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# The Lake Urmia environmental disaster in Iran: A look at aerosol pollution

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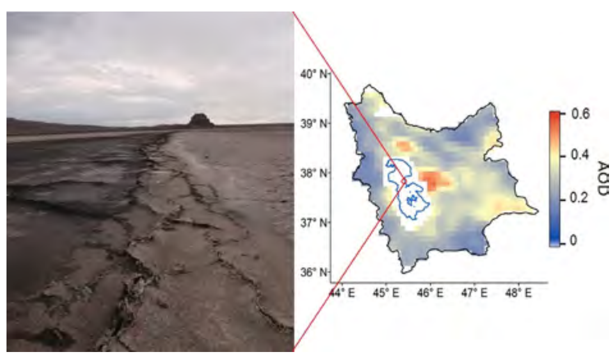
## HIGHLIGHTS

- AOD characteristics examined over Lake Urmia in northwestern Iran between 2001 and 2015.
- No significant relationship found between lake water level and AOD.
- Interannual AOD variability driven mainly by transport from upwind regions.
- Enhanced emissions from salty/soil areas around the lake in the latter years
- Activities like grazing can disturb the remaining playa and lead to salt emissions.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Lake Urmia (LU) once was the second largest hypersaline lake in the world, covering up to 6000 $km^2$, but has undergone catastrophic desiccation in recent years resulting in loss of 90% of its area and extensive coverage by playas and marshlands that represent a source of salt and dust. This study examines daily Aerosol Optical Depth (AOD) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) between 2001 and 2015 over northwestern Iran, which encompasses LU. Intriguingly, salt emissions from the LU surface associated with ongoing desiccation do not drive the study region's AOD profile, whereas pollution transported from other regions and emissions around LU are more important. Signatures of increasing local crustal emissions are most evident outside of the peak dust season (January, February, and October) and on the periphery of LU. AOD has generally increased in the latter half of the study period with the onset of the AOD ramp-up starting a month earlier in the spring season when comparing 2009–2015 versus earlier years. Results indicate that suppression of emissions on the LU border is critical as the combined area of salt and salty soil bodies around LU have increased by two orders of magnitude in the past two decades, and disturbing these areas via activities such as grazing and salt harvesting on the lake surface can have more detrimental impacts on regional pollution as compared to

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benefits. These results have important implications for public health, climate, the hydrological cycle, and pollution control efforts.



## 1. Introduction

Lake Urmia (LU) in northwestern Iran (Fig. 1) is the largest lake in the Middle East and one of the largest permanent hypersaline lakes worldwide. The water in LU formerly covered an area of 5000–6000 km$^2$ and contained about 30,000 million m$^3$ of water (Eimanifar and Mohebbi, 2007). A recent study reported that the lake area has decreased by 90% in recent decades (AghaKouchak et al., 2015; Ghale et al., 2017; Pengra, 2012), with the lake area being <1000 km$^2$ as of August 2014. The dried up areas, with an estimated eight billion tons of salt, represent a major regional aerosol source (Tourian et al., 2015). Many factors in the past decade have contributed to the depletion of water from LU, including drought, upstream water competition and diversion, increased agricultural activity, and anthropogenic changes to the lake system including a constructed causeway (Tourian et al., 2015). In similar cases of saline lake desiccation, such as with the Aral Sea, surfaces of the resulting lakebed have become active sources of salt and dust, vulnerable to wind erosion (Indoitu et al., 2015; Singer et al., 2003). Field measurements near LU have linked the majority of airborne particulate matter with aerodynamic diameter <10 μm ($PM_{10}$) and total suspended particulate matter to saline particulates and other crustal materials, comprised of halite (NaCl), gypsum ($CaSO_4 \cdot 2H_2O$), bassanite ($2CaSO_4 \cdot H_2O$), quartz ($SiO_2$), and hexahydrite ($MgSO_4 \cdot 6H_2O$) (Gholampour et al., 2017; Gholampour et al., 2015).

Since the beginning of the LU desiccation crisis, studies have been conducted on the lake's water regime, water level fluctuations, mineral properties, and changes in water surface temperature (Ahmady-Birgani et al., 2015; Asri and Ghorbanli, 1997; Eimanifar and Mohebbi, 2007; Ghaheri et al., 1999; Kakahaji et al., 2013; Karbassi et al., 2010; Kelts and Shahrabi, 1986; Marjani and Jamali, 2014; Sima et al., 2013; Sima and Tajrishy, 2013; Torgersen et al., 1986; Zarghami, 2011; Zeinoddini et al., 2009), but there are no reports of the long-term characteristics of aerosol levels around LU. A modeling study suggested that aerosol emitted from the lake bed can account for an estimated ~30–60% enhancement in $PM_{10}$ of nearby cities during dust episodes (Sotoudeheian et al., 2016), while other work suggests that crustal soil bordering LU, rather than lakebed salt, is the predominant source of aerosol emissions in the vicinity of LU (Gholampour et al., 2017). An examination of the spatiotemporal nature of aerosol around LU is highly relevant for the ~7.1 million people living in the lake's watershed (http://irandataportal.syr.edu/census/census-2016., 2016) and ~80 million people living within a radius of 500 km (http://sedac.ciesin.columbia.edu/mapping/popest/gpw-v4/., 2016).

