}{19}$$

(4) $$DSIA = \frac{DSI_{annual} - DSI_{lt}}{DSI_{lt}} \times 100$$

where n is the number of dusty days per study month and i refers to the ith value of n stations for i = 1–n. LDE is the local dust event days (daily maximum dust codes: 07-09). MDE indicates the moderate dust event days (daily maximum dust codes: 30 – 32, and 98). SDS shows the severe dust event days (daily maximum dust codes: 33-35).

After calculating the monthly DSIA for all available synoptic stations from 2000 to 2018, the annual mean DSIA values were computed using the arithmetic mean method in Excel 2016 software. The annual DSIA values calculated for all stations were then utilized to compute the mean annual DSIA for the whole area of Iran. Moreover, the annual DSIA values were used to calculate the mean long-term DSIA in the study period (i.e., 2000-2018). Then, the Inverse Distance Weighting (IDW) method, as a simple and widely used method to visualize the spatial changes of dust event activities and air quality (Krasnov et al. 2016; Škrbić and Marinković 2019), was used to draw the spatial distribution of DSIA across Iran for the study years and the long-term period. The DSIA produced maps were reclassified into two categories based on DSIA values greater and smaller than zero. The positive DSI anomalies (DSIA>0) show that the annual dust storm index was higher than the long-term mean value of DSI, while negative DSI anomalies (DSIA<0) indicate that the annual DSI amount was less than the long-term average amount of DSI. Finally, the percentage of the area belonging to each class was obtained by dividing the number of pixels in each class by the total number of pixels in the study area multiplied by 100.

2.3. NDVIA and LSTA Estimation

The LST, vegetation cover, and soil moisture are the principal factors affecting the rate of soil erosion, dust emissions, and air quality (Dupont et al. 2014; Munson et al. 2011; Sirjani et al. 2019). Considering that the effect of soil moisture on SDE activities in western Iran has recently been investigated by Kamal et al. (2019), while the effects of vegetation cover and LST on these events have not been investigated so far, it is focused on the investigation of the effect of these two terrestrial parameters on SDE in western Iran, in this work. For this purpose, the NDVI and LST datasets were used in the current study, since their long-term data are available in 'https://earthdata.NASA.gov/' and have the same spatial resolution. All monthly time series of the NDVI and the LST with a high spatial resolution (1 km* 1 km) were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) products. In total, 1296 granules of monthly MODIS-NDVI and LST products were downloaded from the mentioned data source, because western Iran is situated on the 3 tiles of granules of the MODIS Imagery and the monitoring period is 19 years (2000-2018). Monthly images of tiles were mosaicked using ARC GIS 10.4.1 software and terrestrial variables anomaly were computed. For this purpose, the monthly values of NDVI and LST were firstly averaged according to the following equations:

$$NDVI_{annual} = \sum_{i=1}^{12} \frac{NDVI_i}{12} \tag{5}$$

$$LST_{annual} = \sum_{i=1}^{12} \frac{LST_i}{12} \tag{6}$$

The long-term values of terrestrial variables were then computed based on the equations 7 to 8:

$$NDVI_{lt} = \sum_{i=1}^{19} \frac{NDVI_{annual}}{19} \tag{7}$$

$$LST_{lt} = \sum_{i=1}^{19} \frac{LST_{annual}}{19} \tag{8}$$

Here, $NDVI_{lt}$ and LST_{lt} are values of the mean long-term NDVI and LST respectively.

Finally, the NDVIA and the LSTA for all study years were calculated as:

$$NDVIA = \frac{NDVI_i - NDVI_{lt}}{NDVI_{lt}} \times 100 \tag{9}$$

$$LSTA = \frac{LST_i - LST_{lt}}{LST_{lt}} \times 100 \tag{10}$$

In the above equations, $NDVI_i$ and LST_i refer to mean values of NDVI and LST in the i*th* year at each pixel level of the study area.

2.4. Statistical analysis

The Pearson correlation analysis is a useful statistical method for determining the direction of association between two variables and the strength of their linkage (Pearson 1909). In the current study, the spatiot-emporal correlations between NDVIA-DSIA and LSTA-DSIA were investigated using this statistical technique. It is calculated as expressed in Equation (11).

$$R = \frac{\sum_{i=1}^{n}(x_i - \overline{x_i})(y_i - \overline{y_i})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x_i})^2 (y_i - \overline{y_i})^2}} \tag{11}$$

In which, y_i is dependent or response variable (DSIA) and x_i is independent or explanatory variable (NDVIA or LSTA). i is the ith variable in a given dataset with sample size n. $\overline{x_i}$ is the mean value of DSIA and $\overline{y_i}$ is the mean value of the NDVIA and/or LSTA over the whole study period.

The correlation coefficient value varies between +1 and -1, both of which indicate a strong correlation with the different directions between the variables studied. Values close to zero indicate a weaker correlation between the two variables.

In order to detect the spatial variations of DSIA, NDVIA, and LSTA, their spatial distribution maps were also prepared for the years 2000-2009 and 2010 to 2018 using the IDW method. Finally, the quantity and the type of changes in the study parameters were determined by subtracting the maps from each other in ARC GIS software.

3. Results

3.1. SDE monitoring in western Iran

In this study, the DSIA maps were prepared to display the spatial variations of SDE in the study area during the years 2000 to 2018. In the produced maps (Fig. 3), red areas (DSIA>0) indicate areas that were more susceptible to SDE activities and had a greater effect on the increased dust pollution across western Iran during the study period. The areas affected by SDE during the second half of the study years were mainly distributed in the southern regions of the study area, while in the first half of the study years, their distribution was also observed in the western borders. The inter-annual DSIA variations in the western half of Iran over the entire monitoring period are shown in Fig.4. Temporally, the study area has suffered from higher severities of dust pollution during the years 2012, 2004, and 2009 because the maximum amounts of DSIA were observed in these years (DSIA>+40). In contrast, the area had the best conditions of air quality in 2002 and 2017, when the minimum SDE activity occurred (DSIA<-40).

