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[1] Dynamical processes leading to dust emission over Iran and surrounding countries in the summer as well as the subsequent transport of dust toward northwest Iran are analyzed on the basis of two case studies using a suite of ground-based and spaceborne remote sensing platforms together with modeling tools. Ground-based lidar measurements acquired in Zanjan provide new insight into the vertical distribution of dust linked to transport over northwest Iran and highlight the importance of low-level transport of dust from both Iraq and Iran for air quality issues in Tehran. During the 3–5 August 2007 case, dust emission regions are located in Syria/Iraq and close to Qom, Iran, in a large intermittent salt lake in the western part of the Dasht-e Kavir desert. The visibility in Tehran associated with this event decreases significantly (reaching 7 km) on 5 August 2007 only. During the 11–13 September 2008 case, the dust transported to northwest Iran originates from Syria/Iraq only. The visibility in Tehran during this case is low throughout the period, sometimes less than 5 km due to the transport of dust at low levels. In both cases, emissions in Syria and Iraq occur in response to strong Shamal winds. However, transport of dust toward Iran takes place at different levels: above 700 hPa in August and below 700 hPa in September. This is found to be related to the presence of strong northeasterly winds over the Zagros Mountains as well as in its lee (south of the range) in the August case only. In August also, dust emissions in the Qom region results from strong winds blowing over the Dasht-e Kavir desert.

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1. Introduction

[2] Iran is climatically part of the Afro-Asian belt of deserts that stretch from the Cape Verde islands off West Africa all the way to Mongolia near Beijing, China, generally referred to as the dust belt. It is located in the neighborhood of some important dust sources: the Tigris and Euphrates basin in Iraq as well as Syria to the west, the Arabian Peninsula to the south and southwest and the Turkmenistan basin to the north [*Prospero et al.*, 2002]. These sources are among the most active in the dust belt [*Middleton*, 1986a, 1986b; *Prospero et al.*, 2002; *Leon and Legrand*, 2003]. There also exist some active dust sources within Iran, which are mainly located in the vicinity of dry salt lakes, seasonal lakes and drainage basins in mountainous areas [*Middleton*, 1986a, 1986b] which can be detected from space using the Total Ozone Mapping Spectrometer (TOMS) [*Prospero et al.*, 2002; *Leon and Legrand*, 2003; *Washington et al.*, 2003]. As a result, Iran is prone to dust storms from both internal and external sources, which causes the horizontal visibility to decrease below 11 km (indicating the presence of aeolian dust) more than 30% of the time in summer [*Kutiel and Furman*, 2003].

[3] Due to the specificity of its orography (characterized by the merging of two major mountain ranges; see section 2.1) as well as the proximity of Iraqi sources, northwest Iran is often at the confluence of dust plumes transported from inner Iran, Iraq and Turkmenistan during the summer. As a result, cities in northwest Iran are prone to dust events on a regular basis in the summertime. Figure 1 shows the number of occurrence of episodes characterized by horizontal visibility less than 10 km in Tehran for the period 2006–2009 in August and September. Even though episodes characterized by visibility less than 2 km are quite rare (visibilities less than 2 km are generally considered to be representative of dust storms, see discussion in section 2.3), a significant number of cases when visibility is between 3 and 10 km

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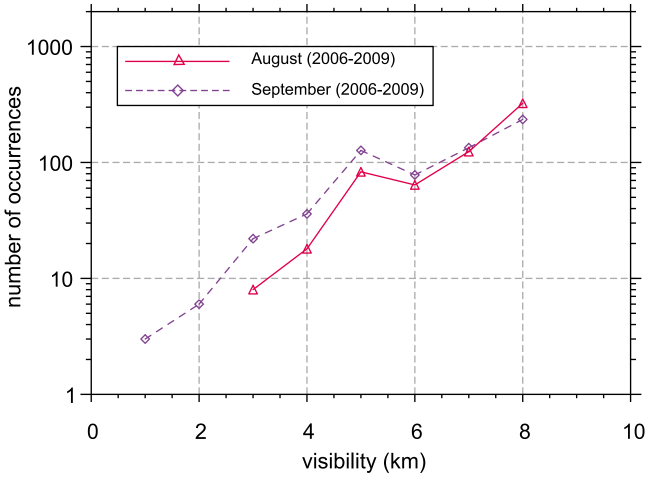

Figure 1. Number of occurrences of events with horizontal visibility at the surface less than 10 km in Tehran. The 3-hourly data are used for the period 2006–2009, in August (red solid line with triangles) and in September (blue dashed line with diamonds).

have been observed in the period 2006–2009, meaning that the city of Tehran is repeatedly impacted by blowing dust (pollution related to industries and traffic has been shown to affect air quality in Tehran mainly during the cold season [*Halek et al.*, 2009]). During dust storm episodes, Tehran officials frequently call people off work because of dust hazards as such storms are known to have an impact on air pollution and public health under hot and dry climate [*Miri et al.*, 2007]. Furthermore, the reduction of visibility associated with dust storms has incidence on both surface and airborne traffic [e.g., *Kutiel and Furman*, 2003, and references therein].

[4] The Iranian Meteorological Service is operating a dense network of surface meteorological stations as well as balloon launching facilities for upper-level measurements. However, this network alone does not provide the observations necessary to improve knowledge on the dynamical processes responsible for dust emission and transport over Iran and adjacent countries that lead to the observation of dust plumes over northwest Iran during the summertime. In this paper, advantage is taken of the suite of remote sensing instruments (ground-based lidar, Sun photometer) operated at the Institute for Advanced Studies in Basic Sciences (IASBS) in Zanjan to analyze the origin and the vertical distribution of the dust plumes transported over northwest Iran from adjacent regions, on the basis of two case studies. The observations key to this paper is the lidar observations from Zanjan. The two cases are selected on the basis of lidar data quality and availability. Just as Tehran, the city of Zanjan (located to the northwest of Tehran; see Figure 2), is prone to dust events (aeolian dust but also dust storms) from both inner and outer source regions.

[5] To the authors best knowledge, this paper is the first to combine ground-based and spaceborne active and passive remote sensing observations with in situ meteorological and numerical weather prediction model reanalyses to investigate dust emission and transport over Iran. Previous works concerning dust activities over Iran mostly focused on synoptic parameters reported by local meteorological stations [*Esmaili et al.*, 2006], passive remote sensing from space [*Esmaili et al.*, 2006; *Prospero et al.*, 2002; *Leon and Legrand*, 2003; *Washington et al.*, 2003], or Sun photometer (SPM) measurements in the Persian Gulf region [*Smirov et al.*, 2001].

[6] The paper is organized as follows: In section 2, the data sets utilized in this study are introduced. Section 3 provides an overview of dust sources impacting northwest Iran in the summer as well as the dust transport patterns. Section 4 and section 5 detail the case studies of transport over Zanjan on 5 August 2007 and 13 September 2008, respectively. Section 6 provides a summary and conclusions.