The goal of this study is to characterize the long-term temporal and spatial characteristics associated with aerosol pollution in the LU region. This investigation is important owing to the unique characteristics of LU as compared to other lakes. Prior to the desiccation crisis, LU exhibited the highest salinity level (23%) by more than a factor of two as compared to other saline lakes worldwide exceeding 5000 km$^2$: Caspian = 1–1.2%, Aral = 0.5–1.0%, Balkhash = 0.05–0.7%, Eyre North = 10%, Issyk-Kul = 0.5–0.6% (Scheffers and Kelletat, 2016) As the lake area has decreased by approximately a factor of two since when the aforementioned data were reported, LU salinity has increased even more, reinforcing the thick layer of salt crust on the lakebed.

## 2. Materials and methods

Aerosol optical depth (AOD) is used here as a columnar proxy of aerosol abundance. It is a dimensionless parameter quantifying the sum of scattering and absorption of solar radiation by particulates. Daily Level 2 AOD data at 10 × 10 km spatial resolution (MOD04_L2; via https://ladsweb.modaps.eosdis.nasa.gov/., 2016) are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra platform. The accuracy of the MODIS Collection 6 Dark Target (C6_DT) AOD product over land is ±0.05 ± 15% (Levy et al., 2013). MODIS was chosen as the source of AOD data among other remote sensors based on the significant correlation between AOD values retrieved by MODIS and the closest AERONET station to the study region located in Zanjan, Iran (Institute for Advanced Studies in Basic Sciences, IASBS; 36.705167° N, 48.507111° E) (Khoshsima et al., 2013). Data are examined over northwestern Iran inside the boundary of Azarbaijan, which is comprised of two provinces (West and East Azarbaijan), covering an

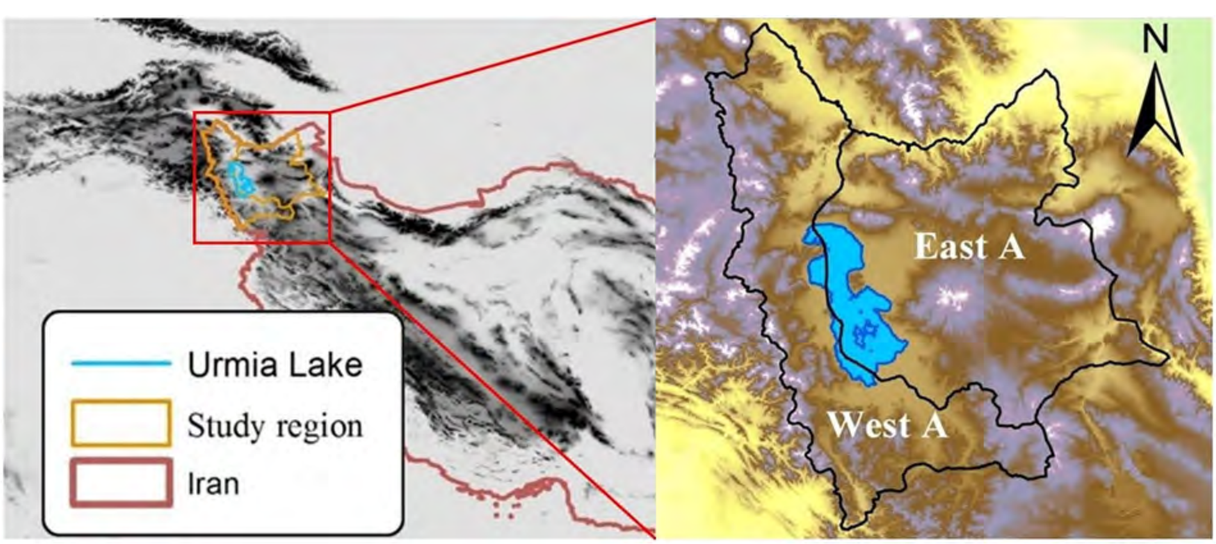


**Fig. 1.** (Left) Location of Azarbaijan provinces (in orange) and LU (in blue). (Right) Close-up of East and West Azarbaijan provinces. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

area of about 82,550 km$^2$ (Fig. 1). Data are analyzed between 2001 and 2015, which includes the period before the main LU crisis began up through the point of intense desiccation and drought.

Spatial maps of the number of days per season with available AOD data are shown in Fig. S1. Over the study region, the highest number of days with available data belongs to the warm summer season (June–August). In contrast, the lowest number of days with available data occurs in of the winter months (December–February) owing to persistent cloud coverage and thus cloud contamination. Data over LU itself are omitted from the analysis owing to a lack of data points passing quality control filtering.

A number of other parameters are obtained from remote sensing and reanalysis products (Table S1). With the exception of precipitation data, which are obtained within the boundaries of Azarbaijan similar to AOD, the other parameters are obtained over the smallest possible area extending around Azarbaijan with the grid resolution shown in Table S1. The parameters include aerosol Angstrom Exponent calculated using AOD at 0.41 and 0.47 μm (i.e., lower values are representative of larger aerosol particles), surface temperature, wind speed and direction at the surface and 500 hPa, planetary boundary layer height (PBLH), black carbon (BC) aerosol optical thickness (AOT) at 0.55 μm, specific humidity, soil temperature and moisture, and Normalized Difference Vegetation Index (NDVI). Fifteen years of monthly mean values for these parameters are shown in Fig. S2 and discussed subsequently. Hereinafter, reference to statistically significant trends indicates that there is at least 95% confidence based on a two-tailed student's t-test.