In this study, to better understand the periodic variations in SDE as well as to identify areas that have experienced worse conditions of air quality in western Iran, the DSIA changes trend was also investigated in two different decades (2000-2009 and 2010-2018). In addition, the drought severity in the western parts of Iran was higher than in other parts of Iran in 2009 (Modarres et al. 2016). Therefore, investigating the changes in DSIA during these two decades can also help to better understand the changes in air quality caused by SDE before and after the most severe droughts occurred in western Iran. The results are illustrated in Fig.5. As shown in this figure, minimum values of DSIA in both periods were -100 (Fig.5; a-b), meaning that the weather in these areas did not experience any dust pollution during the study sub-periods. In some years, for example in 2004, when only 26% of the study area experienced positive anomalies in DSI, dust pollution was more than in other study years, particularly in 2011, which was about 45% of western Iran had anomalies greater than zero. This result indicates that the intensity of the SDE activity in 2004 was higher than in 2011 ($DSIA_{2004} > DSIA_{2011}$; Fig. 4), but these events occurred in a smaller area (Fig. 3), meaning that the regions were highly susceptible to SDE. In contrast, the maximum values of positive anomalies in different parts of western Iran were different. The maximum DSIA is estimated at 378 (Fig. 5a) and 234 (Fig. 5b) for the first and second half of the study years, respectively.

Overall, 48.1% of western Iran has experienced decreasing changes and 51.9% of the total area has experienced increasing changes in SDE during the second period compared to the first period (Fig. 5c). In other words, there are 3.8% more areas experiencing increased changes than those experiencing decreasing changes. Indeed, the overall slope of the spatial changes throughout the monitoring period was weak and upward. The temporal variations in the DSIA also showed a weak upward slope throughout the period (Fig. 4).

3.2. Relationships between NDVIA and LSTA with SDE in temporal scale

In addition to climatic factors, the physical characteristics of the earth's surface also have a significant effect on SDE activity in different regions. Hence, the correlation analysis of both LSTA and NDVIA with DSIA has been performed to explore the linkage between the anomaly of two terrestrial factors and DSI anomaly over the study period.

In the annual time scale, the best vegetation conditions across western Iran were in 2018 (NDVIA= +12.5), 2000 (NDVIA=+9.4), 2011 (NDVIA=+6.4), and 2014 (NDVIA= +5.9) respectively. In contrast, the worse years were 2008 and 2009 (NDVIA= -10.3), 2004 (NDVIA= -7), and 2002 (NDVIA= -4) respectively (Fig. 6a). The western regions of Iran experienced the best ground temperature conditions in 2017 (LSTA= -1.9), 2014 (LSTA= -1.5) and 2002 (LSTA= -0.5) while experienced the worst conditions in 2011 (LSTA= + 0.54), 2009 (LSTA= +0.27) and 2004 (LSTA= +0.2) respectively. The investigation of temporal changes in the annual DSIA and the annual anomalies of the terrestrial variables for the entire area over the study years (2000-2018) revealed the NDVIA and LSTA correlated well with the DSIA (Fig.6; a and b). The findings also indicated that the trend changes in the inter-annual LST anomalies during the study years (Fig. 6b) were relatively similar to the trend changes in the annual DSI anomalies (Fig. 4). However, the temporal variations of NDVIA have been the inverse of the DSIA variations over a long-term period (Fig. 6a). Also, in the first half of study years, the rate of changes in the NDVIA and LSTA were -1.6 and +0.03, while it was +1.03 and -0.13 for the second half of study years respectively.

3.3. Relationships between NDVIA and LSTA with SDE in spatial scale

The remotely sensed data retrieved from MODIS products for western Iran indicated that the average LST and vegetation cover over the study period was about 15 ºC and 27 % respectively. Additionally, the range of LST variations varied between 13 ºC and 15 ºC (Fig. 7b) and NDVI varied from -0.2 to 0.8 across western Iran (Fig. 7a). The results of correlation analysis showed that the R-values between NDVIA-DSIA and LSTA-DSIA changed from +0.1 to -0.6 (Fig. 7c) and 0.02 to 0.7 (Fig. 7d) in western Iran, respectively. In the study area, during the first and second sub-periods, the NDVIA changed from -14.5 to 10.2 (Fig. 8a) and -7.8 to 23.2 (Fig. 8b), respectively. Over the sub-periods mentioned above, the LSTA changed from -0.5 to 2.3 (Fig. 8d) and -0.7 to 1.6 (Fig. 8e) in the study area, respectively. The results obtained from the change detection analysis showed that vegetation losses occurred in about 27% of the study area, especially over the southern parts of the study region (Fig. 8c), where there has also been an increasing change in soil erosion during recent years (Fig. 5c). However, about 73% of the entire region has experienced incremental changes (Fig. 8c) that have resulted in a decrease in soil particle emissions over the second half of the study years. The LSTA values during the years 2010-2018 (Fig. 8e) were less than the LSTA in the early years (Fig. 8d). As seen in Fig. 8f, the decreasing changes in the LSTA occurred in 92.5% of the total area while the increasing changes occurred in 7.5% of the study area during the study period.

4. Discussion

4.1. SDE monitoring in western Iran

The spatial distribution of areas susceptible to SDE may be different from year to year. In western Iran, the southern and southwestern regions have experienced adverse air quality caused by SDE in most years (Fig. 3). These regions have also experienced the dustiest days over the study period (Fig. 2a). One of the most important reasons is that there are vast deserts in neighboring countries of western Iran that have a high potential for dust generation (Boloorani et al. 2013). Furthermore, the dried bed of the Hour Al-Azim wetland, as another major source of dust production in southwestern Iran (Adib et al. 2018), is located on the border between Iran and Iraq. As shown in Fig (2c), Ahvaz is located in the eastern region of Hour Al-Azim Wetland and the prevailing direction of dusty winds in this city is from west to east. Therefore, when dust events occur, part of the eroded dust is injected from the dried bed of Hour Al-Azim into the atmosphere of cities located near this international wetland, especially Ahvaz, and affects the air quality of this region of Iran. Of note, the average speed of dusty winds in the southern and northern areas of the study area varied from 8 to 10 m/s and 10 to 13 m/s over the monitoring period, respectively (Fig. 2b). However, during this period, the number of dusty days across the southern half varied between 150 and 881 days, and in most areas of the northern half varied between 2 to 150 days (Fig. 2c). This is probably because the southern regions are more sensitive to SDE and winds with lower velocities can carry dust particles.

In western Iran, more than 40 % of the total area has suffered from dust pollution during the years 2011, 2008, and 2010 while less than 28 % of the area experienced these conditions during the years 2004 and 2006, respectively (Fig. 3). As a whole, the annual DSI was greater than the long-term DSI (DSIA>0) across about 44 % of the study area and it was lower than the long-term DSI (DSIA<0) in approximately 56% of the study area. The area affected by SDE in the north of the study area has declined between 2014 and 2018. These results indicate a downward trend in dust production in these areas, which is in line with the findings of Ghale et al. (2017), who showed that the activity rate of SDE in these areas from 2014 onwards was lower than in previous years. The decline in DSIA after 2009 reflects a decrease in soil particulate emissions and improved air quality across western Iran in recent years, which agrees with the results of some past works (Kamal et al. 2019; Namdari et al. 2016). It is likely due to reducing some sand-dunes activity (Abbasi et al. 2019) and the development of vegetation cover in some parts of the study area (Ebrahimi-Khusfi et al. 2020b).

