Pollution, 4(1): 53-67, Winter 2018
DOI: 10.22059/poll.2017.235454.286
Print ISSN: 2383-451X   Online ISSN: 2383-4501
Web Page: https://jpoll.ut.ac.ir, Email: jpoll@ut.ac.ir

Spatio-temporal variability of aerosol characteristics in Iran using remotely sensed datasets

Rezaei, M.[1], Farajzadeh, M.[*1], Ghavidel, Y.[1] and Alam, K.[2]

1. Department of Climatology, Tarbiat Modares University, Tehran, Iran
2. Institute of Physics and Electronics, University of Peshawar, Pakistan

Received: 12 Jun. 2017   Accepted: 15 Aug. 2017

ABSTRACT: The present study is the first attempt to examine temporal and spatial characteristics of aerosol properties and classify their modes over Iran. The data used in this study include the records of Aerosol Optical Depth (AOD) and Angstrom Exponent (AE) from MODerate Resolution Imaging Spectroradiometer (MODIS) and Aerosol Index (AI) from the Ozone Monitoring Instrument (OMI), obtained from 2005 to 2015. The high concentration of AOD and AI values (representing high-high cluster) have been observed in the southwest and east regions, while their low concentrations (representing low-low cluster) have been found in the high mountainous areas. Based on AE values, Iran has been divided into three distinct regions, including fine, mixture, and coarse aerosol modes in each season. Results show that the maximum/minimum area under fine aerosols mode has occurred in the autumn, covering an area of 84.15% and in the spring, covering an area of 40.5%. In the case of coarse mode, the maximum/minimum area has been found in the spring, covered area=53.5% / in the Autumn covered area=12. 5%. The different aerosol modes regions strongly coincide with the topographical structure. To analyze the relation between aerosol properties and topography, Aerosol Properties Index (API) has been developed by combining OMI and MODIS datasets. API is a simple indicator, capable of showing the degree of aerosol coarseness in each pixel. There is a negative correlation between API and topography over the studied region, meaning that aerosol concentrations are high in the lowlands, but low in the highlands. However, this relation differs in various geographic regions, as Geographically Weighted Regression (GWR) model shows a higher determination coefficient in all seasons, in comparison to Ordinary Least Squares (OLS).

Keywords: aerosol properties, dominant aerosol modes, Iran, satellite observations.

INTRODUCTION

Atmospheric aerosol particles generally have variable diameters, being either directly emitted into the atmosphere or formed by the oxidation of precursor gasses such as certain oxides or volatile organic compounds, where the resulting oxidation products either nucleate to form new particles or condense on pre-existing ones (Alam et al., 2010). The aerosols are atmospheric components with a very significant role in establishing the earth’s radiative balance, making it essential to know about atmospheric aerosols and their characterization. Aerosols exert a variety of impacts on Earth's climate, like cloud microphysical properties, precipitation, direct radiative influence, chemical weather, human health, and climate change

[*] Corresponding author, Email: farajzam@modares.ac.ir

patterns (Ramanathan et al., 2001; Andreae et al., 2005; Pathak & Bhuyan, 2015). They affect the earth's weather and climatic system, both in a direct way, through solar radiation scattering and absorption phenomena, and indirectly, by influencing the microphysical and radiative properties of clouds, and atmospheric temperature profile (Lyamani et al., 2009; IPCC, 2013), although the magnitude of this influence remains uncertain even today (IPCC, 2007).

Aerosols have been recognized as a major factor when determining the global climatic change (IPCC, 2001), since they play a crucial role in solar and thermal radiative transfer in the atmosphere. They strongly modify the radiation budget on the surface of the earth as well as the cloud microphysical properties, precipitation rate, and hydrological cycle (Lohmann & Feichter, 2004). Apart from their role in radiation balance, they act as one of the factors to cause uncertainty in climatic modeling (Charlson et al., 1992; Penner, 1994). In addition, aerosol pollution negatively affects air quality, human health, and the environment (Berico et al., 1997; Beeson et al., 1998; Pope, 2000 ; McMichael et al., 2006). Also, aerosol particle is critical for epidemiological studies to accurately investigate the fine-scale spatial and temporal changes of particle concentrations (He et al., 2016). These aerosol climatic effects are highly variable, thanks to the large variability of their physical and optical properties, attributed to the variety of their sources (natural and anthropogenic), as well as their dependence on prevailing meteorological and atmospheric conditions (Satheesh & Moorthy, 2005).

Atmospheric aerosols are ubiquitous in the earth's lower atmosphere, existing in both troposphere and the stratosphere globally, though they are highly variable in their number concentration, composition, and various properties (Pöschl, 2005). Quantifying radiative forcing is key to understanding how climate changes at local, regional, and global scales. The greatest part of uncertainty in prediction of radiative forcing is attributed to limited knowledge of spatial and temporal distribution of aerosols, their Physio-chemical properties, and the processes they are involved in (Boucher et al., 2013; Kang et al., 2015; Kumar et al., 2014, 2015; Mehta, 2015; He et al., 2016).

Due to large uncertainties in spatio-temporal distribution of aerosols throughout the globe, the regional and global impact of atmospheric aerosols on the climate is still uncertain. This heterogeneity results from the high variability of sources of origin of different aerosols as well as their short residence time in the atmosphere (Textor et al., 2006; Kinne et al., 2006; Srivastava et al., 2016). The abundance of atmospheric aerosol and its constituents, their physio-chemical and optical properties, vary greatly with respect to time and space (Ram & Sarin, 2010; Ram, et al., 2012). Previous studies such as Dickerson et al. (1997), Kosmopoulos et al. (2008), Alam et al. (2010), Kaskaoutis et al. (2010), Zayakhanov et al. (2012), Cheng et al. (2015), Kumar et al. (2015), He et al. (2016), Floutsi et al. (2016), and Boiyo et al. (2017) investigated the spatio-temporal variation of aerosols in different regions of the world, pointing out the stable atmospheric conditions, high temperature, high humidity, and low elevation that result in high AOD concentration of an area.

Since there is only one Aerosol Robotic Network (AERONET) sunphotometer measurement site in Iran, the satellite data provide a good opportunity to monitor spatio-seasonal heterogeneity of aerosol properties. Satellite-based remote sensing provide long-term and uninterrupted spatial coverage undoubtedly provides a unique opportunity to derive regional, global, and seasonal spatial patterns for aerosol loads and properties. It has been shown that satellite data have enormous potential for mapping the distribution and properties of aerosols, and for deriving indirect estimates of particulate matter (Alam et al., 2011a; Kumar et al., 2015). In Iran, during recent years dust events have had an increasing trend, especially in the west and southwest regions of the country (Zarasvandi et al., 2011).

However, until now, there has been no study on examining the spatio-seasonal heterogeneity of aerosols and their dominant types over this region; therefore, the present study is capable of filling a scientific gap in our current knowledge on the importance of aerosol in different processes, such as air quality, human health, and climatic impacts. The main objective of this study is to identify spatio-seasonal variations of aerosol properties in Iran, using long term (2005-2015) MODIS and OMI satellite datasets. The results are presented in three sections. In the first, the seasonal and spatial variability of aerosols has been investigated in addition to their clusters and outlier's area, which represent high and low AOD concentration regions. In the second, there has been an attempt to identify regions with different aerosol mode, based on AE data in the different season. Finally, in the third section, the role of the topography in the spatial distribution of aerosol properties has been investigated.