## 3. Results and discussion

### 3.1. Meteorological profile

Azarbaijan has a semi-arid climate with temperature usually ranging between 0° and − 20 °C in winter and up to 40 °C in summer (Ghaheri et al., 1999). The monthly profile of meteorological parameters in Fig. S2 shows that while surface air temperature peaks between June–August, soil moisture expectedly reaches its lowest values, which promotes surface erosion of salt and dust. Surface wind speeds are high in the summer months, but also exhibit a second peak between February and April. A summary of the monthly profile of wind direction at the surface and at 500 hPa are shown in Figs. S3–4, respectively, for a representative year (2003). Westerly winds dominate at 500 hPa, while near the surface, winds typically are southerly and southwesterly for most of the year. Precipitation over Azarbaijan is higher between October and May as compared to the summer months. Hassanzadeh et al. (2012) noted that the annual precipitation accumulation decreased from 246.64 mm in 1997 to 204.68 mm in 2007, while the mean annual temperature increased from 9.4 °C in 1997 to a maximum of 12.8 °C in 2001, with subsequent oscillations around 12 °C for the rest of period until 2007. This is also compatible with modeling studies that predicted increases in temperature and reductions in precipitation (Evans, 2009).

The summer months (June–August), with conditions most conducive to salt and dust emissions, exhibit the highest values of BC AOT with a value of 0.009 $\pm$ 0.002 between 2001 and 2015 in contrast to 0.006 $\pm$ 0.001 for the other nine months over the same time range (Fig. S2). This is suggestive of more biomass burning influence in the region in the summer, especially July and August, relative to other seasons. Past work has shown that fires to the north of Iran in countries such as Ukraine, Russia, Kazakhstan, and the Republic of Azerbaijan impact the columnar AOD loading over the northern Iran region during the spring and summer months (March–August) (Crosbie et al., 2014). Fig. S3 shows that surface winds tend to shift from southerly/southwesterly between October–April to more easterly/northeasterly between May–September, consistent with there being more smoke influence over northern Iran in the summer. Hereinafter, all references to Azarbaijan will be to the provinces in Iran.

### 3.2. Interannual variability

The mean annual AOD over all of Azarbaijan varied from 0.25 to 0.37 between 2001 and 2015, with distinctly higher values in 2003 (0.35) and between 2008 and 2012 (0.32–0.37) (Fig. 2). The smallest mean annual values in Angstrom Exponent (1.12–1.36) occurred between 2008 and 2012, suggestive of influence by large aerosol particles (i.e., dust and salt). The interannual profile for West and East Azarbaijan are nearly identical with the exception of systematically higher values in the East (by 0.05 $\pm$ 0.01 over the study period). This likely is owing to the East having more surface area covered by salty and soil bodies (Ghale et al., 2017). In addition, local anthropogenic emissions may contribute too as East Azarbaijan has both a higher population (~3.909,652 vs ~3.265,219 for West Azarbaijan, as of September 2016; https://www.citypopulation.de/Iran-MajorCities.html) and diverse industrial activity in the form of petrochemical processing facilities, oil refineries, manufacturing of various products (e.g., food, glass, paper, chemical, vehicular parts, agricultural machines), and mining.

The AOD difference between the East and West Azarbaijan has exhibited a statistically significant reduction based on mean annual AOD over the 15-year study period ($p$ value < 0.05). As the winds are predominantly westerly aloft over the study area, the decrease in the AOD difference is at least partly due to increased influence from transported aerosol from upwind regions, which has led to overall increase of AOD over both regions. This is further supported by how the difference between West and East Azarbaijan is highest in the two years, 2001 and 2014, exhibiting the lowest region-wide AOD (0.25) with a difference of 0.07 and 0.06, respectively. Although dust and salt emissions contribute more to AOD owing to their coarse size, biomass burning and local anthropogenic emissions potentially contribute. Black carbon AOT peaked over the Azarbaijan region in the years 2009–2012, which included the years with among the highest overall AODs. This result indicates the possibility that advected biomass burning plumes accounted for at least some of the AOD in the study region.

While the LU lake water level (obtained from http://ulrp.sharif.ir/en., 2016) has decreased from 1274.2 to 1270.4 m above sea level (ASL) from 2001 to 2015 (Fig. 2), AOD did not exhibit a gradual increasing trend over the same time period. However, the steepest decline in lake level occurred between 2007 and 2009 (1272.96 to 1271.91 m ASL), coincident with the second largest jump in AOD over a two-year period (0.31 to 0.37) over Azarbaijan (Fig. 2). The increase was larger over the East province (0.07 versus 0.05 for the West) presumably owing to most of the major salt and dust sources in the vicinity of LU being on the East side. Additionally, analysis of surface water extent