2. Data

2.1. Orography

[7] Figure 2 shows a map of orography in Iran as provided by the Global Land One-km Base Elevation Project (GLOBE, available from http://www.ngdc.noaa.gov/mgg/topo/globe.html [*GLOBE Task Team et al.*, 1999]). Iran is situated in a high-altitude plateau surrounded by connected ranges of mountains and divided into drainage basins [*Barth and Boer*, 2002]. The Alborz Mountains run along the northern border of Iran, while the Zagros Mountains run along its western border. The two mountain ranges merge in the northwest corner of Iran. The crest line of both moun-

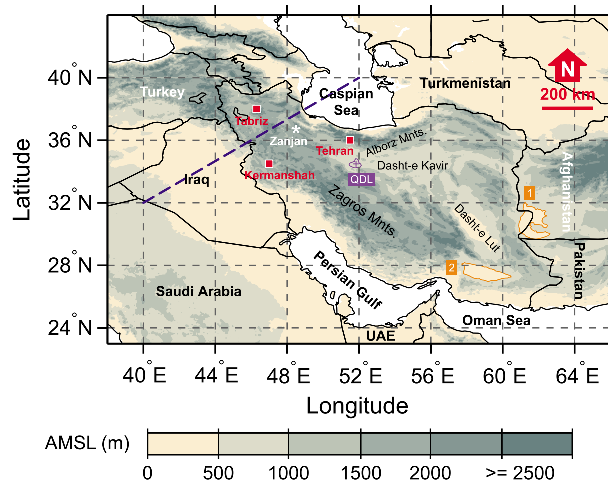

Figure 2. Map of orography in Iran as provided by the Global Land One-km Base Elevation Project (GLOBE, available from http://www.ngdc.noaa.gov/mgg/topo/globe.html). The location of Zanjan is indicated by an asterisk. The QDL, located in the western part of Dasht-e Kavir, south of Tehran, is marked with a plus and a visible boundary. The location of three radiosounding stations (Tehran, Tabriz, and Kermanshah) are indicated as squares. The orange contour labeled "1" delineates the prominent cluster of sources lying in a basin straddling the border between Iran and Afghanistan. The orange contour labeled "2" corresponds to the limits of the Hamoun Jaz-Mourian lake located at the southern end of the Lut Valley (southern tip of the Dasht-e Lut desert). The dashed blue line indicates the location of the cross sections shown in Figure 8.

tains is above 2500 m above mean sea level (msl) along most of their length. The highest points of Alborz mountain are above 4000 m msl.

2.2. Surface-Based Remote Sensing Measurements in Zanjan

[8] In this study all measurements performed in Zanjan (36.7°N/48.5°E) are located at 1800 m msl at IASBS. A backscatter lidar [*Khalesifard et al.*, 2005] is used to investigate the vertical distribution of aerosols over Zanjan. The lidar-derived reflectivity at 532 nm is mostly sensitive to aerosols with radii ranging from 0.1 to 5 μm, and hence to dust aerosols, among others. In the dust belt, close to the sources, desert dust particles are generally considered to be hygrophobic [e.g., *Fan et al.*, 2004] and their properties (e.g., size and shape) do not evolve significantly during transport. Therefore, reflectivity associated with desert dust can be used as a proxy for dust concentration [*Cuesta et al.*, 2008; *Flamant et al.*, 2007], a decrease or an increase in reflectivity being associated with dust sedimentation or dust uplift, respectively.

[9] The vertical and temporal resolutions of the lidar reflectivity profiles shown in this study are 12 m and 1 min, respectively, the latter being obtained after averaging 1200 individual laser shots acquired at a repetition rate of 20 Hz. Finally, usefully backscatter signal is fully recovered above 500 m above ground level (agl) by overlapping of the telescope field of view and laser emission, meaning that no meaningful data can be exploited below that height.

[10] A SPM (CIMEL, model: CE318-2), located close to the lidar, measures the AOD at five wavelengths [*Bayat et al.*, 2010]. Data are only available in September 2008.

2.3. Regional Networks

[11] Local meteorological measurements performed by an automatic weather station (CIMEL, model: ENERCO 408p) in Zanjan is used in this study. The station reports surface data including pressure, temperature, humidity and wind speed and direction. The horizontal visibilities are provided by Zanjan and Qom meteorological station (see Figure 2 for location). Horizontal visibility reported by ground station observers are an indication of the presence of high aerosol loads in the lower atmosphere (the data is available from http://www.irimo.ir).

[12] A crucial criterion for the existence of a dust source is the availability of fine deflatable material, which can be lifted up from the ground when the surface wind velocity exceeds a certain threshold wind speed. This threshold has been shown to be between 4 and 12.5 m s^{-1} in western Sahara [*Fernandez et al.*, 1986; *Pye*, 1987; *Helgren and Prospero*, 1987]. Hence, wind speed observations can provide valuable information regarding the potential activation of given dust sources.

[13] The horizontal visibility is the maximum distance at, which an observer can see and identify an object lying close to the horizontal plane on which he or she is standing (American Meteorological Society glossary). In this paper, dust storms are considered to be associated with visibility values of 2 km or less. This threshold value on visibility is different than the internationally agreed definition of a dust storm, which involves a reduction of visibility to less than 1 km [*Middleton*, 1986b; *Engelstaedter et al.*, 2003; *Kurosaki and Mikami*, 2003]. However, *Mahowald et al.* [2007] suggested that such low visibility values may be caused by small scale aerosol events and that visibility values representative of long-range transport are in the range 2–9 km. Using the 2 km value is thought to be more in line with the idea that the dust storms are not from local sources but rather are associated with long-range transport from remote sources. Furthermore, the 2 km threshold on visibility is also more consistent with the definition used by the Iran Meteorological Services to compile a climatological record of dust storm events through the country (available through their web site at www.irimo.ir). In the case of propagative dust storms, the arrival of airborne dust at a given site is generally associated with a significant decrease in visibility. At the other end of the spectrum, visibility values above 12 km are considered to be representative of clean air conditions, as visibility values associated with blowing dust is generally considered to be less than 11 km [*Kutiel and Furman*, 2003]. Values of visibility ranging from 3 to 10 km can therefore be associated with more or less thick aeolian dust plumes.

[14] The Zanjan meteorological office does not have its own balloon launching facilities. Instead, data from the closest radiosonde stations are used, namely Tehran-Mehrabad (35.7°N, 51.3°E, 1204 m msl, ≈250 km from Zanjan), which releases two radiosondes per day at synoptic hours (0000 and 1200 UTC), Tabriz (38.1°N, 46.3°E, 1367 m msl, ≈235 km from Zanjan), which launches a single radiosonde per day at 0000 UTC, and Kermanshah (34.3°N, 47.1°E, 1420 m msl, ≈290 km from Zanjan), which launches two radiosondes per day at 0000 and 1200 UTC. Of particular interest for our study is the height of elevated temperature inversion which is an indication of the location of atmospheric lids responsible for the vertical stratification of aerosols at the regional scale. The radiosonde data are taken from the radiosondes data center of University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html).

2.4. Spaceborne Observations

[15] The regional distribution of dust aerosols (mobilization and transport) is described using two complementary satellite products. First, the Moderate-resolution Imaging Spectroradiometer (MODIS) fields of aerosol optical depth (AOD) are obtained from the MODIS/AQUA Deep Blue Collection 005 over desert surfaces (MOD08 product). Note that only the daily level-3 AOD product at 550 nm are used. This product is processed with the deep blue algorithm [*Hsu et al.*, 2004] and available from the Giovanni web portal (http://disc.sci.gsfc.nasa.gov/giovanni). Since dust absorbs radiation in the blue wavelength range, and because absorption by these aerosols in this part of the spectrum increases with increasing altitude (as in the ultraviolet), elevated dust plumes are generally detected better than aerosol layers confined at low levels. This can lead to an underestimation of the AOD associated with shallow dust plumes located near the Earth's surface. The MODIS AOD product used in this study is a level-3, gridded (1° × 1°), daily product, representative of the aerosol load at midday. Second, the vertical distribution of the aerosols is documented at the regional scale using the spaceborne Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) [*Winker et al.*, 2007] on board the Cloud-Aerosol Lidar and

Infrared Pathfinder Satellite Observations (CALIPSO) satellite (launched in April 2006).

[16] CALIOP-derived particle extinction coefficient profiles (at 532 nm) are obtained from our own calculation (using level 1B version 2 data) as in work by *Cuesta et al.* [2009] and *Messager et al.* [2010]. The atmospheric extinction coefficient profiles are retrieved with a vertical resolution of 60 m and a horizontal resolution of roughly 12 km. We expect the uncertainty on the extinction coefficient and on the AOD to be on the order of 30%, accounting for an uncertainty of 20% on both the BER and the multiple scattering coefficient. Data from 2 overpasses (1 daytime and 2 nighttime overpasses) are used to analyze the August 2007 case study: around 0858 and 2302 UTC on 3 August 2007 as well as around 2249 UTC on 5 August. The daytime (nighttime) overpass on August is as close as 10 km (40 km) from Zanjan.