MATERIALS AND METHODS

Figure 1 illustrates the Geographical location of Iran along with the distribution of topographical structure. The two important mountain ranges of Iran are Alborz and Zagros, stretching in the northwest-northeast and northwest-southeast directions, respectively. Iran is situated in the southwest of Asia with an area of about 1,648,000 km^2, between a latitude of 25° to 40° North and a longitude of 44° to 64° East. Iran's climate is affected by different factors such as proximity to the sea, elevation, and the presence or absence of large atmospheric phenomena like subtropical high pressure (Modarres, 2006). The central and eastern parts of Iran are affected by arid and semiarid climate with hot and dry deserts that can be sources of dusts (Gerivani et al., 2011).

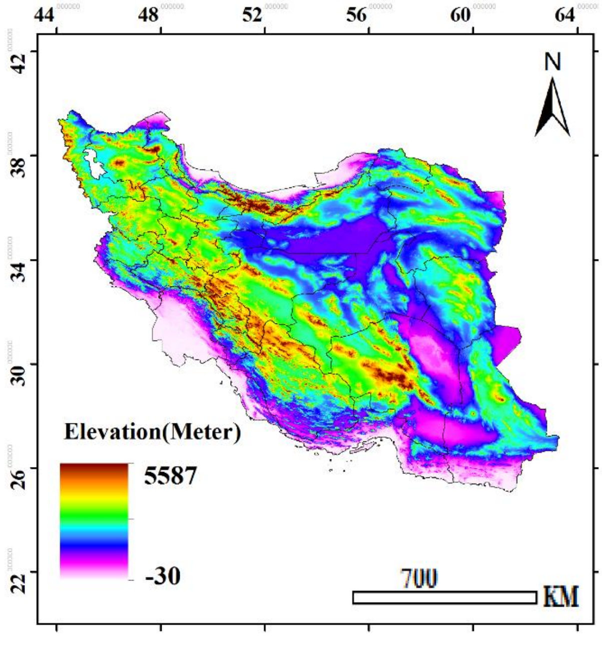

Fig. 1. The geographical location of Iran and topography distribution

The MODerate resolution Imaging Spectroradiometer (MODIS) is a remote sensor on board two Earth Observing System (EOS) Terra and Aqua satellites, both operating at an altitude of 705 km, with Terra spacecraft crossing the equator at about 10:30 LST (Local Standard Time, ascending northward), while Aqua crosses the equator at around 13:30 LST (descending southward; Remer et al., 2008). The MODIS measures the top of the atmosphere radiances in 36 channels from 0.41 to 14 μm at different spatial resolutions (250, 500, and 1000 m; King et al., 2003). In this study, we used the monthly MODIS (Terra) Collection 6 Level 3 aerosol optical depth and angstrom exponent data with 1°×1° grid for the long period between 2005 and 2015 over Iran.

Chu et al. (2002) believed that MODIS aerosol products can be used quantitatively in many applications. The root mean square (RMS) errors are ≤ 0.1 in the continental inland regions and up to 0.3 in the coastal regions. For oceans, Remer et al. (2002) concluded that MODIS-retrieved aerosol optical thickness at 660 nm and 870 nm fall within the expected uncertainty, meaning that MODIS aerosol products are valuable for research analysis. We also used OMI Aerosol Index data with a spatial resolution of 1°×1°, available at http://disc.gsfc.nasa.gov/Aura/OMI/omto3 g_v003.shtml, from NASA Goddard Earth Sciences Data and Information Services Center (GES DISC). The Ozone Monitoring Instrument (OMI) onboard EOS-Aura (2004–present) satellite was employed to have an understanding of spatio-seasonal aerosol properties over Iran. AI is especially sensitive to the presence of UV absorbing aerosols, such as smoke, mineral dust, and volcanic ash. The index value is positive when absorbing aerosols are present (Guan et al., 2010).

To determine the locations of significant clustering of high and low AOD and AI values, we used cluster and outlier analysis (Anselin Local Morans I). This technique aims at identifying feature clusters with similar values in magnitude. This method identified outliers through comparison with neighboring features and the mean of the entire population.

Based on AE values, Iran is divided into three dominant aerosols mode reigns, including fine, mixed, and coarse modes. The AE values greater than 0.95 and less than 0.85 are considered to represent fine and coarse mode, respectively, while the AE values between 0.85 and 0.95 show the mixed aerosol mode in this study. Previous studies such as Slutsker and Kinne (1999), Kaskaoutis et al. (2009), Pathak et al. (2012), Li et al. (2013), Kannemadugu et al. (2014), Kumar et al. (2015) determined aerosol types, based on AOD and AE threshold values. For example, AE values close to 0.9 was considered for mixed type of aerosol (Kaskaoutis et al., 2009). It seems that these thresholds are appropriate for the classification of aerosols mode over Iran.

The higher values of AOD and AI indicate the high concentration of aerosol, and the AE, their size. Therefore, combining these data represents aerosol properties and degree of aerosols coarseness in a region. According to Equation (1), higher API values indicate the coarse mode in a region, while the low ones show fine aerosol mode.

$$API = AOD + AI - AE \qquad (1)$$

The parameters aerosol properties index consists of the AOD, AI, and AE; therefore, the relation between aerosol properties index and topography could be useful to understand the relation between aerosol characteristics and topography.

In order to analyze the effects of topography on spatial distribution of API values, the Ordinary Least Squares (OLS) and Geographyically Weighted Regression (GWR) models are compared. More details on GWR can be found in the studies of Charlton et al. (2009).

RESULTS and DISCUSSION

Figure 2 shows spatial and seasonal properties of AOD, AE, and AI over Iran. The average value of AI in Iran during winter, spring, summer, and autumn were 0.96, 1.24, 1.13, and 0.89, respectively, with the maximum values of AI belonging to southwestern Iran (in south of Khuzestan province) in all seasons. For example, in the spring, AI in the south of Khuzestan province reached 2.25. Likewise, the average AOD values during winter, spring, summer, and autumn were 0.15, 0.16, 0.14, and 0.10, respectively. SImilar to AI concentrations, the maximum AOD concentration was observed in the southwest in all seasons. Average AE values during winter to autumn were 1.04, 0.79, 0.8, and 1.13, respectively. Low AE values represent the larger size of aerosol particles. Minimum values of AE (0.18, 0.46) belonged to both spring and autumn in the southwest region as well as winter and summer in eastern (0.44) and northeastern regions**.** As can be seen in Figure 2, maximum and minimum values of AOD and AI were observed in the spring and autumn, respectively. This temporal pattern was similar to the studies by Zayakhanov et al. (2012), Cheng et al. (2015), and He et al. (2016), who found that the aerosols were higher in spring and summer, while relatively low in autumn and winter in their study areas, namely Gobi Desert, Shanghai, and China, respectively. The high AOD values during the spring and summer were mainly attributed to more stable atmospheric conditions in these seasons, which lead to the accumulation of aerosols in the atmosphere (Kosmopoulos et al., 2008); desert dust influx, originated from arid regions (El-Askary et al., 2006; Papadimas et al., 2008; Tariq & Ali. 2015); higher concentration of water vapor and humidity (Ranjan et al., 2007; Alam et al., 2010; Li & Wang, 2014); and higher temperature during summer, which makes photochemical reactions more active, in turn increasing the aerosol loading during this season (Dickerson et al.,1997).