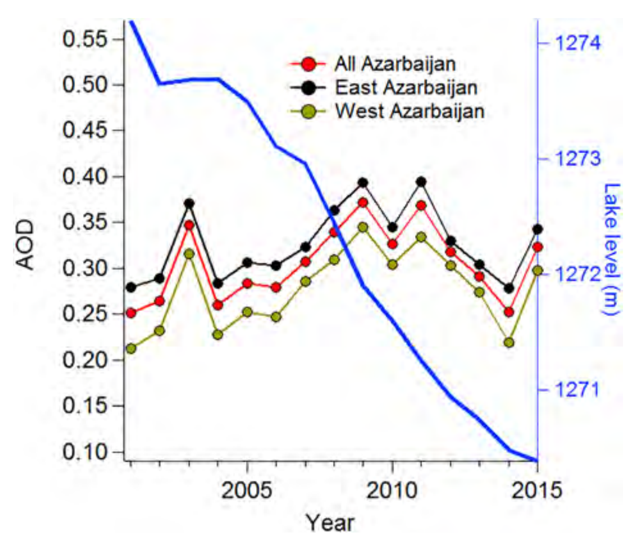


**Fig. 2.** Interannual AOD profile for all of Azarbaijan, West Azarbaijan, and East Azarbaijan, in addition to the mean LU water level elevation.

between 2000 and 2014 showed that the onset of steepest decline started in 2008 (Tourian et al., 2015). A combination of reasons can explain why, after 2009, AOD did not continue to increase as the lake level continued to decrease: (i) reduced contribution to AOD from upwind sources, and (ii) greater ease of soil and alluvial sediments bordering LU to be emitted as compared to the thick surface salt layer on the lakebed. As the discussion surrounding Fig. 2 already suggested, there has been increasing influence of transported aerosols from upwind regions over the study period; therefore, the second reason, also supported by in situ field measurements (Gholampour et al., 2017), seems more plausible.

To probe deeper into the influence from neighboring areas, Fig. 3 compares the AOD interannual profile for eight regions (labeled 1–8) surrounding a center grid containing the Azarbaijan provinces. The highest AOD levels are to the southwest over Iraq (Region 1), with features resembling those over Azarbaijan such as higher values beginning after 2008 and a dip in AOD in 2014. These similarities are indicative of long-range transport playing a major factor in governing AOD over Azarbaijan rather than just local emissions. Areas to the west (Region 2, Iraq) and northwest (Region 3, Georgia/Turkey) of Azarbaijan also exhibited higher values starting in 2008, with Region 2 being the closest match with similar adjacent AOD peaks in 2009 and 2011, with an