The areas affected by air quality degradation are mainly distributed in the eastern and southern regions of the study area (Fig. 5c). Furthermore, the sensitivity of these regions to the SDE over the latter period was more than in other areas. Therefore, it can be concluded that the inhabitants of these areas were more exposed to environmental hazards caused by the SDE, while residents of other parts of the study area, especially the western ones, were somewhat safe from the SDE hazards. In general, the border regions between Iran and Iraq experienced positive anomalies in both study periods (Fig. 5; a and b), meaning that the region has suffered from dust pollution throughout the entire of study period. These findings are in line with the findings of those who identified this area as the dustiest area in western Iran (Dehghanpour et al. 2014; Javan and Teimouri 2019).

According to the hypothesis of the present study, long-term variations in NDVIA and LSTA had significant effects on the activity rate of the SDE and the air quality across western Iran. This is further analyzed and discussed in the following sections.

4.2. Relationships between NDVIA and LSTA with SDE in temporal scale

It is important to understand how changes in dust pollution across different regions depend on changes in its controlling factors (Ebrahimi-Khusfi et al. 2021). In recent years (2010-2018), the physical characteristics of the earth's surface and air quality have improved across western Iran (Figs. 4 and 6). Although a comprehensive study of the spatiot-emporal variability of vegetation cover and LST has not been conducted for this region of Iran, improvement of vegetation conditions in recent years on the local scales in Iran (Nateghi et al. 2018), Mongolia (Nanzad et al. 2019) and China (Feng et al. 2017) have also been proven which are partly consistent with the findings of this study. The obtained results of statistical analysis showed that the annual DSIA had a significant positive correlation with the LSTA ($R=+0.52$, $P<0.05$; Fig.6a and Table 1) and a negative correlation with the NDVIA ($R= -0.41$, $P<0.05$; Fig. 6b and Table 1) across the whole monitoring period. Although based on these results, it can be concluded that both variables affect DSIA changes in western Iran, land surface fluctuations had a greater impact on the DSIA than the NDVIA variations. In agreement with the findings of this work, the inverse and linear relationship between the dust emissions and vegetation cover have also been reported in many previous studies (Azoogh and Jafari 2018; Kergoat et al. 2017; Sofue et al. 2018). In addition, a recent study concluded that LST is one of the main factors controlling dust events in many arid and semi-arid regions of Iran because it has shown a significant direct relationship with changes in DSI in these areas (Ebrahimi-Khusfi and Sardoo 2021), which also confirms the findings of the present study.

4.3. Relationships between NDVIA and LSTA with SDE in spatial scale

In addition to the temporal change impact of terrestrial parameters on DSIA, their impact may vary from one place to another place. Hence, the spatial correlation analysis was conducted to explore the effect of spatial variability in the LSTA and NDVIA on the DSIA variations. Spatially, areas that have experienced the most dust pollution during the monitoring period, are mainly distributed in the vicinity of the inland wetlands (Fig. 5 and Fig. 1a). The increase of air quality degradation over these areas may be due to the destruction of the Bakhtegan, Meighan, Shadegan, and Hour Al-Azim wetlands in the western half of Iran (Ansari and Golabi 2019; Arsanjani et al. 2015; Ebrahimi-Khusfi et al. 2020a). The high susceptibility of many dried-up Iranian wetlands to SDE, which has been reported in some previous studies (Karami et al. 2021; Lababpour 2020; Sedaghat and Nazaripour 2020) is in line with the findings of this study.

The spatial correlation results showed that the NDVIA was negatively correlated with the DSIA in many parts of the study area (Fig. 7c). However, the LSTA was positively correlated with the DSIA in the whole of the study area (Fig. 7d). The results also showed that the NDVIA had different behavior in a small part of the study region, especially in higher elevation areas, because the vegetation anomaly was positively correlated with the DSIA. Moreover, these regions experienced less air quality destruction in most years of the study period base on DSIA monitoring maps (Fig. 3). Given that the source of dust pollution in the western parts of Iran is located in Iraq (Boloorani and Nabavi 2017), hence it may be due to the transport of aeolian sediments from adjacent countries to these regions. Another reason may be changing in land use and conversion of rangelands to agricultural lands due to overexploitation of groundwater which requires further climatic and terrestrial information to prove these assumptions. Also, given that the vegetation coverage in these areas is denser than in its adjacent western areas, this relationship is expected to be reversed as a result of further vegetation losses. Based on the results of the present study, the LSTA was positively correlated with the DSIA throughout the study area (Fig. 7d). Because the earth's surface temperature is significantly dependent on the air temperature (Good et al. 2017) and its increase can accelerate the process of evapotranspiration (Sun et al. 2016). As a result, soil moisture decreases and dust production increases since the wind erosion threshold velocity decreases (Chepil 1956; Fécan et al. 1998). In this study, it was also found that the relationship between LSTA and DSIA as well as NDVIA and DSIA across arid and semi-arid regions was stronger than the humid and sub-humid regions. These results show more susceptibility of drier climates to the ground physical characteristics fluctuations and soil deflation than to wetter climates in western Iran.

The periodic variations in the terrestrial variables anomalies revealed that the NDVIA value has significantly increased in recent years compared to the early years (Fig. 8c). This implies an increase in vegetation cover in the second half of the study years compared to the long-term average vegetation cover across western Iran. The incremental changes in vegetation-covered surfaces in the northwest, southwest, and central areas of western Iran are almost consistent with the findings of other researchers (Faramarzi et al. 2018; Sadeghi et al. 2017). Also, the outcomes indicated that the LSTA value has dramatically decreased in the latter period than in the previous period (Fig. 8f) and had a significant effect on DSIA (Fig. 6b). This finding is almost in agreement with the findings of An et al. (2018), who stated that change in near-surface temperature was one of the main reasons for changes in Asian SDE over recent years.

It was also observed that many areas affected by vegetation degradation are mainly different from those that have suffered from rising ground temperatures from 2009 onwards. This can indicate the separate effect of these two ground factors on the level of SDE activity, especially in this region of western Iran. It may be related to the type of land use and the difference in the roughness of the land surface, assumptions that need more information to prove for western Iran.

As a whole, given that the spatiot-emporal variations in the LSTA and NDVIA had a relatively notable effect on the DSIA variations over western Iran during the study period, it can be deduced that the results of this study support the hypotheses of this study.