2.5. Numerical Prediction Model Reanalyses and Back Trajectory Analyses

[17] Synoptic-scale meteorological conditions are established using 6-hourly ECMWF reanalyses of horizontal winds at the surface, 700 and 500 hPa. The resolution of reanalyses for the region covering middle east is about 1.12° [*Buizza*, 1997]. Wind speeds issued from the reanalyses can provide valuable information regarding the potential activation of given dust sources at the regional scale. In addition, ECMWF reanalyses are used to document the dynamical conditions over the dust source areas (QDL and over Iraq).

[18] The dust transport patterns between the source regions and Zanjan is assessed from back trajectory analyses using the HYSPLIT4 (HYbrid Single-Particle Lagrangian Integrated Trajectory) model (R. R. Draxler and G. D. Rolph, 2003, http://www.arl.noaa.gov/ready/hysplit4.html; G. D. Rolph, Real-time Environmental Applications and Display sYstem (READY), 2003, http://www.arl.noaa.gov/ready/hysplit4.html). These are computed using the Global Forecast System model from the National Centers for Environmental Prediction. There has been some discussion of the applicability of HYSPLIT-derived back trajectories when they pass through the convective atmospheric boundary layer (ABL), as they are solely computed from the three components of the wind and boundary layer mixing is not accounted for [*Wiacek et al.*, 2010; *Knippertz et al.*, 2009]. This may be a limitation for the interpretation of the trajectories arriving in Zanjan, since strong mixing is expected within 4 km deep ABLs in the daytime over northwest Iran, as generally observed over the deserts. In order to account for the inherent uncertainty of trajectory calculations, the back trajectories are calculated as ensembles arriving within a specific arrival domain as in work by *Sodemann et al.* [2006]. Horizontally, arrival points of trajectories are set up as a triangle with Zanjan in the middle. The coordinate of the 3 points are (37.2°N/48.0°E), (36.2°N/48.0°E) and (36.6°N/49.2°E). Vertically, 6 arrival levels ranging between 0.5 and 4 km agl (0.5 and 3 km agl) are chosen for the August (September) case. The start-point altitude and time for the back trajectories are defined based on the ground-based lidar observations. In total, ensembles with 72 h back trajectories from 18 starting points are calculated every 6 h for each case.

[19] Finally, since ECMWF reanalyses are used for looking at synoptic circulation and NCEP reanalyses for running the HYSPLIT model, the consistency between the two reanalyses is crucial. A comparison between the National Centers for Environmental Prediction and ECMWF wind fields at 10 m, 700 hPa and 500 hPa conducted on both cases highlights the coherence between the two reanalyses (not shown).

3. Overview of Dust Sources and Transport Patterns

[20] In the summer, the thermal lows over interior Iran and southeastern Saudi Arabia are at peak strength. Conditions are mostly cloud-free, hot, dry and windy, the latter two characteristics are favorable to the activation of existing dust sources.

3.1. Sources Outside of Iran

[21] Dust activity in the Tigris-Euphrates basin begins in May, reaches a maximum in July, and is much reduced in September–November [*Prospero et al.*, 2002]. During this summer season the region is dominated by northwesterly Shamal winds. According to *Middleton* [1986a, 1986b], the strong Shamal winds lift up dust from the lower Tigris-Euphrates basin and carry it down at the Persian Gulf.

[22] North of Iran, there is persistent dust activity in the region between the Caspian and Aral Seas (Caspian sea eastern shoreline), as well as at southeast end of the Turan Plain (eastern Turkmenistan). Activity generally starts in May and extends through August with the peak in June and July [*Prospero et al.*, 2002].

[23] Dust activity is visible over much of the Arabian Peninsula all year long, but is maximum in June and July when much of the peninsula is covered with dust [*Prospero et al.*, 2002; *Washington et al.*, 2003].

[24] Depending on the prevailing conditions, the dust lifted up in these source regions can be advected over Iran. However, direct transport over Iran is often complicated by the presence of mountains between the dust sources to the north, west and southwest and central Iran (Figure 2). The Alborz and Zagros Mountains act as barriers for impinging air masses, and control the partition between flow around and flow above the mountain range [*Smith*, 1989]. In order for dust to be transported into Iran, it must reach the height above, which the impinging air is forced to flow over a mountain. This can be achieved via several dynamical mechanisms: diurnal vertical mixing or dynamical lifting (e.g., low-level cold air outbreaks) as evidenced for instance over west and north Africa [*Cuesta et al.*, 2009]. In the former case, the dust lifted up from the ground may get well mixed in the vertical throughout the depth of the ABL during the daytime. In the summer and over the desert-type environments such as those prevailing in the dust belt region, ABLs may get relatively deep, their top sometimes reaching 4 to 5 km. These heights are sufficient in order for aerosols to be transported over the mountains and into Iran in the form of elevated dust layers. In the latter case, cold air fronts associated with midlatitude troughs can induce low-level intrusions of clean and cold air and favor uplift of dust along isentropes (a process termed "upliding" by *Hoskins et al.* [1985]). However, frontal systems usually do not reach

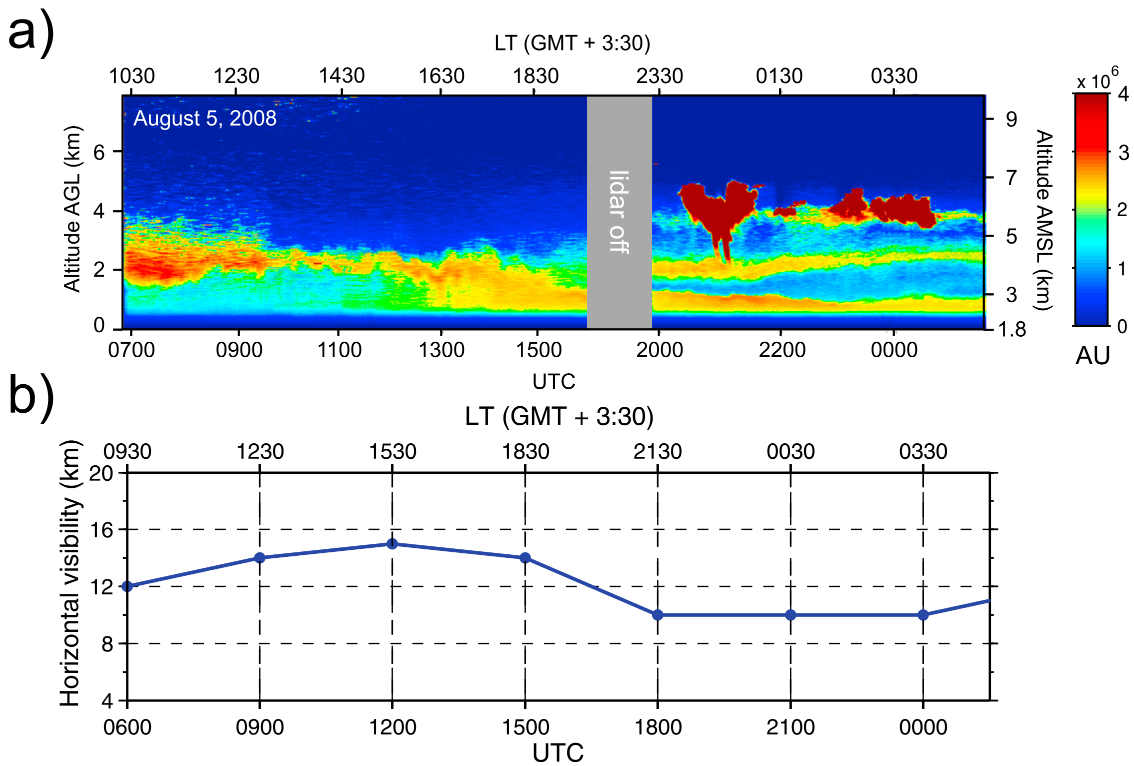

Figure 3. (a) Time-height series of lidar attenuated backscatter profiles recorded in Zanjan (at 532 nm) between 0700 UTC on 5 August 2007 and 0200 UTC on 6 August 2007. Both UTC time (bottom axis) and local time (top axis) as well as both altitude above ground level (left axis) and above sea level (right axis) are indicated. (b) Horizontal visibility reported by the Zanjan meteorological station observer on 5 August 2007.

this area during the summer and this latter process is not expected to play a role in the lifting up the dust over Iraq, the Arabian Peninsula or Turkmenistan.