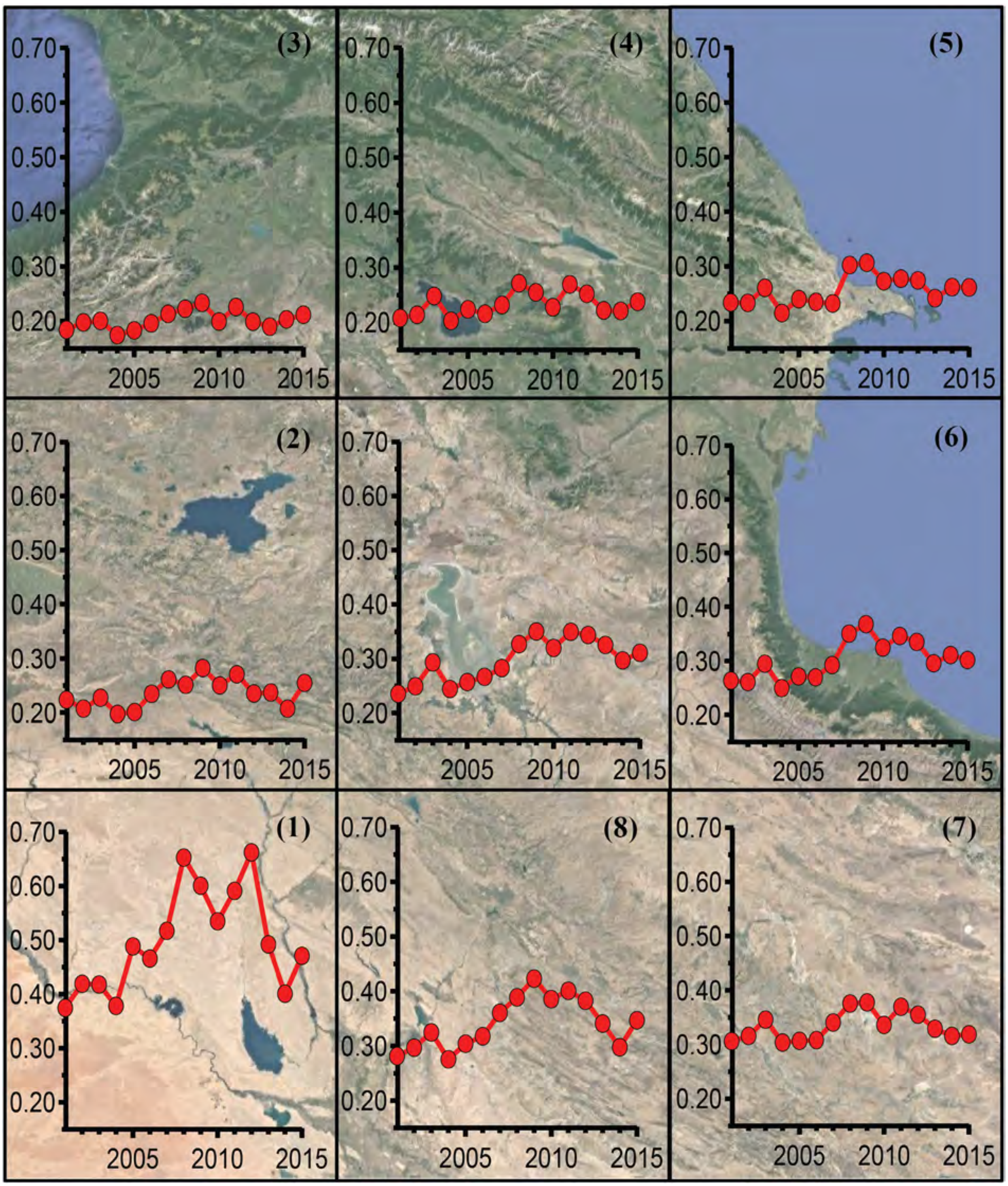


**Fig. 3.** Interannual profile of AOD averaged over the spatial areas encompassed by each box. Shown are eight regions (labeled 1–8) neighboring the center grid containing within it the two provinces of Azarbaijan.

AOD enhancement in 2003 and a reduction in 2014. AOD over the center area containing Azarbaijan exhibited statistically significant correlations with values over all neighboring regions ($p$ value < 0.01) indicative of the interconnectedness of dust across the broad region. Of major importance are westerly winds from Iraq, which has a severe arid climate with extremely dry summers and significant dust emissions (Moridnejad et al., 2015).

### 3.3. AOD Jump in 2003

The year 2003 warrants attention owing to the striking feature that the highest AOD jump between successive years over Azarbaijan occurred between 2002 and 2003 (0.26 to 0.35). In contrast, the neighboring eight regions in Fig. 3 exhibited a much smaller AOD increase (or even a decrease) in 2003 (≤0.03). Among several environmental parameters examined from Table S1, the ones exhibiting a unique feature in 2003 included the highest mean annual precipitation accumulation (607.1 mm) and 0–10 cm soil moisture (26.5 kg $m^{-2}$). This is a counter-intuitive result, as more precipitation and soil moisture suppresses direct emissions of salt and dust.

A closer look at monthly resolution data over Azarbaijan shows that AOD in 2003 was anomalously high in April (0.40 versus 0.32 $\pm$ 0.04 in April of other years) and July (0.55 versus 0.33 $\pm$ 0.05 in July of other years), largely being responsible for the high overall AOD value in 2003. A spatial map of average AOD over a broad area containing the Azarbaijan provinces reveals that LU was an area of peak AOD with neighboring areas having reduced values (Fig. S5); this indicates that the high AOD values in April 2003 are related to emissions from the combination of LU and its periphery within Azarbaijan rather than from neighboring areas. Also, Angstrom Exponent values are significantly lower in April of 2003 as compared to April in the other years (0.92 versus 1.18 $\pm$ 0.17), which is suggestive of local emissions of coarse particles.

In terms of other environmental parameters from Table S1 that could be influential, the monthly accumulation of precipitation in March was highest in 2003 as compared to any other year by a large amount (97.0 mm versus 56.7 $\pm$ 12.5 mm in March of other years). Considering that the lake level had not begun its major reduction yet in 2003 (Fig. 2), a possibility is that enhanced precipitation could have disturbed and re-distributed surface matter leading to more alluvial sediments and sources of dust in flatter areas at lower elevation in the study region. NDVI was the lowest in April of 2003 (0.25) as compared to that month in other years (0.29 $\pm$ 0.03). Surface wind speeds in April of 2003 were also near maximum levels as compared to that month in other years (6.2 m $s^{-1}$ versus 5.3 $\pm$ 0.6 m $s^{-1}$). These various factors suggest that the source of high AOD in April 2003 was wind-blown crustal aerosol, which extended downwind to the east and northeast based on the predominant wind direction (Figs. S3–4) and AOD spatial profile over the broad region shown in Fig. S5.

Of all July months between 2001 and 2015, July in 2003 nearly exhibited the lowest amount of precipitation (10.9 mm versus 19.1 $\pm$ 7.1 mm in the other years) but the highest NDVI (0.29 versus 0.25 $\pm$ 0.02 mm in the other years) owing to significant vegetative growth that year following enhanced precipitation in preceding months. However, high NDVI values suggest that there should be suppressed dust emissions due to more vegetation (Indoitu et al., 2015; Lopez et al., 2015). Aside from NDVI, other environmental parameters in Table S1 did not exhibit anomalously different values in July of 2003. Therefore, long-range transport becomes the most logical source of high AOD, which is confirmed by the spatial AOD map of the broader region encompassing LU showing the source of high AOD being located mostly in Region 5 (Fig. 3) to the northeast of the study region (Fig. S6). Region 5 exhibited a mean AOD value in July 2003 well above one standard deviation of the 15-year average of that area (0.45 versus 0.31 $\pm$ 0.06). Biomass burning plumes often are transported from that direction towards Iran during the summer (Crosbie et al., 2014); surface winds that month (Fig. S3) are consistent with northerly/easterly winds blowing pollution towards Azarbaijan.