Figure 3 shows the spatial clusters and outliers map of AOD and AI, separately for each season. This technique is well capable of identifying low and high clusters of AOD and AI data in Iran. In winter there is a high-high cluster of AOD in the southwest region (in Khuzestan province). Also in winter, high AI values can be seen in south-western and eastern regions of country (high-high clusters). The low-AOD region, which indicates low-low cluster, is consistent with Zagros mountains. During the spring, there is a high-high cluster of AOD values in the southwestern region, while in the summer high-high cluster can be seen in southwestern and southeastern areas. During these seasons low-low cluster is not observed. In spring and summer, the high-high cluster of AI, observed in the south strip regions and low-low cluster, show close coincidence with the topography. And eventually in the autumn, the high-high and low-low clusters can be observed in the southwestern and northwestern regions, respectively. Also, for AI data, there are high-high clusters in the southwestern, eastern, and northeastern areas with low-low clusters observed in the highlands of southern Iran. The high concentration of aerosols in the western regions is due to active sources of the dust storm, located in west and north of Syrian and Iraq Desert (Zoljoodi et al., 2013). In the eastern region (especially Sistan), after a dry period at the end of 1999s, and due to land-use changes and desiccation of the Hamoun wet lands, the frequency and severity of dust storms increased, significantly. Thus, Hamoun is responsible for the dramatic increase in AOD over the downwind areas (Rashki et al., 2012; Alam et al., 2011b).

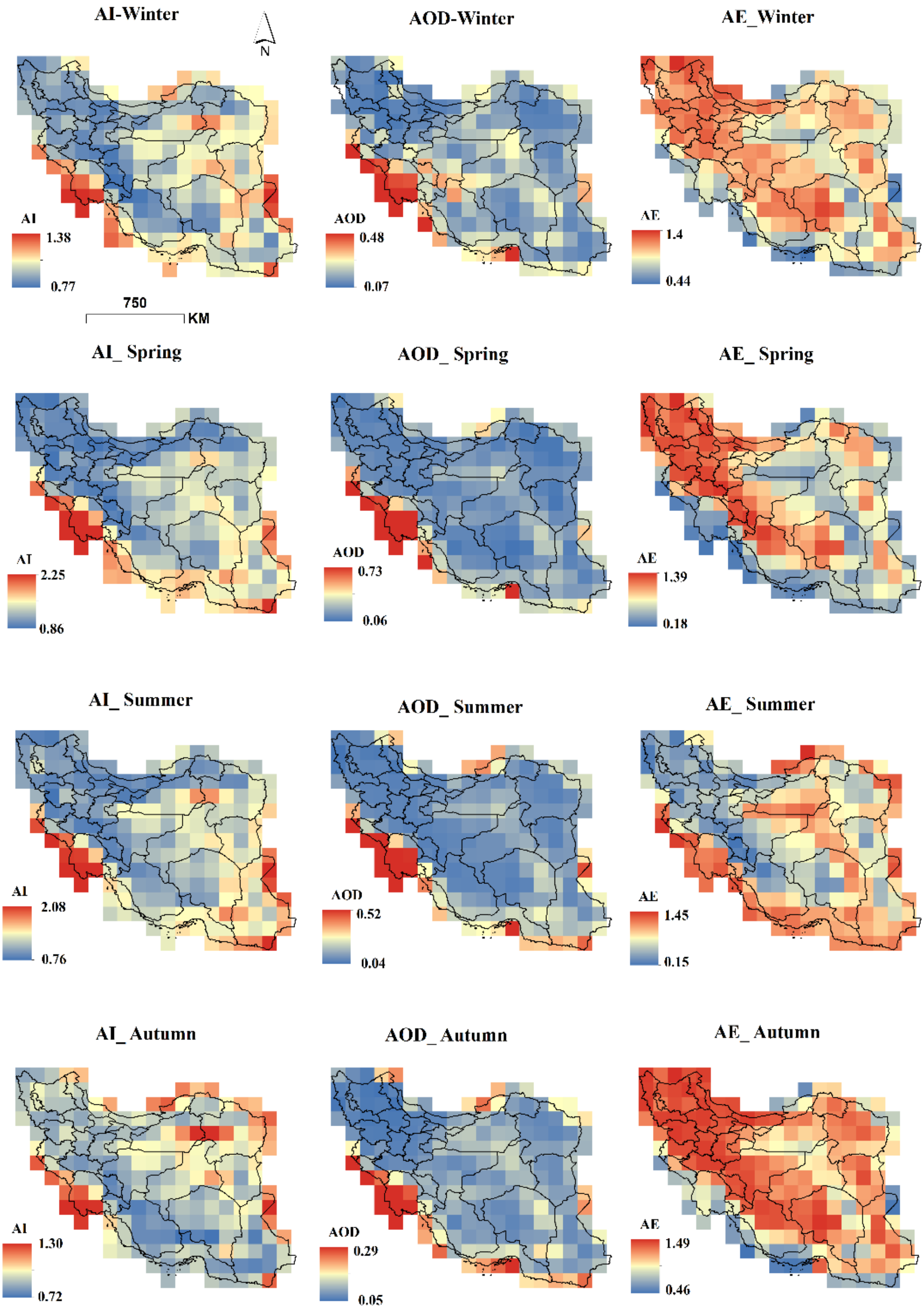

Fig. 2. Spatio-Seasonal variation of AOD AE and AI between 2005 and 2015 over Iran