4. Conclusion

In this study, the DSIA was applied for monitoring the air pollution caused by SDE in western Iran from 2000 to 2018. The spatiot-emporal alterations in NDVIA and LSTA, as well as their correlations with the DSIA, were also investigated in this work. Temporarily, the highest degradation in air quality occurred in 2012 and 2004 while the lowest degradation occurred in 2017 and 2002 over western Iran. Spatially, about half of the study area which mainly covers southern areas has suffered from dust pollution. Furthermore, this study showed that fluctuations in LSTA and NDVIA had significant effects on SDE activities in western regions of Iran. Air quality improvement due to the increase in NDVIA and the decrease in LSTA across a small area of the border between Iran and Iraq were other achievements of the current study. Moreover, the dual behaviors of LSTA and NDVIA were observed in areas that experienced the least dust pollution during the monitoring period. However, the stronger correlation between these variables and DSIA was mainly observed in the dustiest areas. Therefore, appropriate and adaptive measures should be taken to reduce the environmental hazards caused by soil erosion and dust pollution for the residents of western Iran, especially the southern areas of the study area, which were more sensitive to the SDE in most study years. Proposed measures include the restoration of degraded vegetation, the identification of dust particle transport pathways, and the development of heat-resistant vegetation windbreakers in these areas. Determining the contribution of human activities in vegetation degradation is also of great importance, which is suggested to be examined in future studies. Investigating the seasonal changes in LSTA and NDVIA and their effects on SDE activities across western Iran is another interesting topic that is suggested to be addressed in future research.

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Declarations

Ethical Approval:

Not applicable.

Consent to Participate:

Not applicable.

Consent to Publish:

Not applicable.

Authors Contribution:

ZE analyzed and interpreted the meteorological and remotely sensed data, and was a major contributor in writing the manuscript. FR prepared maps and wrote the introduction section of the article. All authors read and approved the final manuscript.

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Competing:

The authors declare that they have no competing interests.

Availability of data and materials:

The datasets used during the current study are available from the corresponding author on reasonable request.

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Figures

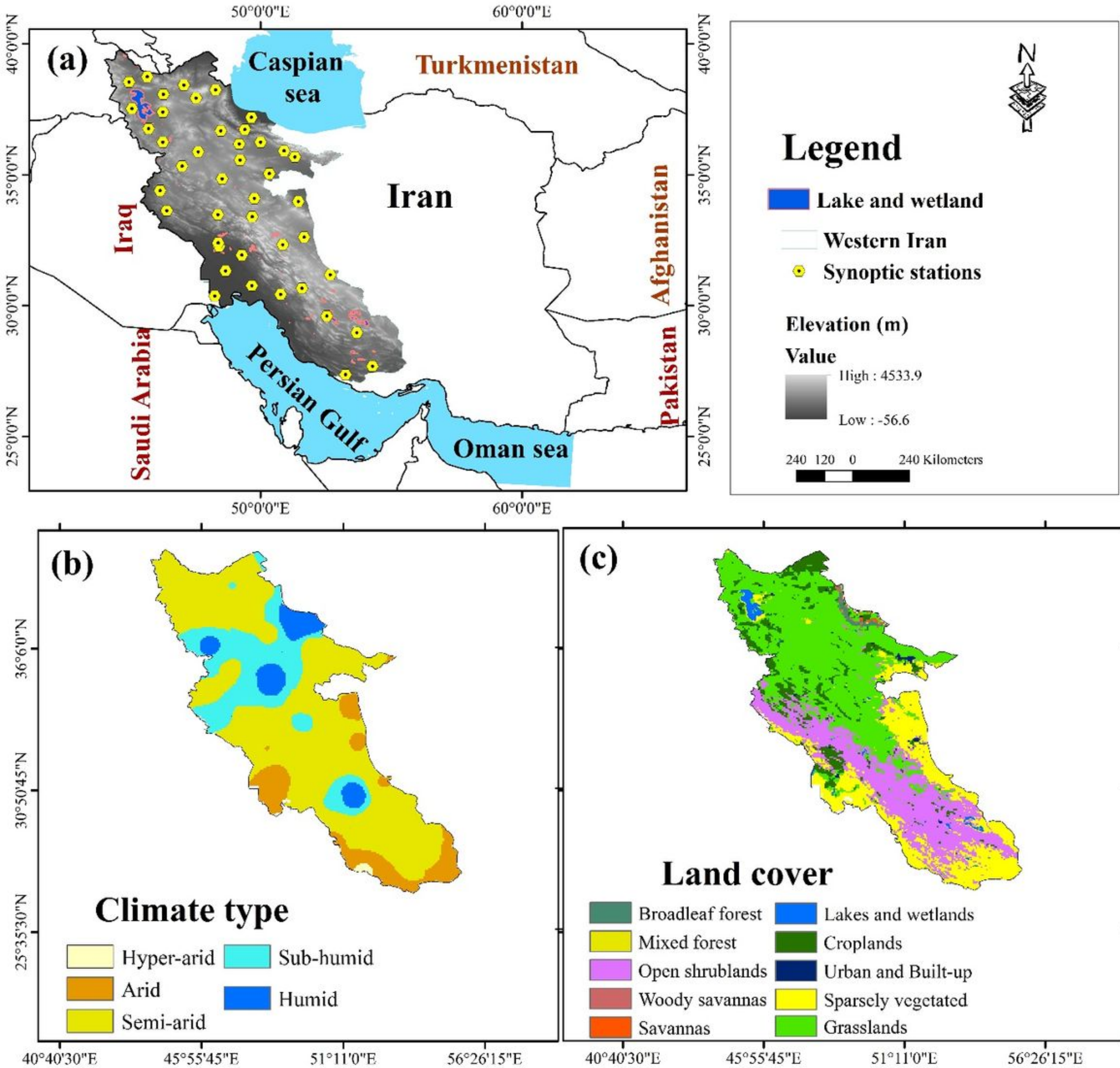

Figure 1

(a) Situation of the study area and synoptic stations in Iran, (b) different climate regions, and (c) land cover maps in western Iran.