### 3.4. Monthly variability

AOD exhibits its lowest and highest values in the months of November–January and April–August, respectively (Fig. 4a). The enhancement in the dry and warm months is driven to a large extent by direct emissions of dust, which rely on low soil moisture and high wind speeds. These particles are emitted either locally or from upwind countries such as Iraq and Syria. No inverse relationship exists between lake level and AOD on monthly time scales indicative of how desiccation effects on AOD are likely best observed over longer time scales.

When breaking up the study period in four parts, intriguing results emerge in the colder months. When comparing the years with the highest mean annual AOD (2009–2012) versus the most recent years with relatively lower AOD values (2013–2015), the AOD values were similar between October and February, and they additionally exceeded AOD values in those same months in 2001–2004 and 2005–2008. When taking the ratio of AOD between two time periods (2009–2015 versus 2001–2008), it is evident that AOD is enhanced in each month in the second half of the study period (Fig. 4b). Of particular note is that the highest ratio is observed in February, suggestive of earlier onset of the aerosol loading ramp-up into the spring season. February AOD values have increased with statistical significance over the 15-year time period ($p$ value < 0.05). A similar type of result has been observed for the southwestern region of the United States, where the onset of the spring season shifted to be 1–2 weeks earlier over a 20-year time frame from 1995 to 2014 due to drier conditions, more wind, and less vegetation (Hand et al., 2016). Other months in this study exhibiting a statistically significant ($p$ value < 0.05) AOD increase over the 15-year time period include January and October. Since February, January, and October represent months outside the dust season in the Middle East, there is likely greater influence by dust and salt sources within Azarbaijan in these

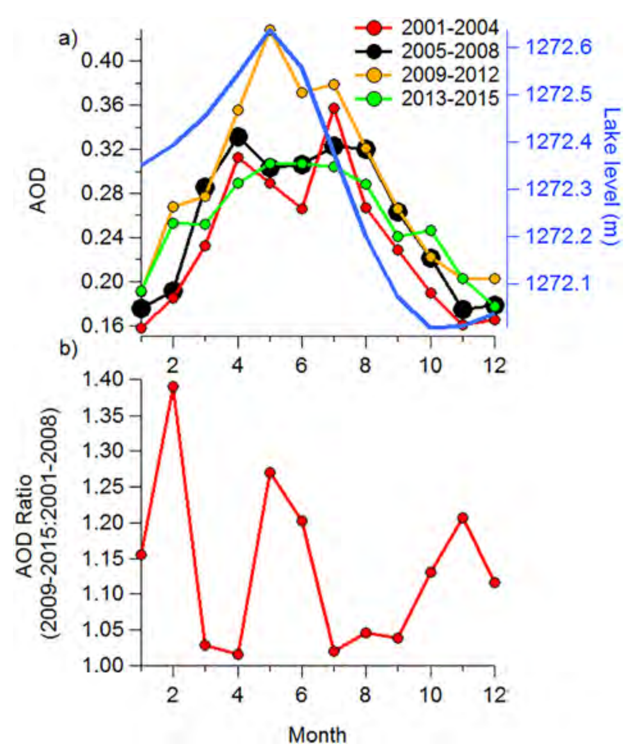


**Fig. 4.** Monthly profile of (a) lake level and AOD over entire study region for four multi-year periods between 2001 and 2015, and (b) AOD ratio for 2009–2015 relative to 2001–2008.

months when the superimposed effects of neighboring deserts (e.g., Iraq, Syria) and biomass burning sources to the north are dampened. This explains why the AOD values are still comparable between 2013 and 2015 and 2009–2012 in colder months even though the latter period has much higher AOD values during dusty summer months. This does not preclude the possibility that dust and salt emissions over Azarbaijan have increased over time in the warmer months.

### 3.5. Spatial variability

The spatial distribution of annual mean AOD shown in Fig. 5 confirms that long-range transport of pollution does not solely drive AOD values in the region, otherwise AOD would be spatially uniform. The distinct hotspots of high AOD, especially around the borders of LU, are indicative of the importance of locally generated aerosol. As winds