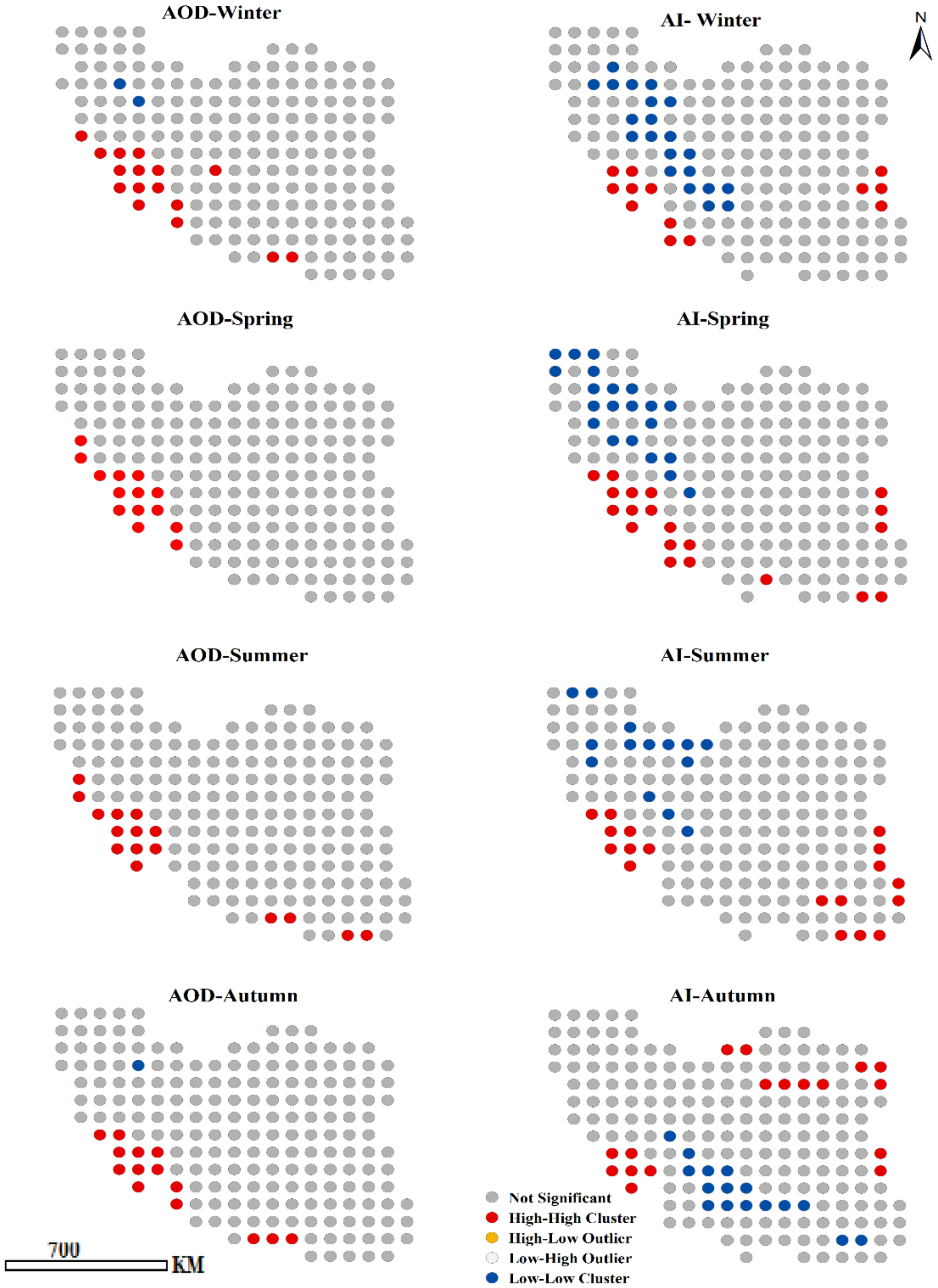

Fig. 3. Clusters and outliers long-term seasonal AOD and AI between 2005 and 2015

AE is a qualitative indicator, providing information for each fine- and coarse-mode aerosol (Lee et al., 2010). As mentioned in the methodology section above, based on AE values, the regions with different aerosol modes are determined, hence dividing Iran into three distinct regions, namely fine, mixture, and coarse aerosols mode in each season (Fig. 4, right side).

Table 1 gives the average of AOD, AI, and AE as well as their elevation for each aerosol mode regions. In the first class, representing the fine mode, the average of elevation and API are much higher and lower, compared to other regions, respectively (e.g. the average elevation of this class in summer reached to 1700.4 meters with an API of -0.15). Having a with northwest-southeast trend, this region closely coincide with Zagros mountains.

Similar to the first region, the second one, representing the mixture mode, has a good agreement with mountains and foothills of Alborz and Zagros; however, this region's elevation is less than the fine mode one (summing up to 1328.93 m in the summer). The coarse mode region can be observed in lowland areas of eastern and southern Iran with an elevation of 292.8 m in autumn.

With regards to the results above, it seems that the aerosols mode is well associated with the topographical structures. The fine aerosol (minimum value of API) can be found in the highland areas, and the coarse aerosol in the lowland regions. As can be seen in Table 1, the maximum area under fine aerosols mode is observed in autumn (covered area= 84.15%, AOD=0.08 and AE=1.26) and winter (coverage area= 70.32%, AOD=0.12 and AE= 0.90). Nonethelss, the percentage of the covered area of fine aerosols mode plummets in spring and summer, falling as low as 40.5% and 40.98%, respectively.

The maximum area under coarse aerosols mode is observed in the spring (covered area= 53.5%, AOD=0.19 and AE=0.55) and summer (covered area= 50.8%, AOD=0.19 and AE=0.54). By considering these values and based on the study of Kumar et al. (2015), dominant type of aerosol in this region is desert dust. The minimum percentage of coverage area in coarse aerosols mode declines significantly in autumn (coverage area= 12.5%, AOD=0.18 and AE=0.73) and winter (coverage area= 15.9%, AOD=0.21 and AE=0.72).

The mixture aerosols mode is low in comparison to the other two. Figure 5 shows the percentage of covered area, related to each aerosol mode in Iran.

Based on the results above, topographical structure has a close relation with the aerosol type regions over Iran. In addition, aerosol types have changed with changes in season. The AOD values in the coarse mode area are higher in warm seasons (summer and spring) compared to the cold ones (winter and autumn). High area of coarse mode during summer and spring is mainly due to to long-range transportation of mineral dust from the arid regions (Pathak et al., 2012), while precipitation acts as a wet removal process (Papadimas et al., 2008) during winter and autumn.

Table 1. Three aerosol modes and their properties along with API, elevation, and percentage of coverage area in all seasons in Iran

Season	Modes	AE	AOD	AI	API	Elevation (Meter)	Coverage area (%)
Winter	Fine	1.18	0.12	0.90	-0.14	1441.5	70.32
	Mix	0.89	0.17	1.04	0.32	589	13.7
	Coarse	0.72	0.21	1.07	0.56	390.5	15.93
Spring	Fine	1.16	0.10	1.01	-0.05	1665.02	40.5
	Mix	0.89	0.10	1.13	0.34	1285.45	6
	Coarse	0.55	0.19	1.37	1.02	772.2	53.5
Summer	Fine	1.16	0.07	0.93	-0.15	1700.4	40.98
	Mix	0.90	0.08	1.12	0.14	1328.93	8.19
	Coarse	0.54	0.19	1.28	0.92	704.9	50.81
Autumn	Fine	1.26	0.08	0.87	-0.3	1326.3	84.15
	Mix	0.91	0.16	1.01	0.26	339	3.2
	Coarse	0.73	0.18	1.00	0.45	292.8	12.56