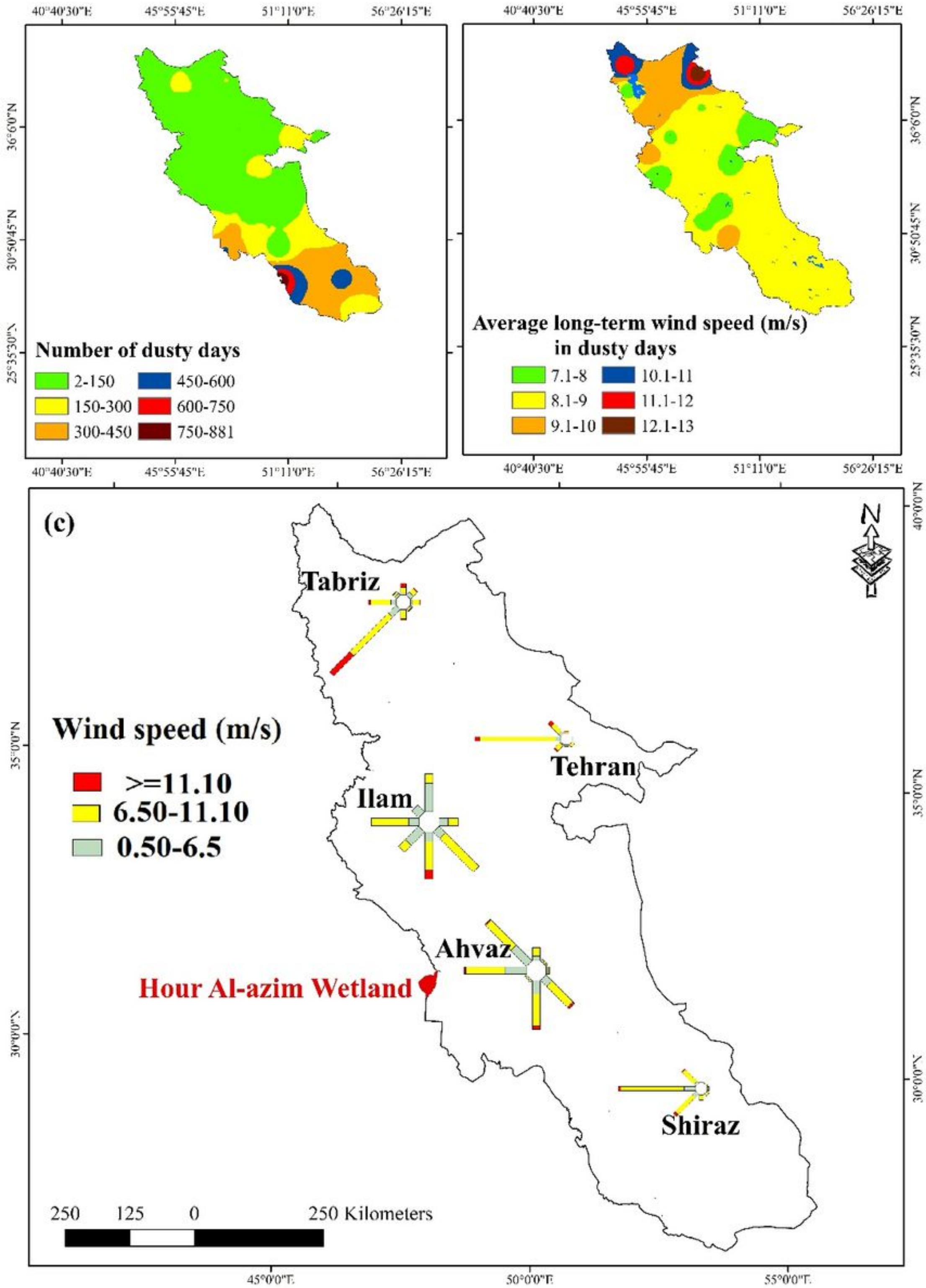

Figure 2

(a) Spatial distribution of number of dusty days, (b) average wind speed, and (c) directions of dusty winds during 2000-2018 in western Iran.

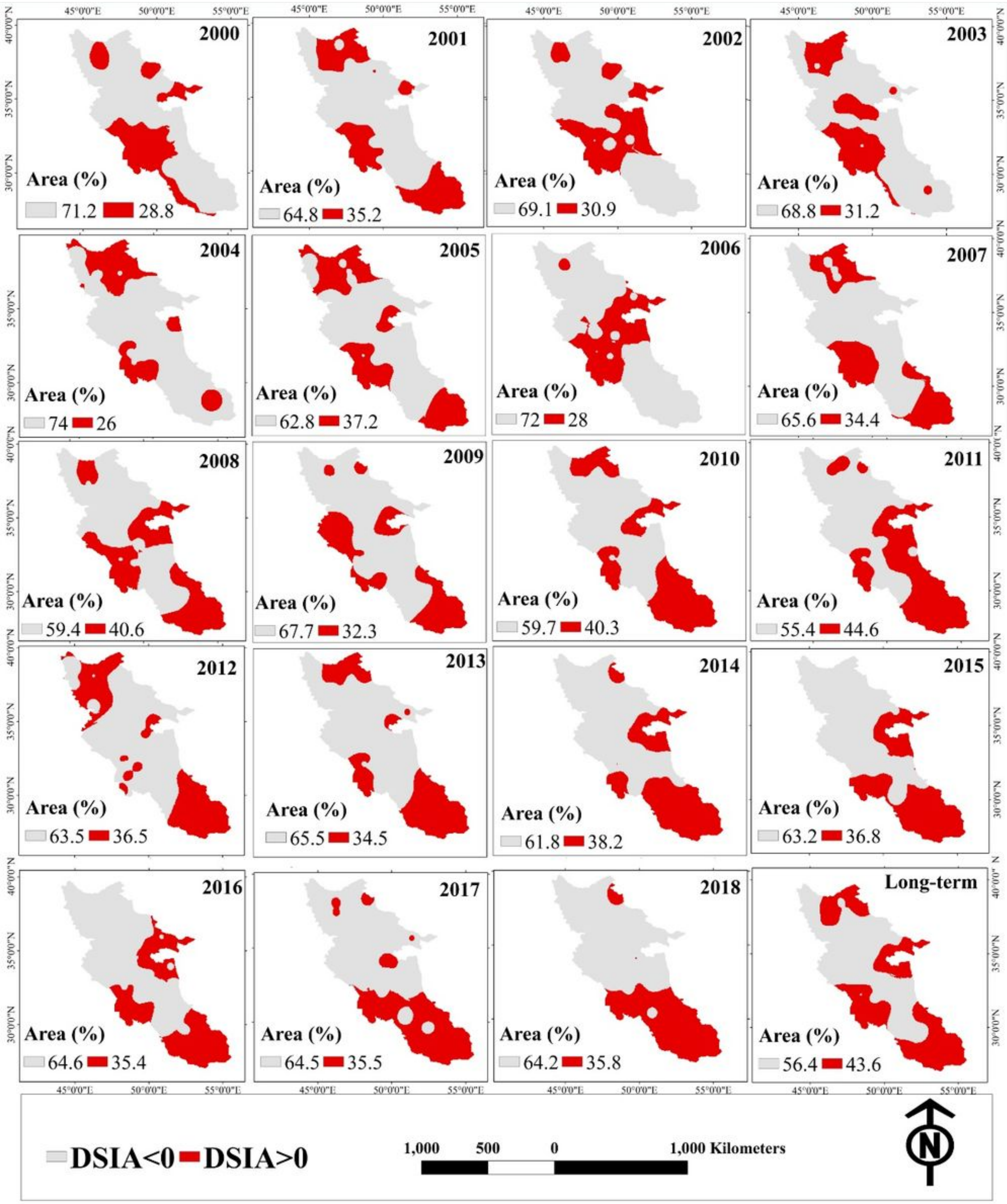

Figure 3

The spatial distribution of low-dust areas (DSIA<0) and high-dust areas (DSIA>0) in western Iran from 2000 to 2018.