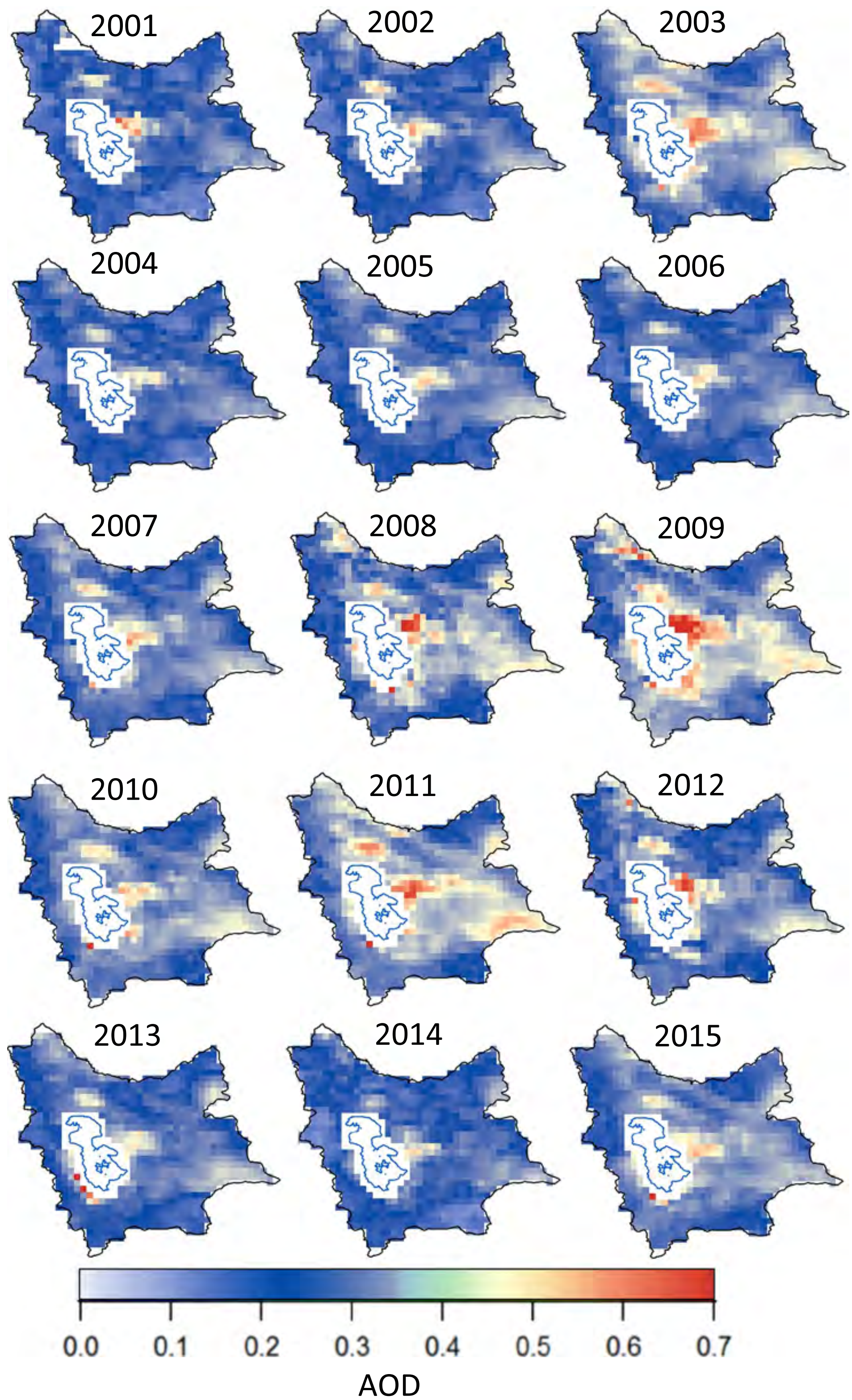


**Fig. 5.** Spatial distribution of mean annual AOD between 2001 and 2015. Uncolored pixels represent an insufficient number of data points.

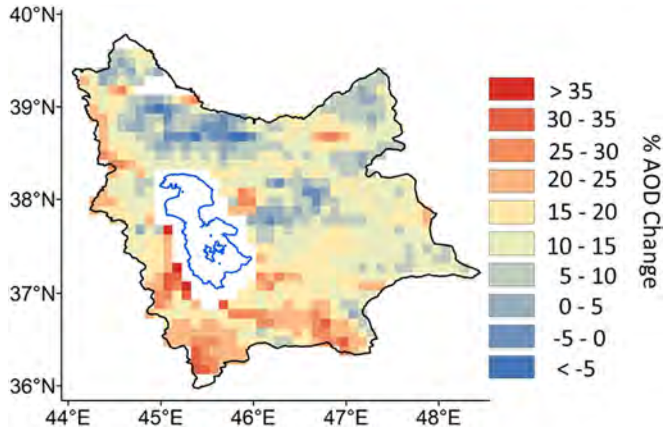


**Fig. 6.** Spatial distribution of AOD percent change between 2008 and 2015 as compared to 2001–2007. Uncolored pixels represent an insufficient number of data points.

originating over Lake Urmia at 60° (northeasterly) and 240° (southwesterly) have the greatest impact on areas in the vicinity of LU (Nasiri et al., 2014), it is reasonable that the regions of maximum AOD are to the northeast of LU and, to a smaller extent, on the southwest side. The considerable terrain in the study region (Fig. 1) contributes to the spatial AOD profile in Fig. 5, including the consistently low values over the far west where there is mountainous terrain. It is notable that a large portion of areas with the highest AOD values are located in eastern part of study region, which is also where most of salty soil lands remain from lake desiccation.

The greatest AOD differences between the most recent half of the study period versus the earlier half is around the immediate periphery of LU, especially the southwest side and to a lesser extent the northeast side. Both of these areas are along the northeasterly/southwesterly axis of predominant wind directions over LU (Fig. 6).