3.2. Iranian Sources

[25] Dust storms occur, with varying frequency, in all parts of Iran [*Middleton*, 1986b]. In TOMS, dust activity starts in April and May, becomes strong in June and July, and is greatly weakened in September [*Prospero et al.*, 2002; *Leon and Legrand*, 2003], a cycle consistent with the seasonality of dust storm reports [*Middleton*, 1986b].

[26] A prominent cluster of sources lies in a basin centered at 31°N, 61.5°E, straddling the border between Iran and Afghanistan (labeled “1” in Figure 2). The basin receives much runoff from the Sistan Mountains to the west in Iran and the eastern mountains in Afghanistan. The area is affected by the wind of 120 days, a northerly wind that can blow at speeds of over 28 m s^{-1} for days during the main season of activity, i.e., May, June and July [*Middleton*, 1986b].

[27] The central part of Iran is covered by two large deserts, the Dasht-e Kavir (centered around 34.3°N, 55.2°E, covering an area of 77600 km^2) and the Dasht-e Lut (centered around 31.3°N, 58.8°E, covering an area of 51800 km^2). TOMS shows a particularly intense source centered over the western part of the basin (in the region close to Tehran) where there are many large drainage channels and a number of ephemeral lakes and marshes, including a large intermittent salt lake, Daryacheh-ye Namak (1825 km^2), close to the city of Qom, often referred to as the Qom Dry Lake (QDL; see Figure 2). The QDL is the active dust source nearest to the Zanjan area. The Hamoun Jaz-Mourian lake (1087 km^2) is a seasonal lake known to be an active dust source located at the southern end of the Lut Valley (southern tip of the Dasht-e Lut desert, labeled “2” in Figure 2).

[28] Under particular conditions, strong low-level winds may be observed in the lee side of the mountains, associated with the flow around the range and/or downslope winds. In this case (strong winds flow over Iranian sources regions), the dust sources can be activated [e.g., *Middleton*, 1986b]. Gap flows through deep passes in the Zagros and Alborz Mountains can also lead to strong low-level jets downstream of the range that can blow over dust sources, as is the case over Hamoun Jaz-Murian lake [*Liu et al.*, 2000] (but for a winter time case).

4. The 3–5 August 2007 Case

[29] In the following, we analyze the vertical distribution of dust over Zanjan on 5–6 August and the related planetary boundary layer (PBL) diurnal cycle. Links with regional dust transport from Iran and surrounded countries are also assessed.

4.1. Observations of the PBL Residual Layer

[30] Figure 3a shows the time-height series of lidar reflectivity recorded at IASBS on 5 August 2007. In the morning and early afternoon (0700–1100 UTC, 1030–1430 LT) an

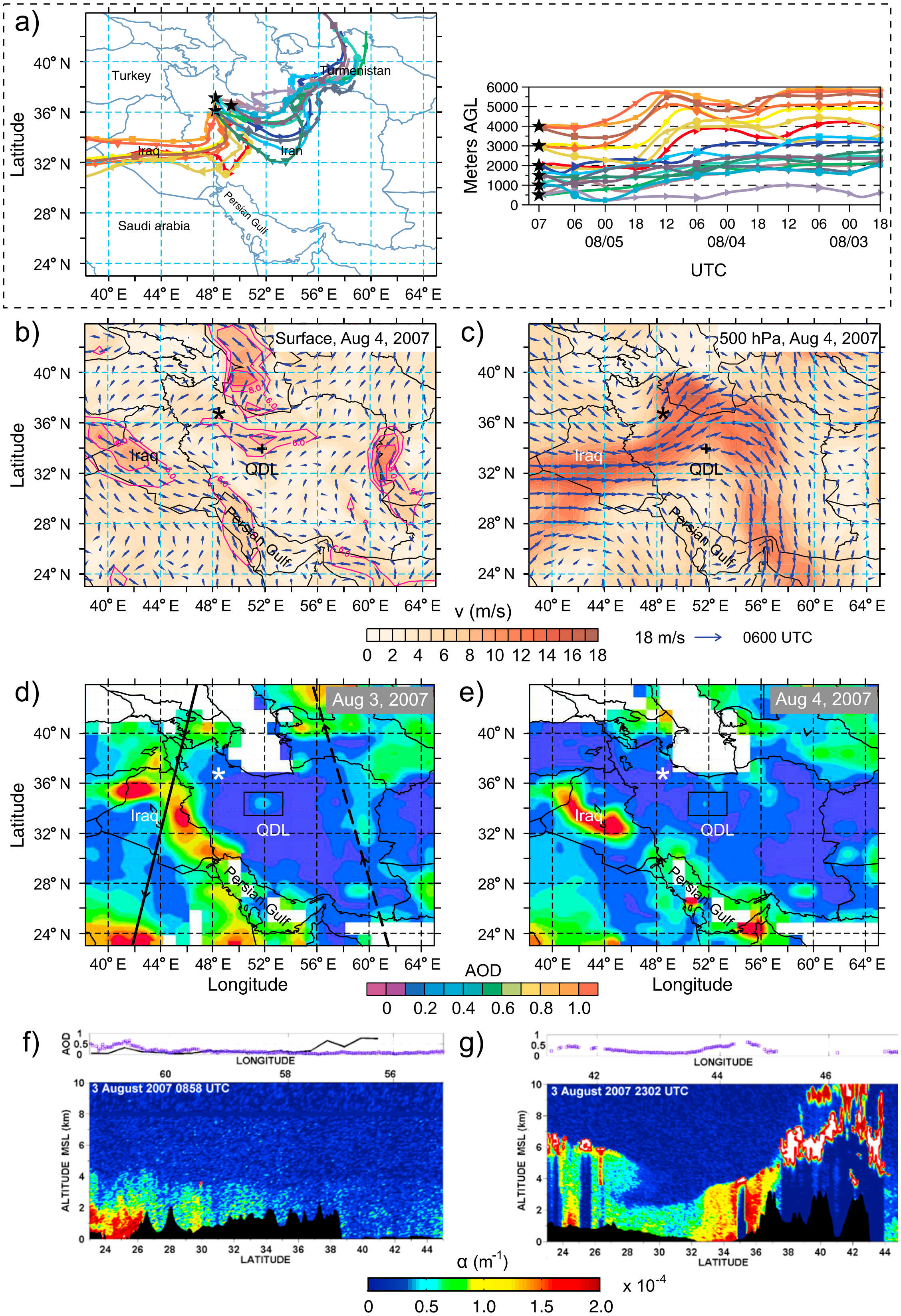
a)
Turkey
Turmenistan
Iraq
Iran
Saudi arabia
Persian Gulf
Latitude
Meters AGL
UTC
08/05
08/04
08/03
b)
Surface, Aug 4, 2007
QDL
c)
500 hPa, Aug 4, 2007
v (m/s)
18 m/s
0600 UTC
d)
Aug 3, 2007
e)
Aug 4, 2007
Longitude
AOD
f)
3 August 2007 0858 UTC
g)
3 August 2007 2302 UTC
LONGITUDE
LATITUDE
ALTITUDE MSL (km)
α (m^{-1})
x 10^{-4}

Figure 4

aerosol layer (larger values of reflectivity between 2 and 4 km agl) is advected over Zanjan in the PBL residual layer (RL) (see *Stull* [1988] for a description of the diurnal evolution of the PBL structure). This dusty layer is observed to be on top of a clean layer, characterized by lower reflectivity values. Above the aerosol layer, very low reflectivity values are observed in the free troposphere, suggesting nearly aerosol-free conditions. The thickness of the aerosol layer decreases with time from nearly 2 km to a few hundred meters, while the depth of the clean layer increases with time. The top of the clean layer reaches 2 km at 1100 UTC. The horizontal visibility is greater than 12 km in Zanjan during that period according to the meteorological office report (Figure 3b).