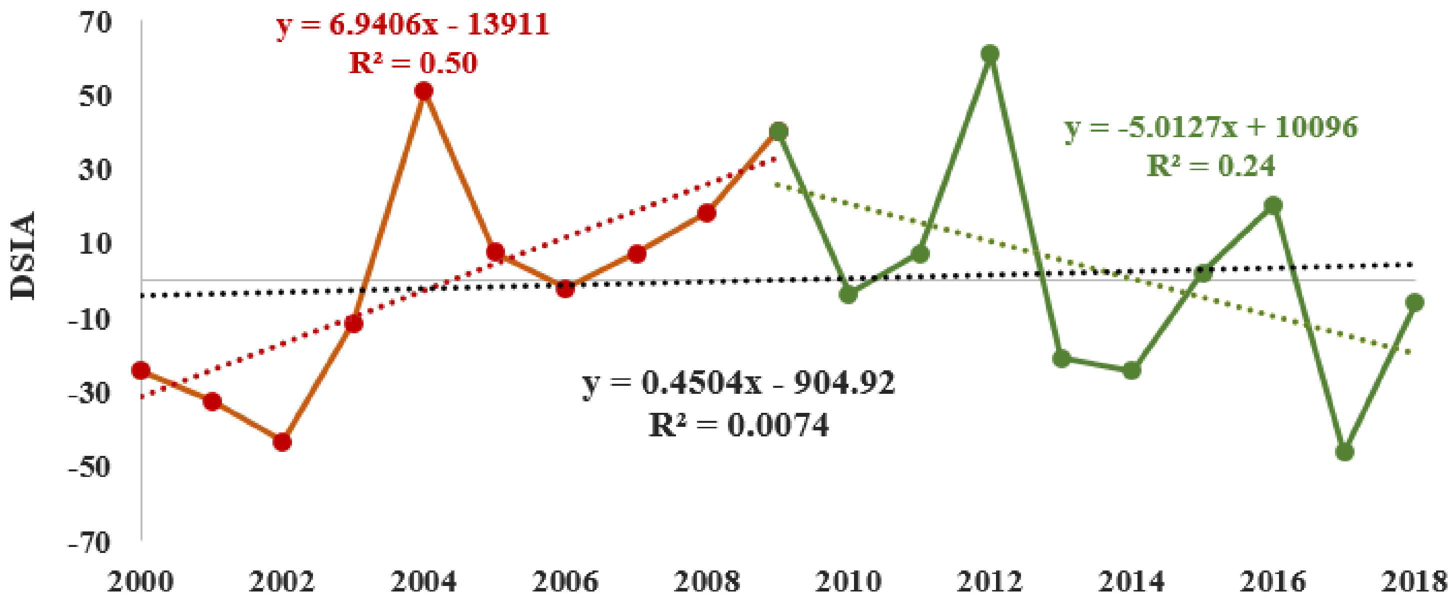

Figure 4

Inter-annual variations in dust storm index anomalies (DSIA) across western Iran during the years 2000-2018. The overall slope of the temporal changes in the DSIA during the period 2000 to 2008, 2009 to 2018 and the whole study period are shown with red, green and black dotted lines, respectively.