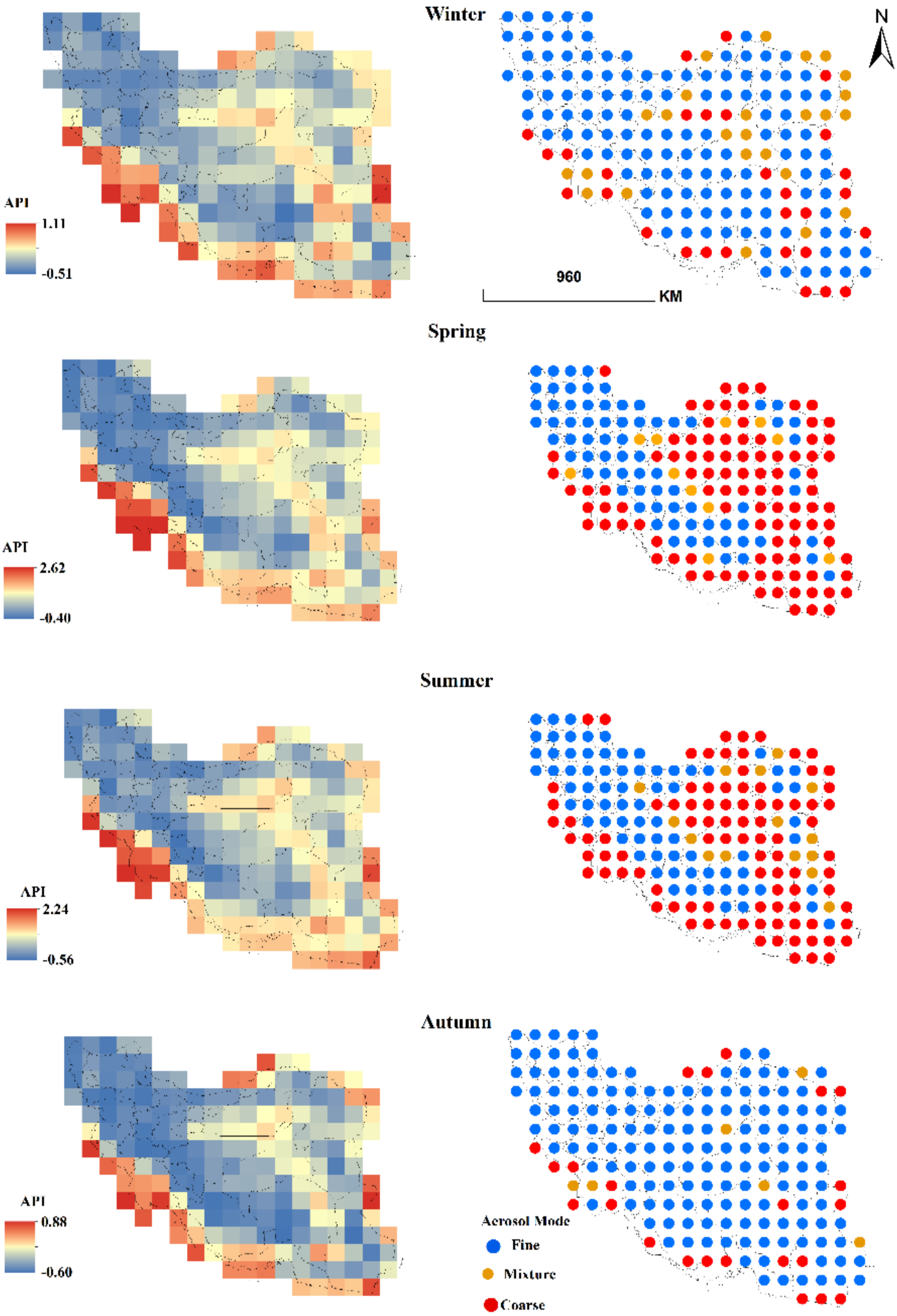

Fig. 4. Geographical distribution of Aerosols mode and API over Iran in different seasons

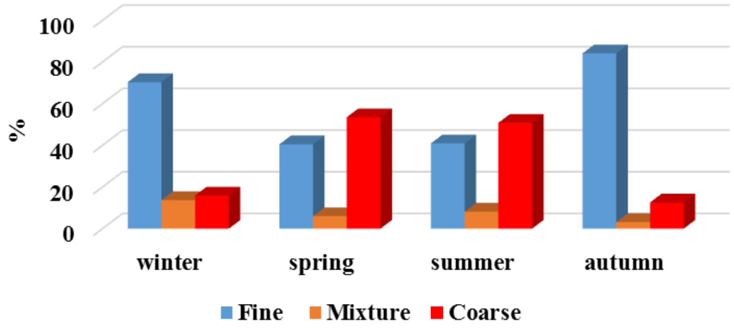

Fig. 5. Percentage of coveraed area related to each aerosol mode over Iran in all season

Since the geographical distribution of API is closely related to topography, this section attempts to investigate the relation between elevation and API values, using GWR and OLS models. In Figure 6, scatter diagram shows the relation between predicted API values and the observed one, using GWR and OLS. As can be seen, GWR, in comparison to OLS, shows a better coefficient of determination in all seasons. The maximum coefficient of determination has been observed in the spring (R^2=0.9) from GWR model, while OLS shows lower coefficient of determination (R^2=0.56), indicating that the API geographical distribution is strongly influenced by topographic conditions. In other words, in some regions a strong correlation (R^2>0.8) between API and elevation has been observed, while in others, there is just a moderate correlation (R^2 >0.4).

He et al. (2016) found that the highest AOD values tended to be located in flat areas with low elevation, while they were generally low in mountainous and highland areas, such as the Tibetan Plateau.

As seen in Figure 7, the maps of local R^2 value represent the model's performance in each pixel during all seasons. The overall local R^2 for Iran during winter, spring, summer, and autumn are 0.42, 0.46, 0.43, and 0.44, respectively. In all seasons, the maximum performance of the model (High R^2 values) has been observed in the eastern and western region, suggesting that in these regions, height and API values are low and high, respectively. For example, in the spring maximum local R^2 has been seen in the western region (latitude= 33.5, longitude= 45.5, height= 56 m, API= 2.08) with an amount of 0.96, whereas the minimum values have been observed in the southeast and northeast of Iran. In the northwest region, despite the high elevation (height = 2045 m) relatively high API values (API= -0.2) can be seen. This is probably due to the transfer of aerosols from distant areas. For example, in the spring, minimum local R^2 (0.18) has been seen in the northwest (latitude=37.5 longitude=47.5, height = 2045 meter, API= -0.2).

There has been little literature about the relation between topography and aerosol properties; however, our results are consistent with the previous studies that showed the association of topographical structure and spatial distribution of aerosol properties. Engelstaedter et al. (2003) mentioned that in non-forested regions, dust storm frequency increased as the fraction of closed topographic depression rose, likely due to the accumulation of fine sediments in these areas. Luo et al. (2014) reported that two low AOD centers were located in China: the high-latitude region in Northeast China with AOD of about 0.2 and the high-altitude region in Southwest China with AOD from 0.1 to 0.2. They mentioned that the Tibetan Plateau in the west could be regarded an important large topography in aerosol distribution over China.