[31] The elevated dust layer seen in the lidar data over Zanjan corresponds to a dust plume transported from Iraq into Iran, as demonstrated now. Back trajectories starting at 3 and 4 km agl show that the thick aerosol layer observed in Figure 3a at these heights have traveled over Syria and Iraq the previous 2 days (on 3 and 4 August 2007, Figure 4a). The strong Shamal winds blowing over Syria and Iraq on 4 August (Figure 4b) is responsible for dust emissions in that region, the lifted dust subsequently traveling toward the Zagros Mountains (Figure 4c). MODIS-derived AOD fields show the existence of a large dust plume spanning over Syria and Iraq around midday on 3 and 4 August (Figures 4d and 4e), associated with summer Shamal. Large AODs (in excess of 0.8) are associated with this plume.

[32] CALIOP nighttime measurements on 3 August (Figure 4g) confirm the existence of large MODIS-derived AOD values observed over Iraq (AODs reaching 0.8 along the southern flank of the Zagros mountains) and provide insight into the vertical structure of the dust plume. Dust aerosols around 33–36°N are observed to be well mixed over the depth of an ABL as deep as 3.5 km (Figure 4g). During this period, the height of top of the aerosol layer is seen to rise over the elevated terrain in northwest Iran. Shallow clouds sometimes are observed at the top of the ABL (water clouds are associated with very large values of the extinction coefficient and appear in white in Figure 4g). Much deeper clouds over northwest Iran and further north prevented lidar extinction coefficient retrievals in the lower levels (38–44°N).

[33] The near-surface layer characterized by low extinction coefficients seen in the lidar data over Zanjan corresponds to the advection of relatively clean air masses from Turkmenistan, as shown now. Back trajectories computed with HYSPLIT starting around Zanjan at 0700 UTC on 5 August evidence that the air masses below 2 km agl originated from Turkmenistan two days before their arrival in Zanjan (on 3 August, Figure 4a) and passed in the vicinity of the QDL one day before their arrival in Zanjan, i.e., before the QDL dust source was activated (see Figure 4e). Very low extinction values are observed over Turkmenistan during the daytime overpass on 3 August (north of 38°N, Figure 4f), indicating a nearly dust-free troposphere in this region, at the origin of the clean air observed with the Zanjan lidar below 2 km agl. While the MODIS and CALIOP AOD retrievals are found to be consistent over Iraq, large discrepancies are found over Turkmenistan, with MODIS exhibits large AOD values ranging between 0.5 and 0.6 (Figure 4d). Meteosat 7 images (not shown) evidence that most of Iran and Turkmenistan appear to be cloud free at 1200 UTC on 3 and 4 August, in the region where high MODIS AOD values are observed. Establishing the reason why MODIS fails in this region is beyond the scope of this paper.

4.2. Observations of the PBL Convective Layer

[34] Lidar observations show that the convective boundary layer (CBL) begins to develop relatively late, around 1230 LT (0900 UTC, the exact time cannot be determined due to the fact that the lidar is "blind" in the first 500 m agl). The presence of the elevated layer of dust (and the induced shading at the surface) could be the reason for the delay in the development of the CBL. Lidar data also suggest that the top of the CBL reached the elevated aerosol layer at 1800 m agl (3600 m msl) around 1230 UTC. The temperature profiles derived from the 1200 UTC soundings in Tehran and Kermanshah suggest this layer to be a dry adiabatic layer, topped by a more stably stratified layer between 3600 and 5800 m msl, within which long-range transport from Iraq and Syria occurs.

[35] After 1300 UTC, the increase of lidar reflectivity data down to the surface evidence the vertical turbulent mixing of the elevated dust layer throughout the depth of the CBL. This leads to a decrease of the horizontal visibility between 1200 and 1500 UTC. After 1400 UTC, it appears that the elevated dust plume is entirely mixed into the CBL, all the way down to the surface.

4.3. Observations of the PBL Stable and Residual Layers

[36] Around 1530 UTC (1900 LT, i.e., at sunset), lidar measurements evidence a decoupling between two aerosol laden layers. A layer characterized by low reflectivity values (i.e., clean air) is seen to separate the two aerosol laden

Figure 4. (a) HYSPLIT-derived 72 h back trajectories ending in three locations around Zanjan at 0700 UTC on 5 August 2007 at six levels between 0.5 and 4 km agl (see section 2.5 for details). (b) ECMWF analyses of horizontal wind field speed (color) and direction (arrows) at 10 m above the surface on 4 August 2007 at 0600 UTC. (c) Same as Figure 4b but at 500 hPa. The locations of Zanjan and QDL are marked with an asterisk and a plus, respectively. Daily MODIS Deep Blue AOD at 550 nm, on (d) 3 August and (e) 4 August. The location of Zanjan is marked with a star, while the QDL area is highlighted using an open rectangle. The locations of the CALIPSO tracks are also overlain, with solid black lines indicating nighttime overpasses and the dashed black lines indicating the daytime overpasses. (f) (bottom) Vertical cross section of CALIOP particle extinction coefficient profiles (at 532 nm) around 0858 UTC on 3 August 2007; (top) CALIOP-derived AOD (blue open squares) and MODIS AOD derived along the CALIPSO track (solid black line). (g) Same as Figure 4f but around 2302 UTC. Water clouds are associated with very large values of the extinction coefficient and appear in white (off-scale).

layers. The depth of the lower layer decreases continuously with time, while the upper layer ascends during the same period (between 1500 UTC on 5 August and 0200 UTC on 6 August). Finally, a third layer characterized by enhanced reflectivity values is observed around 4 km agl. Clouds are also seen to be present at that level (features appearing in maroon). This layer also is separated from the intermediate dust layer by clean air. The 6 August 0000 UTC sounding in Tehran and Kermanshah indicate the presence of a temperature inversion at 3100 m msl, corresponding to the top of the lower aerosol layer (not shown). A second temperature inversion is detected around 5800 m msl in both Tehran and Kermanshah, which corresponded to the top of the upper aerosol layer. The intermediate layer is not observed to be associated with an outstanding feature on the temperature profiles.

[37] HYSPLIT-derived back trajectories starting at 2100 UTC around Zanjan indicate that the lower aerosol layer seen in the lidar data is associated with air masses having traveled at low-level over the QDL region approximately nine hours prior to arriving in Zanjan (Figure 5a). An area characterized by strong surface wind speed is seen, in the ECMWF reanalyses, to develop over the Dasht-e Kavir desert at this time on 5 August, with surface wind speed larger than 6 m s^{-1} over QDL (Figure 5b). The strongest surface winds in Qom during that period are observed on 5 August at 0600 UTC (Figure 5c). The surface wind in the Qom region are underestimated in the ECMWF reanalyses on 5 August (Figure 5c), the observed surface winds being stronger than the modeled ones by as much as 4 m s^{-1} at 0600 UTC. Consistently with the notion of source activation, the horizontal visibility in Qom (Figure 5d) is reported by the observer to decrease on 5 August after the strongest wind episode recorded during the 3–5 August period (surface wind speed reaching 10 m s^{-1} at 0600 UTC). Furthermore, large AOD values are observed with MODIS in the QDL region around midday on 5 August (Figure 5e).