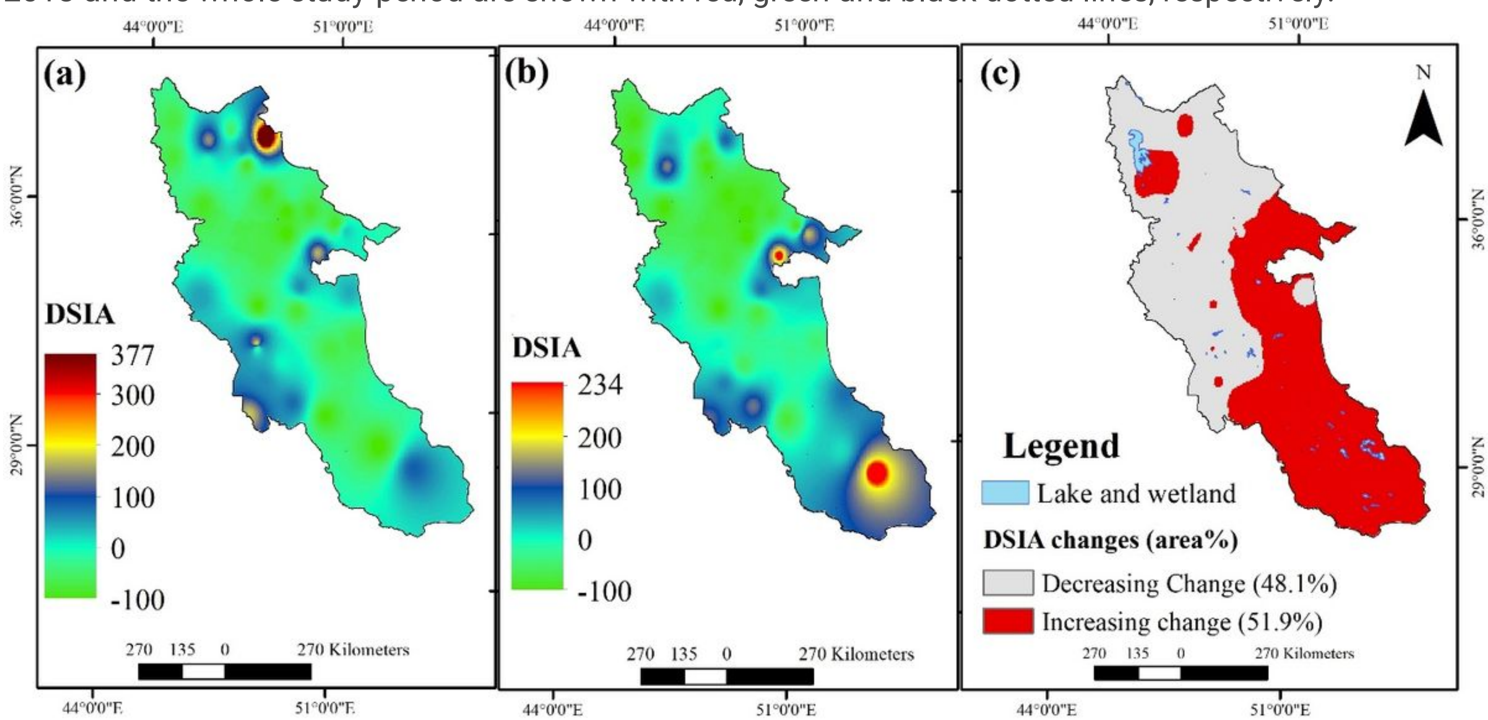

Figure 5

The DSIA variations across two separate periods: (a) 2000-2009 and (b) 2010-2018, and (c) its changes trend between two sub-periods.

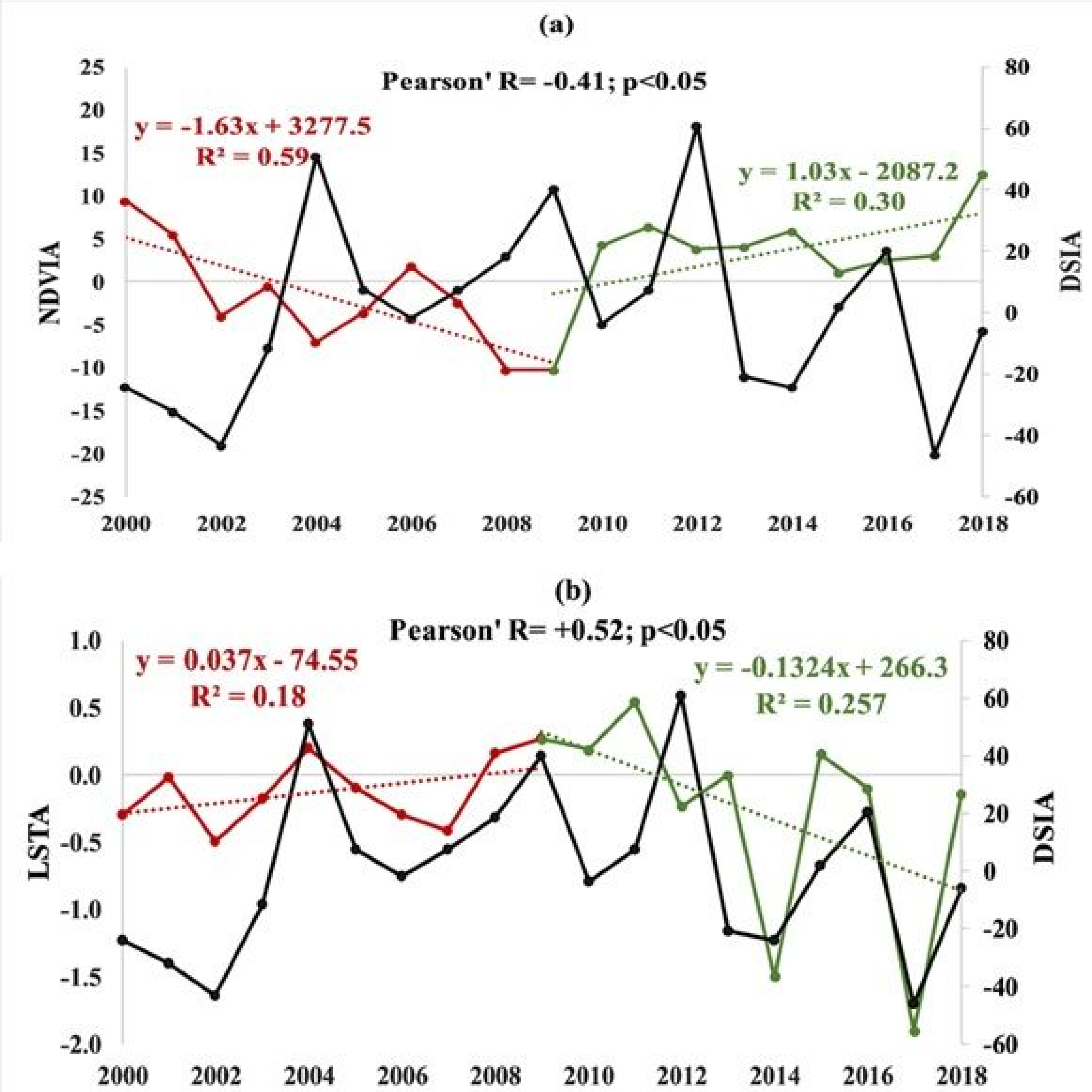

Figure 6

Inter-annual variations in the (a) LST anomaly; (b) NDVI anomaly and their relation with DSIA in western Iran during 2000-2018.