To examine whether the AOD hotspots over the study region vary between different times of the year, spatial maps of mean AOD from 2001 to 2015 are shown in Fig. 7a–b for the colder months with the most significant increase in AOD over that time range (January/February/October) in addition to the peak dust months (April–August). The spots with the highest AOD in the two subsets of months are similar, again on the LU periphery with the highest values on the northeast side. Therefore, regardless of varying meteorology throughout the year, the general AOD spatial profile is preserved with the difference between different months being the absolute value of AOD. Fig. 7c–d show that the percentage increase of AOD in the latter half of the study period (2008–2015) was more enhanced around the vicinity of LU as compared to the first few years for the colder months of January/February/October as compared to the peak dust months. This supports the conclusion from Fig. 4 that it is in these colder months when there is less influence from transported pollution (i.e., dust, smoke) when emissions in the vicinity of LU are of greater importance relative to the total columnar aerosol burden. Owing to more precipitation in these colder months, there is more hydration and dehydration of salty soils remaining from lake bed desiccation. Surfaces prone to repetitive watering and dewatering near the lake are more susceptible to formation of puffy salt crusts, which are likely to be eroded by wind (Buck et al., 2011).

## 4. Conclusions

This study reports on 15 years of remote sensing data (2001–2015) over northwestern Iran, with a focus on AOD characteristics surrounding LU. The main result was that there was no obvious signature of increasing AOD linked to emissions from the LU surface owing to the influence of emissions around LU and pollution transported from upwind regions. There is growing evidence based on this and other studies using remote sensing (Ghale et al., 2017) and in-situ observations (Gholampour et al., 2017) that, rather than the LU salt crust on the lakebed, aerosol are emitted more effectively from bordering lands including desiccated areas, dried watercourses, and river deltas. The

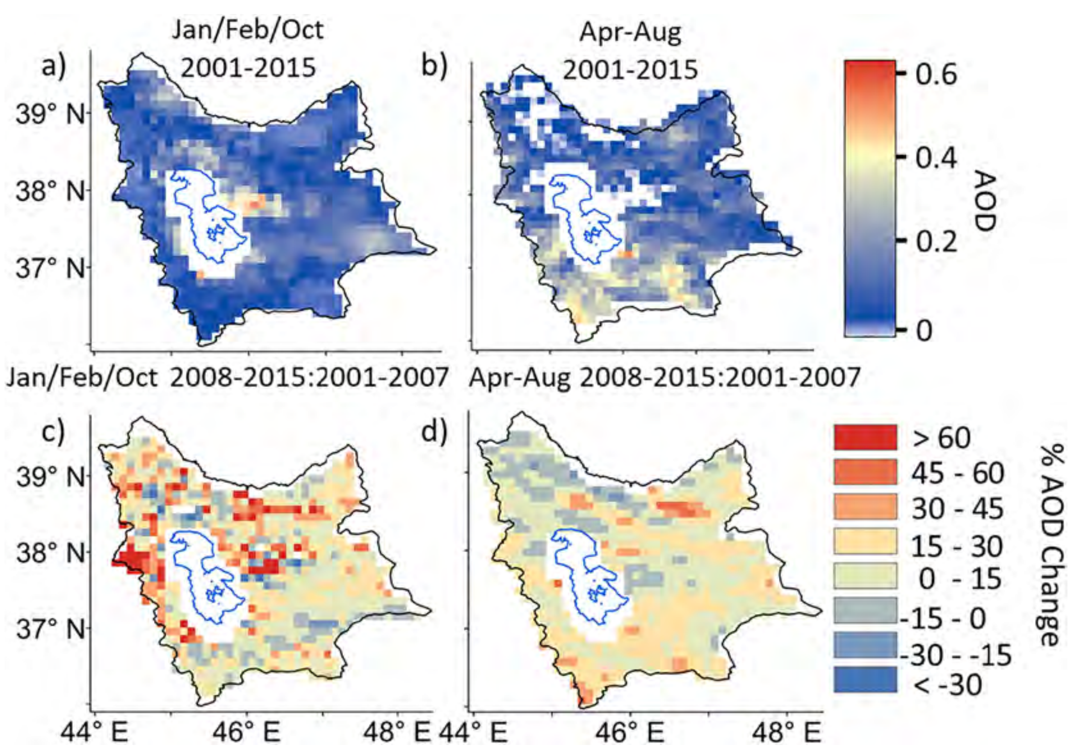


**Fig. 7.** Spatial map of mean AOD for the months of (a) January/February/October and (b) April–August between 2001 and 2015. Spatial map of the AOD percentage change for the months of (c) January/February/October and (d) April–August between 2008 and 2015 versus 2001–2007. Uncolored pixels represent an insufficient number of data points.

bordering areas are also affected by the same factors leading to LU desiccation (e.g., drought, upstream water competition and diversion, increased agricultural activity, anthropogenic changes to the lake system). Suppression of emissions on the LU border is critical as the combined area of salt and salty soil bodies around LU have increased from 63 $km^2$ in 1995 to >5200 $km^2$ in 2014 (Ghale et al., 2017), and disturbing these areas via activities such as grazing and salt harvesting can have more detrimental impacts on regional pollution as compared to benefits. A useful strategy for pollution control would be protection of the bordering areas of LU, especially with vegetation (Mahmoudzadeh, 2007), in addition to minimal disturbance of the lakebed salt crust. Regardless of ongoing and upcoming efforts to suppress aerosol emissions by LU, the impact of transported aerosol to the region cannot be discounted, especially in the summer months when dust and smoke are more abundant. While the effects of all pollutants are linked to health effects, their effects on the regional air quality, climate, cloud formation, and the water cycle warrant research as well.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.03.148.

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