[38] As a result of dust emissions in the QDL region, horizontal visibility near surface remains low in Zanjan after 1800 UTC (Figure 3b). The persistence of the lower aerosol layer (observed until 0200 UTC on 6 August) is consistent with that fact that the QDL dust source is activated for at least 12–15 h (Figure 5d).

[39] The visibility is estimated to be on the order of 10 km (light aeolian dust burden) at the Tehran meteorological station for the 3–5 August period, except on 5 August between 0200 and 0500 UTC when it decreases to 7 km (not shown). The decrease is consistent with the arrival of the dust plume from the west on that day. The light aeolian burden observed otherwise are an indication of fairly low levels of anthropogenic pollution. Hence, high backscatter coefficient values observed in the lidar data at low-level are likely not related to anthropogenic aerosols from Tehran.

[40] The layer observed at 4 km agl over Zanjan can unambiguously be related to long-range transport from Syria and Iraq (Figure 5a) where a large dust plume is observed on 3 and 4 August as discussed previously. The origin of the uppermost and lowermost aerosol layer is found to be the same for back trajectories starting at 0100 UTC on 6 August.

[41] The origin of the intermediate layer is less obvious. HYSPLIT-derived back trajectories starting at 2100 UTC to the east of Zanjan at 2 km agl indicate that this layer has traveled over Turkmenistan and northern Iran before reaching Zanjan. Back trajectories starting to the west of Zanjan at 2 km agl indicate that this layer originates from Iraq (Figure 5a). Nevertheless, CALIOP data over Turkmenistan on 3 August (Figure 4f) show no evidence of the presence of dust north of the Alborz Mountains. The intermediate aerosol layer is observed to be slightly higher, around 3 km agl at 0100 UTC on 6 August. Back trajectories starting at this time and at 3 km agl suggest that the layer is coming from the west, i.e., Iraq and Syria. It is unlikely that a layer that looks so continuous (time-wise) in the lidar time series should come from such different origins. Rather, it is believed that this mismatch is linked to the coarse vertical resolution of the Global Forecast System analyses. Therefore, it is likely that the intermediate dust layer originates from Iraq rather than Turkmenistan. Nevertheless, the clean air mass separating the lowermost two dust layer could originate from Turkmenistan.

[42] The upper aerosol layer as well as the clouds over Zanjan region are also observed in the CALIPSO data at 2249 UTC (Figure 5f). CALIOP revealed that a thick dust plume (nearly 5 km) is present over Iraq (around 46.5°E) and that the Iraqi dust plume ascended over the Zagros Mountains, its top reaching 6 km msl over Zanjan. Over northwest Iran (in the mountainous area, between 35 and 37°N), a three-layer structure is observed, with the presence of a cleaner air mass between an elevated dust plume from Iraq and a plume close to the surface. However, due to the presence of high level clouds, no information on the aerosol distribution can be retrieved over Zanjan because of extinction in the cloud (optically thick clouds prevent the laser beam from sensing the atmosphere below the cloud).

5. The 11–13 September 2008 Case

[43] Figure 6a shows the time-height series of lidar reflectivity recorded at IASBS on 13 September 2008. High reflectivity values are observed from 0530 to 1430 UTC, together with high AOD values measured from the SPM at IASBS and low horizontal visibility as reported by the Zanjan meteorological station observer (Figure 6b). The high lidar reflectivity values and visibilities are associated with low-level dust transported from Iraq over northwest Iran as discussed in the following.

[44] As is illustrated in Figure 6a, the CBL started to develop shortly after 0530 UTC (0900 LT). At this time, a RL extending between 0.5 and 1.3 km agl is also observed. Note that the reflectivity values characterizing the residual layer are on the order of those in the developing CBL. The CBL develops until 0830 UTC when it reaches a depth of 1.2 km. In the course of its development, the CBL gradually erodes the residual layer and aerosols contained in the latter are mixed within the former. The largest lidar reflectivity values are observed in the morning in Zanjan shortly after the residual layer is fully eroded by the CBL (around 0830 UTC). This is consistent with the decrease of horizontal visibility after 0830 UTC (Figure 6b). The depth of the ABL continues to increase until reaching approximately 1.5 km. Lower reflectivity values are observed in the ABL between 0900 and 1100 UTC, consistently with the values of AOD decreasing between 0.6 and 0.4. Reflectivity in the ABL increased after 1100 UTC. This increase is accom-