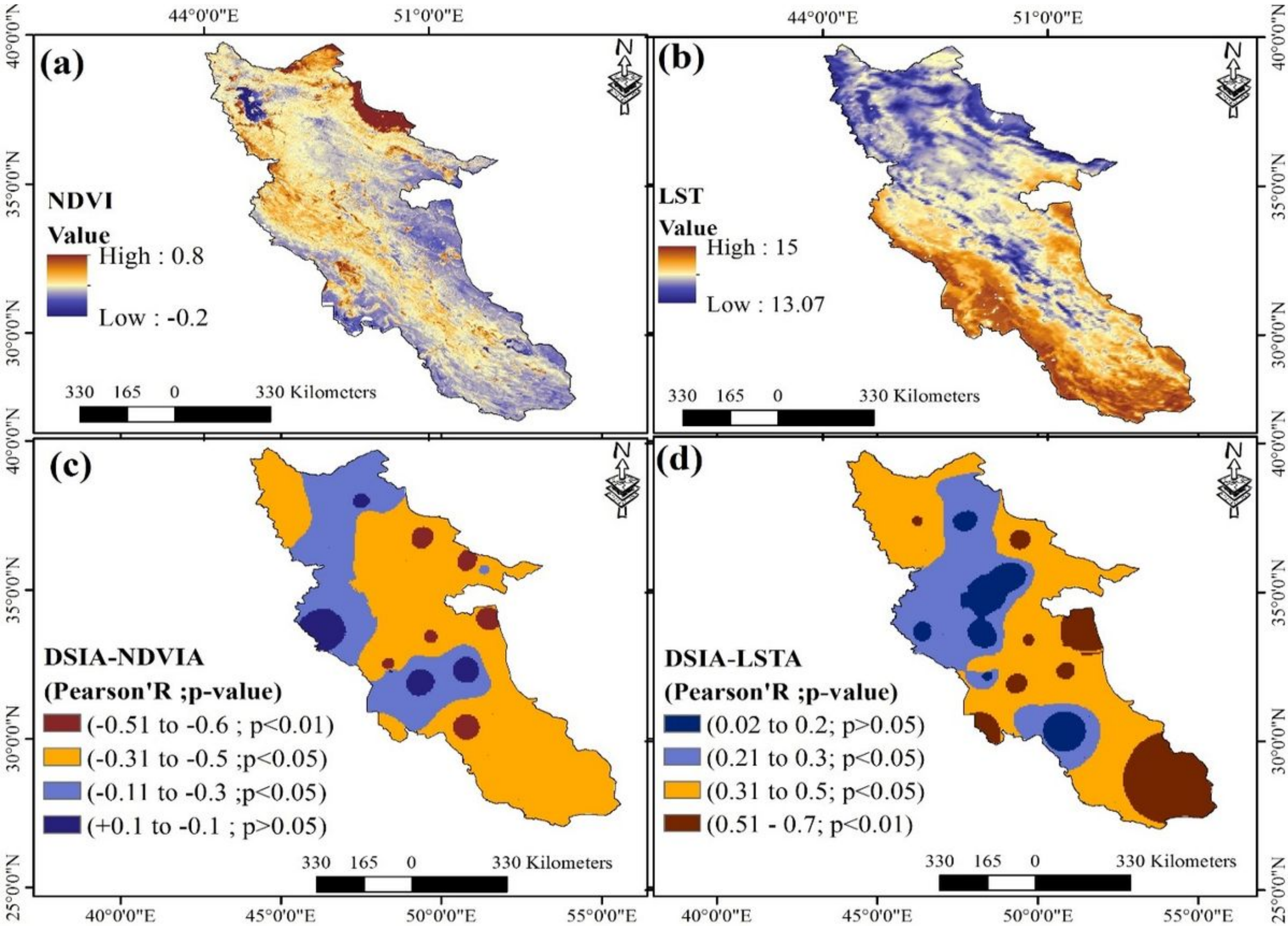

Figure 7

Spatial variations of (a) vegetation cover and (b) land surface temperature across western Iran. Spatial correlation coefficients between DSIA with (c) NDVIA and (d) LSTA in the area during 2000-2018.

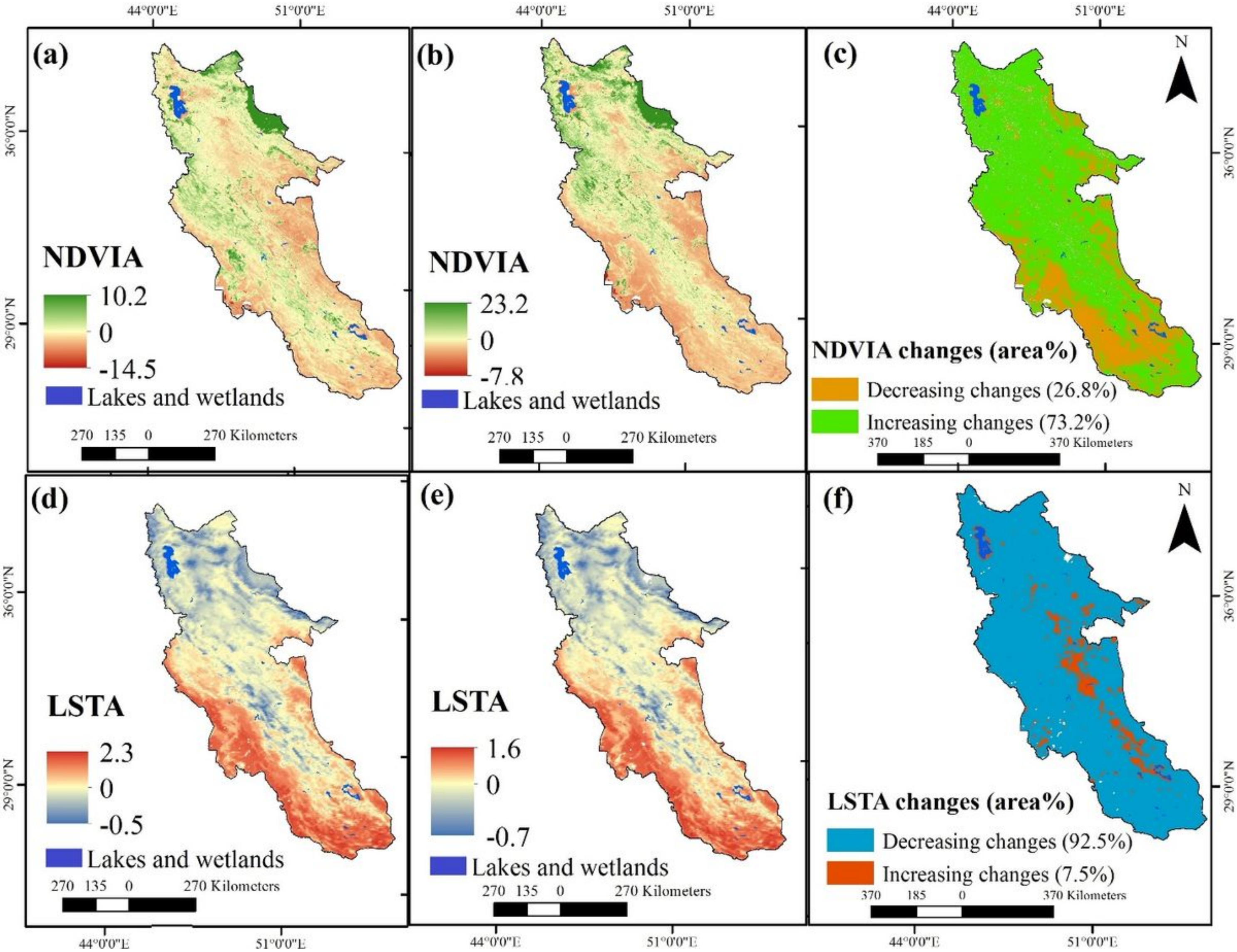

Figure 8

The periodic variations in NDVI anomaly and LST anomaly over study periods: (a;d) 2000-2009 and (b;e) 2010-2018. Trends of changes in vegetation anomaly (c) and land surface temperature anomaly (f) between two periods.

Supplementary Files

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- Supplementaryfiles.docx