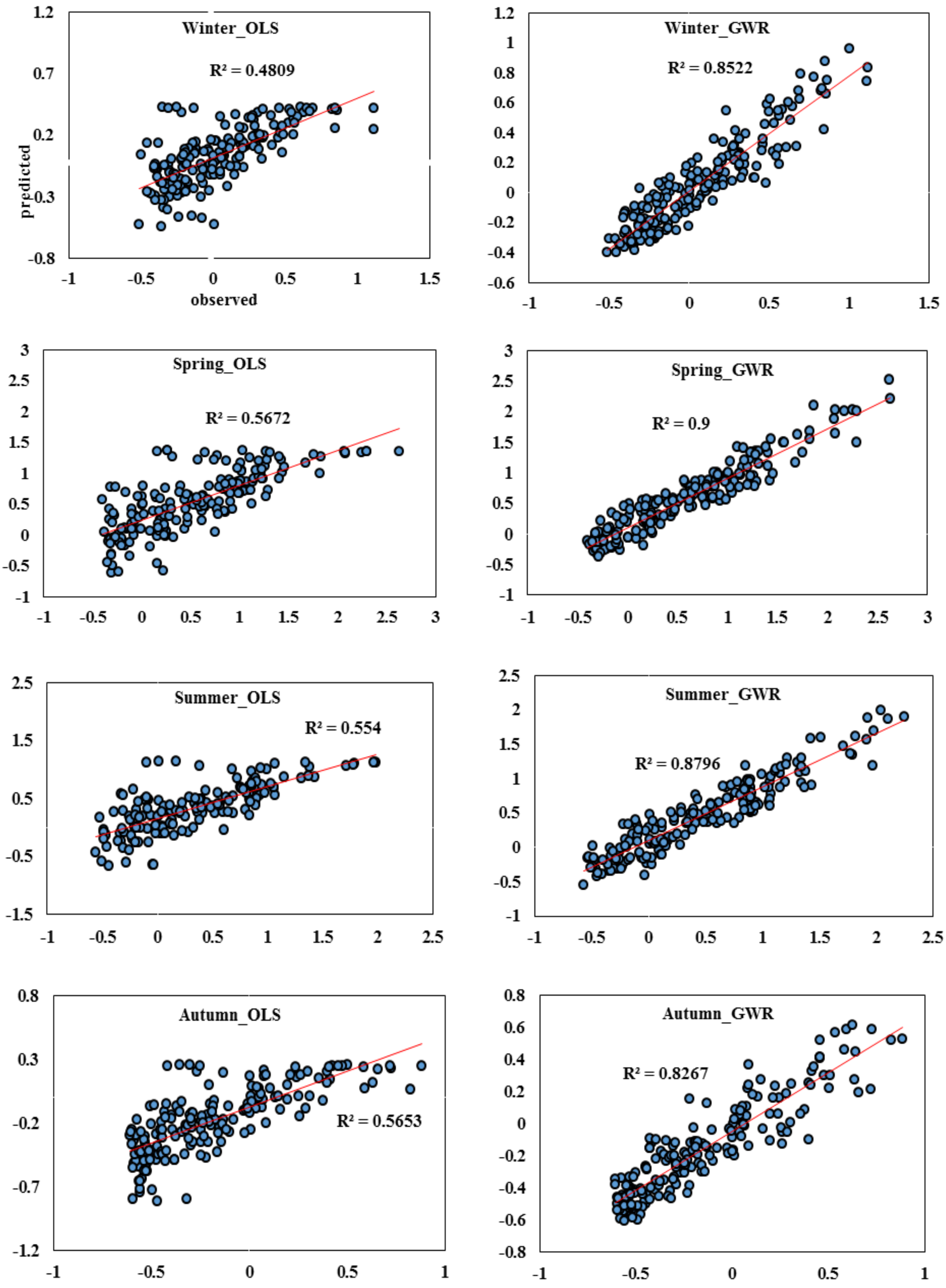

Fig. 6. Scatter diagram of observed and predicted values of API by OLS (left side) and GWR (right side) models

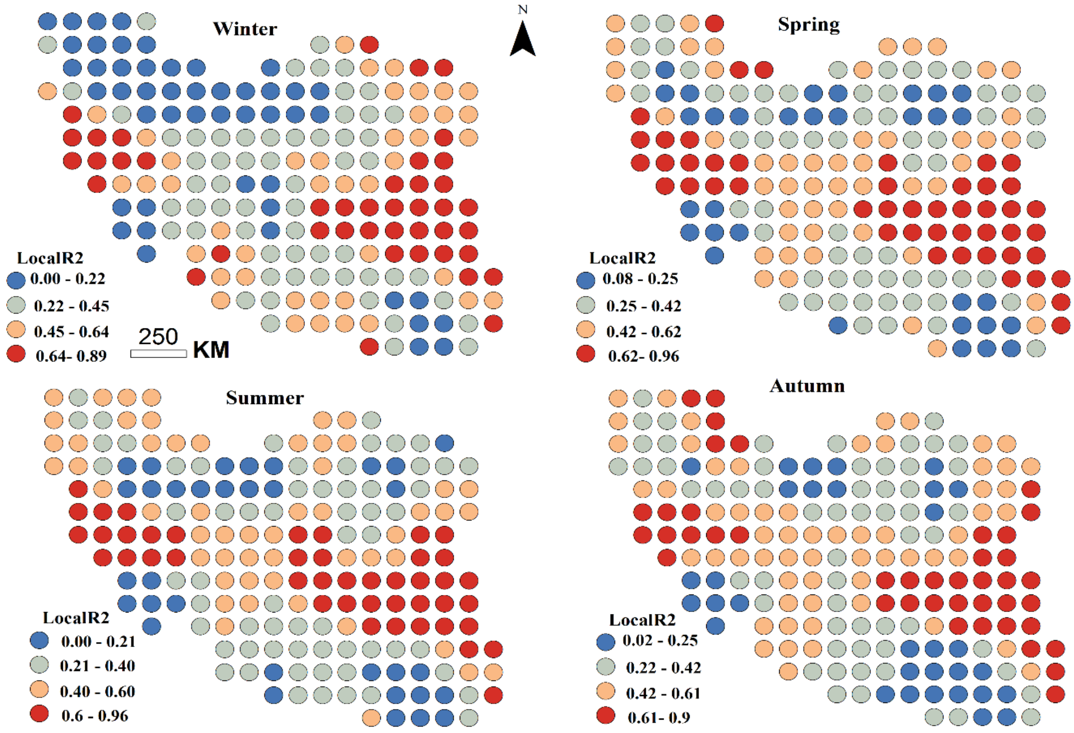

Fig. 7. Geographical distribution of local R^2 in Iran during different seasons

CONCLUSION

The present study analyzed AOD, AE, and AI dataset from MODIS and OMI sensors for eleven years (2005–2015), in order to evaluate the spatio-seasonal variability of aerosol and spatial classification of their dominant type over Iran. The main results of this study are as follows:

- For both datasets (MODIS and OMI), the maximum and minimum concentration of aerosols were observed during spring and autumn seasons, respectively. High clusters of AOD and AI (that indicate maximum aerosol concentration) were observed in the southwest and east regions, while the low clusters belonged to high mountainous areas of Zagros and northwest Iran.
- Based on the AE values, Iran was divided into three distinct regions, i.e. fine, mixture, and coarse aerosol modes in each season. Fine mode aerosols were observed to cover a maximum area of about 84.15% in autumn, and a minimum one of 40.5% in spring. In the case of coarse mode, the maximum area had a percentage coverage of about 53.5% in spring and a minimum of 12.5% in autumn. The different aerosol modes regions greatly coincided with the topographical structure.
- The fine and coarse aerosol modes were observed in the highland and lowland areas, respectively, with the API having a negative correlation with topography distribution. This relation varied in different geographic regions since the GWR model, compared to OLS, showed a higher coefficient of determination in all seasons. In all seasons the high R^2 values were observed in the eastern and western regions of Iran, while the minimum values belonged to the southeast and northeast Iran, which was probably because of the relatively high and low values of API in the highland and lowland areas, respectively.

REFERENCES

Alam, K., Qureshi, S. and Blaschke, T. (2011a). Monitoring spatio-temporal aerosol patterns over Pakistan based on MODIS, TOMS and MISR satellite data and a HYSPLIT model. Atmos Environ, 45(27): 4641-4651.