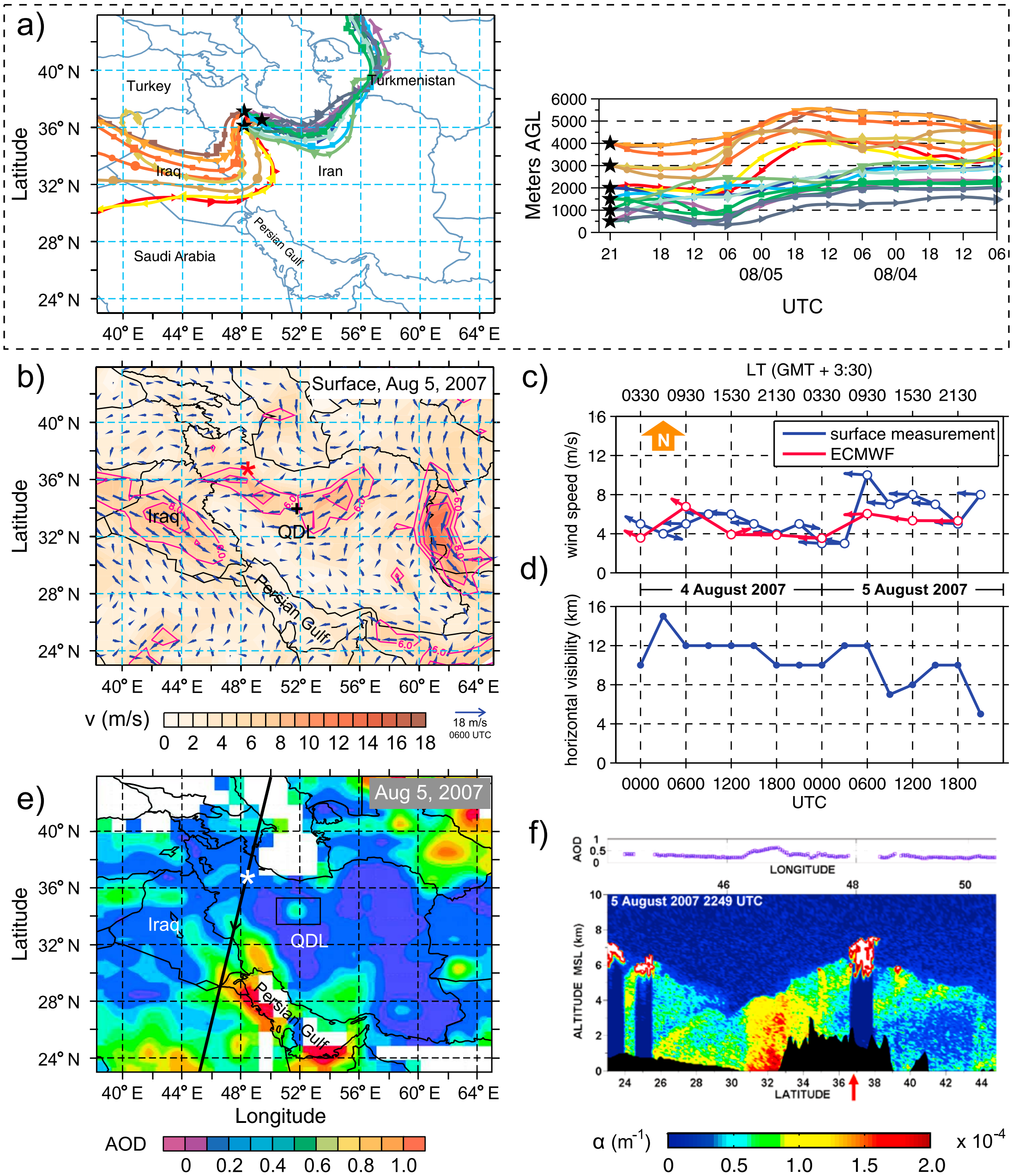

Figure 5. (a) HYSPLIT-derived 72 h back trajectories ending in three locations around Zanjan at 2100 UTC on 5 August 2007 at six levels between 0.5 and 4 km agl (see section 2.5 for details). (b) ECMWF analyses of horizontal wind field speed (color) and direction (arrows) at 10 m above the surface on 5 August 2007 at 0600 UTC. The locations of Zanjan and QDL are marked with a star and a plus, respectively. (c) Wind speed (blue solid line) and wind direction (blue arrows) reported by the Qom meteorological station on 4 and 5 August 2007. The red solid line and red arrows correspond to the wind speed and direction, respectively, extracted from the ECMWF reanalyses at the grid point nearest to Qom. (d) Horizontal visibility reported by the Qom meteorological station ground observer on 4 and 5 August 2007. (e) MODIS Deep Blue AOD at 550 nm on 5 August. The location of Zanjan is marked with a star, while the QDL area is highlighted using an open rectangle. The locations of the CALIPSO tracks are also overlain, with the solid black lines indicating the nighttime overpass on 5 August. (f) (top) CALIOP-derived AOD along the CALIPSO track (solid black line in Figure 5e); (bottom) vertical cross section of CALIOP particle extinction coefficient profiles (at 532 nm) around 2249 UTC on 5 August 2007.

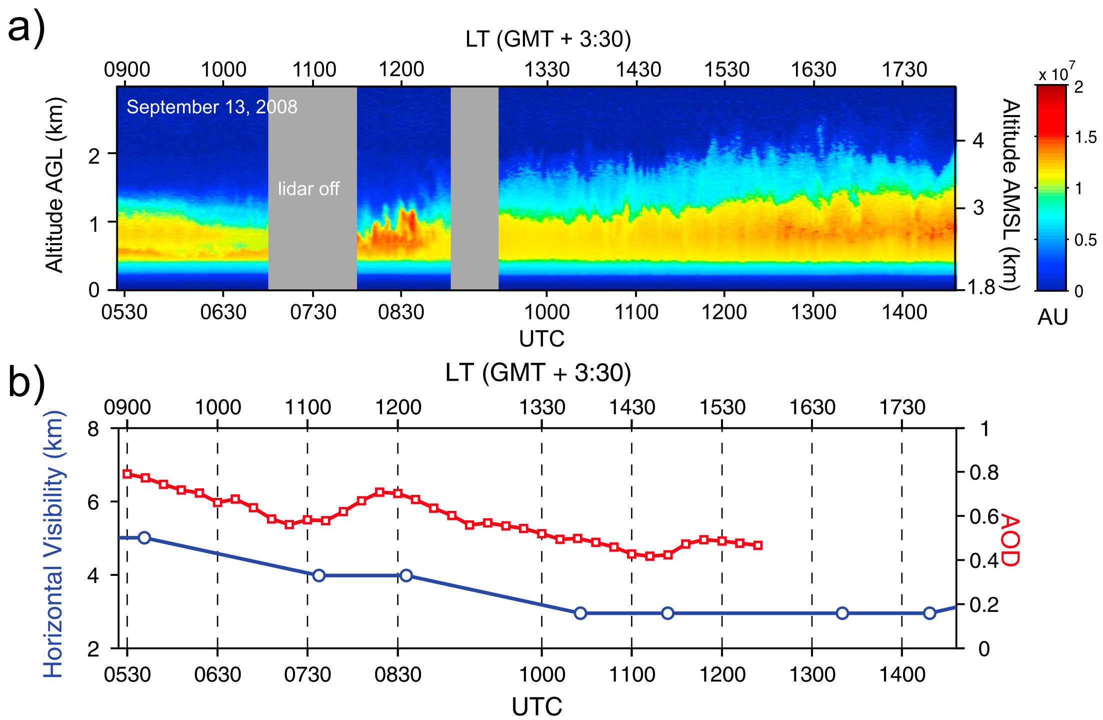

Figure 6. (a) Time-height series of lidar attenuated backscatter profiles recorded in Zanjan (at 532 nm) between 0530 UTC and 1430 UTC on 13 September 2008. Both UTC time (bottom axis) and local time (top axis) as well as both altitude above ground level (left axis) and above sea level (right axis) are indicated. (b) AOD measured by the SPM in Zanjan between 0525 UTC and 1230 UTC at 670 nm (the SPM stopped working after 1230 UTC) and horizontal visibility reported by the Zanjan meteorological station ground observer between 0520 UTC and 1500 UTC on 13 September 2008.

panied by an increase in AOD. During this period, the horizontal visibility remains quite low (3 km, Figure 6b).

[45] The temperature profile derived from the 1200 UTC soundings in Tehran and Kermanshah reveals the existence of a dry adiabatic layer up to 3150 m msl (not shown), corresponding to the top of the PBL. A marked temperature inversion is observed to cap that dry adiabatic layer. Above the temperature inversion, a more stably stratified layer is observed.

[46] HYSPLIT-derived back trajectories starting in Zanjan at 0500 UTC on 13 September indicate that the air masses between 0.5 and 3 km have traveled over northern Iraq the previous day (12 September), and Turkey the day before (11 September) as shown in Figure 7a. ECMWF reanalyses show that the strongest surface winds on 11 September (Figure 7b) are found over Syria and Iraq (related to northwesterly Shamal flow). Winds over Iraq and Syria are seen to be in excess of 6 m s^{-1} and have the potential to activate dust sources. This is confirmed by the MODIS-derived AOD field on 11 September which shows an area characterized by values in excess of 1 over Iraq (Figure 7d) consistent with dust source activation. AODs between 0.8 and 1 are also observed over northwest Iran (Figure 7d) as the result from eastward long-range transport of dust lifted over Iraq toward the Zagros Mountains and northwestern Iran (Figure 7c).

[47] On 12 September, the aerosol plume previously observed over Iraq is over northwest Iran (Figure 7e) as also corroborated by visibility values as low as 2.5 km in Tabriz (not shown). Low values are seen over Iraq which suggests that the Iraqi dust source is no longer active on that day. It is consistent with the low surface winds shown by the ECMWF analysis (not shown).

[48] On 13 September, the optically thick dust plume from Iraq previously positioned west of Zanjan (Figure 7f) is now located over Zanjan. The MODIS AOD values associated with this plume are seen to decrease from over 1 to 0.7 between 12 and 13 September. The visibility in Tabriz remained very low on that day as well (around 2.5 km, not shown). Furthermore, it is worth noting that visibility in Tehran is low on all three days, sometimes less than 5 km (nor shown).

6. Summary and Conclusion

[49] Transport of desert dust over northwest Iran in the summertime has been studied using a suite of ground-based and spaceborne remote sensing platforms as well as modeling tools.