Alam, K., Trautmann, T. and Blaschke, T. (2011b). Aerosol optical properties and radiative forcing over a mega city Karachi. Atmos. Res., 101: 773-782.

Alam, K., Iqbal, M.J., Blaschke, T., Qureshi, S. and Khan, G. (2010). Monitoring spatio-temporal variations in aerosols and aerosol-cloud interactions over Pakistan using MODIS data. Adv Space Res, 46(9): 1162-1176.

Andreae, M.O., Jones, C.D. and Cox, P.M. (2005). Strong present-day aerosol cooling implies a hot future. Nature, 435(7046): 1187-90.

Beeson, W.L., Abbey, D.E. and Knutsen, S.F. (1998). Long-term concentrations of ambient air pollutants and incident lung cancer in California adults: Results from the AHSMOG study. Environ. Health Persp., 106(12): 813-822.

Berico, M. and Luciani A.F.M. (1997). Atmospheric aerosol in an urban area–measurement of TSP and PM10 standards a pulmonary deposition assessment. Atmos Environ., 31(21): 36-59.

Boiyo, R., Kumar, K.R., Zhao, T. and Bao, Y. (2017). Climatological analysis of aerosol optical properties over East Africa observed from space-borne sensors during 2001-2015. Atmos Environ., 152: 298-313.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., … and Zhan, X.Y. (2013). Clouds and aerosols. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 571-657.

Charlson, R.A., Schwatz, S.E., Hales, J.M., Cess, R.D., Coakley, J.A., Hansen, D.J.H. (1992). Climate forcing by anthropogenic aerosols. Science, 255: 423-430.

Charlton, M., Fotheringham, S. and Brunsdon, C. (2009). Geographically weighted regression. White paper. National Centre for Geocomputation. National University of Ireland Maynooth.

Cheng, T., Xu, C., Duan, J., Wang, Y., Leng, C., Tao, J., … and Yu, X. (2015). Seasonal variation and difference of aerosol optical properties in columnar and surface atmospheres over Shanghai. Atmos Environ., 123: 315-326.

Chu, D.A., Kaufman, Y.J., Ichoku, C., Remer, L.A., Tanré, D. and Holben, B.N. (2002). Validation of MODIS aerosol optical depth retrieval over land. Geophys Res Lett, 29(12).

Dickerson, R.R., Kondragunta, S., Stenchikov, G., Civerolo, K.L., Doddridge, B.G. and Holben, B.N. (1997). The impact of aerosols on solar ultraviolet radiation and photochemical smog. Science, 827-830.

El-Askary, H., Gautam, R., Singh, R.P. and Kafatos, M. (2006). Dust storms detection over the Indo-Gangetic basin using multi sensor data. Adv Space Res., 37(4): 728-733.

Engelstaedter, S., Kohfeld, K.E., Tegen, I. and Harrison, S.P. (2003). Controls of dust emissions by vegetation and topographic depressions: An evaluation using dust storm frequency data. Geophys Res Lett, 30(6).

Floutsi, A.A., Korras-Carraca, M.B., Matsoukas, C., Hatzianastassiou, N. and Biskos, G. (2016). Climatology and trends of aerosol optical depth over the Mediterranean basin during the last 12years (2002–2014) based on Collection 006 MODIS-Aqua data. Sci Total Environ, 551: 292-303.

Gerivani, H., Lashkaripour, G.R., Ghafoori, M. and Jalali, N. (2011). The source of dust storm in Iran: a case study based on geological information and rainfall data. Carpath J Earth Env, 6: 297-308.

Guan, H., Esswein, R., Lopez, J., Bergstrom, R., Warnock, A., Follette-Cook, M., … and Iraci, L.T. (2010). A multi-decadal history of biomass burning plume heights identified using aerosol index measurements. Atmos. Chem. Phys., 10(14): 6461-6469.

He, Q., Zhang, M. and Huang, B. (2016). Spatio-temporal variation and impact factors analysis of satellite-based aerosol optical depth over China from 2002 to 2015. Atmos Environ., 129: 79-90.

Houghton JT, Y, D., DJ, G., M, N., PJ, van der L., X, D., … C, J. (2001). Climate Change 2001: The Scientific Basis. Climate Change 2001: The Scientific Basis, 881.

IPCC. (2001). climate change 2001: the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by JT Houghton, Y. Ding, DJ Griggs, M. Noguer, PJ van der Linden, X. Dai, K. Maskell and CA Johnson (eds). Cambridge University Press, Cambridge, UK, and New York, USA, 2001. No. of pages: 881. Price£ 34.95, US $49.95, ISBN 0-521-01495-6 (paperback).£ 90.00, US $130.00, ISBN 0-521-80767-0 (hardback). International Journal of Climatology, 22(9), 1144-1144.

IPCC. (2007). Climate change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel. Genebra, Suíça.

IPCC. (2013). Summary for policymakers. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 33.

Kang, N., Kumar, K.R., Yin, Y., Diao, Y. and Yu, X., (2015). Correlation analysis between AOD and cloud parameters to study their relationship over China using MODIS data(2003−2013): impact on cloud formation and climate change. Aerosol Air Qual. Res., 15: 958-973.

Kannemadugu, S., Baba, H., Joshi, A.K. and Moharil, S.V. (2014). Aerosol optical properties and types over Nagpur, Central India. Sus. Environ. Res., 24(1): 29-40.

Kaskaoutis, D.G., Nastos, P.T., Kosmopoulos, P.G., Kambezidis, H.D., Kharol, S.K., and Badarinath, K.V.S. (2010). The Aura-OMI aerosol index distribution over Greece. Atmos Res., 98(1): 28-39.

Kaskaoutis, D.G., Badarinath, K.V.S., Kumar Kharol, S., Rani Sharma, A. and Kambezidis, H.D. (2009). Variations in the aerosol optical properties and types over the tropical urban site of Hyderabad, India. J Geophys Res Atmos, 114(D22): 1-20.

Kaskaoutis, D. G., Kambezidis, H. D., Hatzianastassiou, N., Kosmopoulos, P. G., and Badarinath, K. V. S. (2007). Aerosol climatology: on the discrimination of aerosol types over four AERONET sites. Atmos. Chem. Phys., 7(3), 6357–6411.

King, M.D., Menzel, W.P., Kaufman, Y.J., Tanré, D., Gao, B.C., Platnick, S., ... and Hubanks, P.A. (2003). Cloud and aerosol properties, precipitable water, and profiles of temperature and water vapor from MODIS. IEEE T. Geosci. Remote, 41(2): 442-458.

Kinne, S., Schulz, M., Textor, C., Guibert, S., Balkanski, Y., Bauer, S. E., … and Tie, X. (2006). An AeroCom initial assessment – optical properties in aerosol component modules of global models. Atmos. Chem. Phys., 6: 1815-1834.

Kosmopoulos, P.G., Kaskaoutis, D.G., Nastos, P.T. and Kambezidis, H.D. (2008). Seasonal variation of columnar aerosol optical properties over Athens, Greece , based on MODIS data. Remote Sens. Environ., 112: 2354-2366.

Kumar, K.R., Yin, Y., Sivakumar, V., Kang, N., Yu, X., Diao, Y., … and Reddy, R.R. (2015). Aerosol climatology and discrimination of aerosol types retrieved from MODIS, MISR and OMI over Durban (29.88°S, 31.02°E), South Africa. Atmos Environ., 117: 9-18.

Kumar, K.R., Sivakumar, V., Yin, Y., Reddy, R.R., Kang, N., Diao, Y., Adesina, A.J. and Yu, X., (2014). Long-term (2003–2013) climatological trends and variations in aerosol optical parameters retrieved from MODIS over three stations in South Africa. Atmos. Environ., 95: 400-408.

Lee, J., Kim, J., Song, C.H., Kim, S.B., Chun, Y., Sohn, B.J. and Holben, B.N. (2010). Characteristics of aerosol types from AERONET sunphotometer measurements. Atmos Environ., 44(26): 3110-3117.

Li, L. and Wang, Y. (2014). What drives the aerosol distribution in Guangdong-the most developed province in Southern China? Scientific Reports, 4, 5972.

Li, Z., Gu, X., Wang, L., Li, D., Xie, Y., Li, K., ... and Li, L. (2013). Aerosol physical and chemical properties retrieved from ground-based remote sensing measurements during heavy haze days in Beijing winter. Atmos. Chem. Phys., 13(20): 10171-10183.

Lohmann, U. and Feichter, J. (2004). Global indirect aerosol effects: a review. Atmos. Chem. Phys., 4(6): 7561-7614.

Luo, Y., Zheng, X., Zhao, T. and Chen, J. (2014). A climatology of aerosol optical depth over China from recent 10 years of MODIS remote sensing data. Int J Climatol, 34(3): 863-870.

Lyamani, H., Olmo, F.J. and Alados-Arboledas, L. (2009). Physical and optical properties of aerosols over an urban location in Spain: seasonal and diurnal variability. Atmos. Chem. Phys., 9(5): 18159-18199.

McMichael, A.J., Rosalie, E. and Woodruff, S.H. (2006). Climate change and human health: present and future risks. Lancet, 367: 859-869.

Mehta, M. (2015). A study of aerosol optical depth variations over the Indian region using thirteen years (2001−2013) of MODIS and MISR Level 3 data. Atmos. Environ., 109: 161-170.

Modarres, R. (2006). Regional precipitation climates of Iran. J. Hydrol (New Zealand), 13-27.

Papadimas, C. D., Hatzianastassiou, N., Mihalopoulos, N., Querol, X., & Vardavas, I. (2008). Spatial and temporal variability in aerosol properties over the Mediterranean basin based on 6-year (2000–2006) MODIS data. Journal of Geophysical Research: Atmospheres, 113(D11).

Pöschl, U. (2005). Atmospheric aerosols: composition, transformation, climate and health effects. Angewandte Chemie International Edition, 44(46): 7520-7540.

Pathak, B. and Bhuyan, P.K. (2015). Climatology of columnar aerosol properties at a continental location in the upper Brahmaputra basin of north east India: Diurnal asymmetry and association with meteorology. Adv Space Res., 56(7): 1469-1484.

Pathak, B., Bhuyan, P.K., Gogoi, M. and Bhuyan, K. (2012). Seasonal heterogeneity in aerosol types over Dibrugarh-North-Eastern India. Atmos Environ., 47: 307-315.

Penner, K.E.T. and J.E. (1994). Response of the climate system to atmospheric aerosols and greenhouse gases. Nature, 369: 734-737.

Pope, C.A. (2000). Epidemiology of fine particulate air pollution and human health: Biologic mechanisms and who’s at risk, Environ. Health Persp, 108 (SUPPL. 4): 713-723.

Ram, K., Sarin, M.M. and S.N.T. (2012). Emporal trends in atmospheric PM2. 5, PM10, EC, OC, WSOC and optical properties: Impact of biomass burning emissions in the Indo-Gangetic Plain. Envir. Sci. Tech., 46: 686-695.

Ram, K. and Sarin, M.M. (2010). Spatio-temporal variability in atmospheric abundances of EC, OC and WSOC over Northern India. J Aerosol Sci., 41(1): 88-98.

Ramanathan, V. (2001). Aerosols, climate, and the hydrological cycle. Science, 294(5549): 2119-2124.

Ranjan, R.R., Joshi, H.P. and Iyer, K.N. (2007). Spectral variation of total column aerosol optical depth over Rajkot: A tropical semi-arid Indian station. Aerosol Air Qual Res., 7(1): 33-45. Retrieved from http://www.airitilibrary.com/Publication/Index?FirstID=16808584-200703-7-1-33-45-a.

Rashki, A., Kaskaoutis, D.G., Rautenbach, C.J., deW, Eriksson, P.G., Qiang, M. and Gupta, P. (2012). Dust storms and their horizontal dust loading in the Sistan region, Iran. Aeolian Res., 5: 51-62.

Remer, L.A., Kleidman, R.G., Levy, R.C., Kaufman, Y.J., Tanr, D., Mattoo, S., … and Holben, B.N. (2008). Global aerosol climatology from the MODIS satellite sensors. J Geophys Res Atmos, 113(14): 1-18.

Remer, L.A., Tanre, D., Kaufman, Y.J., Ichoku, C., Mattoo, S., Levy, R., ... and Martins, J.V. (2002). Validation of MODIS aerosol retrieval over ocean. Geophys Res Lett, 29(12).

Satheesh, S.K. and Moorthy, K. (2005). Radiative effects of natural aerosols: A review. Atmos Environ., 39(11): 2089-2110.

Slutsker, I. and Kinne, S. (1999). Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols. J Geophys Res, 104(3133331349), 00093-5.

Srivastava, A.K., Misra, A., Kanawade, V.P. and Devara, P.C.S. (2016). Aerosol characteristics in the UTLS region: A satellite-based study over north India. Atmos Environ., 125: 222-230.

Tariq, S. and Ali, M. (2015). Spatio–temporal distribution of absorbing aerosols over Pakistan retrieved from OMI onboard Aura satellite. Atmos Pollut Res., 6(2): 254-266.

Textor, C., Schulz, M., Guibert, S., Kinne, S., Balkanski, Y., Bauer, S., … and Tie, X. (2006). Analysis and quantification of the diversities of aerosol life cycles within AeroCom. Atmos. Chem. Phys., 6: 1777-1813.

Zarasvandi, A., Carranza, E.J.M., Moore, F. and Rastmanesh, F. (2011). Spatio-temporal occurrences and mineralogical–geochemical characteristics of airborne dusts in Khuzestan Province (southwestern Iran). J. Geochem. Explor., 111(3): 138-151.

Zayakhanov, A.S., Zhamsueva, G.S., Naguslaev, S.A., Tsydypov, V.V., Ayurzhanaev, A.A., Sakerin, S.M. and Oyunchimeg, D. (2012). Spatiotemporal characteristics of the atmospheric AOD in the Gobi desert according to data of the ground-based observations. Atmos Oceanic Opt., 25(5): 346-354.

Zoljoodi, M., Didevarasl, A. and Saadatabadi, A.R. (2013). Dust events in the western parts of Iran and the relationship with drought expansion over the. Atmos. Clim Sci., 2013(July): 321-336.