[50] During the 3–5 August 2007 case, dust emission regions were located in Syria/Iraq and in the QDL region in Iran. Emissions in Syria and Iraq occurred in response to strong Shamal winds. The lifted dust then got mixed throughout the depth of the deep ABL, before being advected eastward toward the Zagros Mountains. The strong easterly flow blowing over Iran and southwest of the Zagros

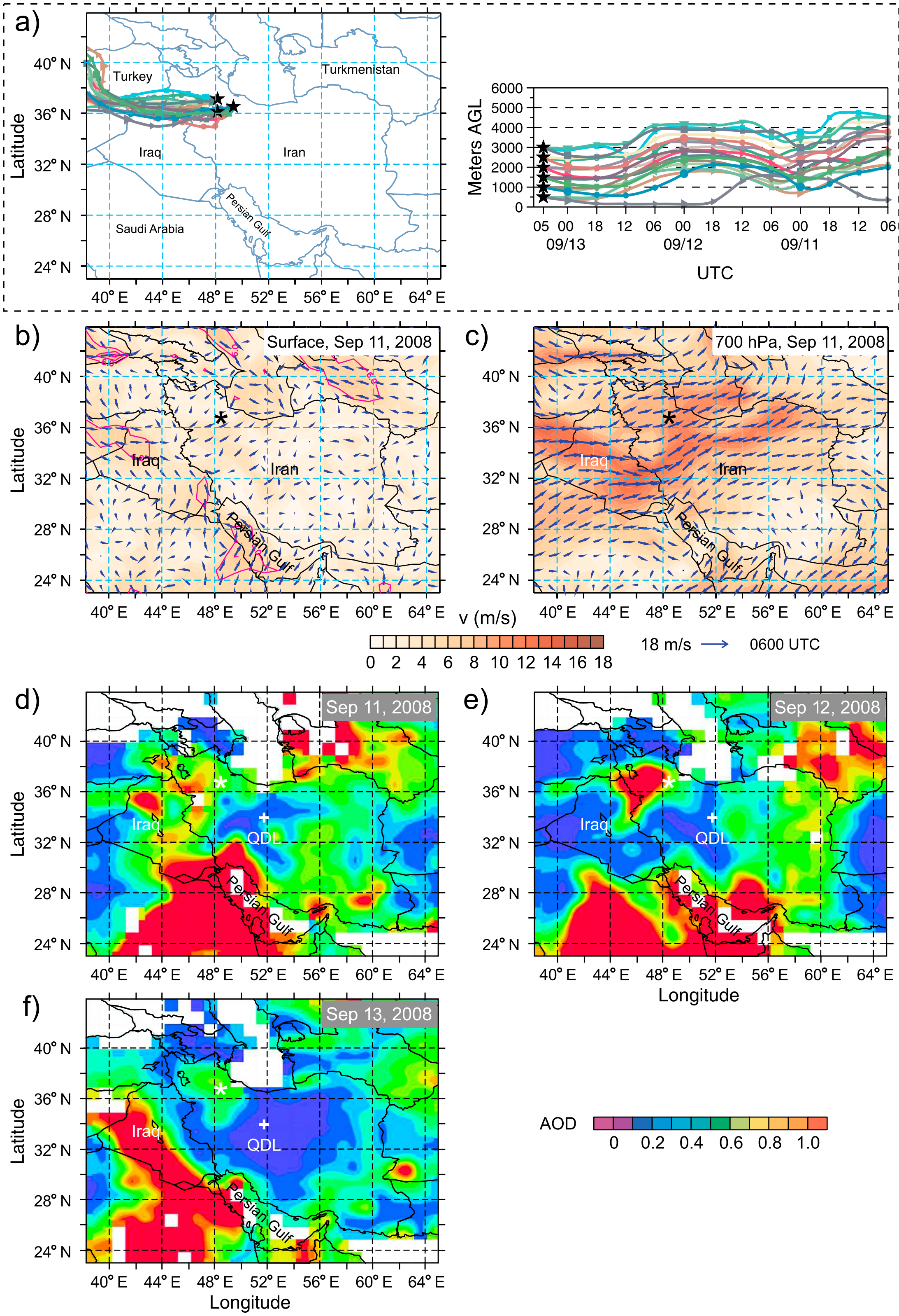

Figure 7. (a) HYSPLIT-derived 72 h back trajectories ending in three locations around Zanjan at 0700 UTC on 13 September 2008 at six levels between 0.5 and 3 km agl (see section 2.5 for details). (b) ECMWF analyses of horizontal wind field speed (color) and direction (arrows) at 10 m above the surface on 11 September 2008 at 0600 UTC. (c) Same as Figure 7b but at 700 hPa. The location of Zanjan is marked with a star. Daily MODIS Deep Blue AOD at 550 nm on (d) 11 September, (e) 12 September, and (f) 13 September 2008. The location of Zanjan is marked with a star.

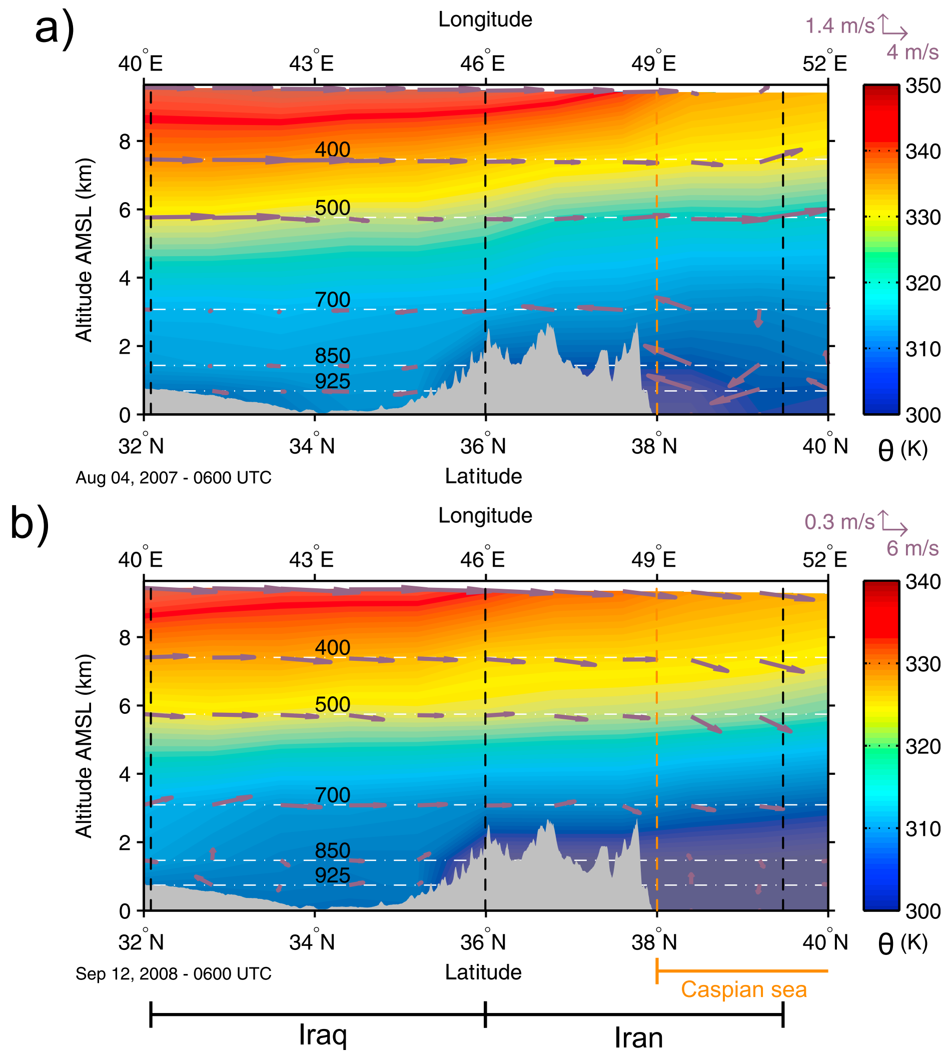

Figure 8. Vertical cross section of potential temperature extracted between 40°E/32°N and 52°E/40°N (see Figure 2) from the ECMWF analyses at 0600 UTC on (a) 4 August 2007 and (b) 12 September 2008. The wind along the cross section is shown as vectors. The orography interpolated from GLOBE along the cross section is shown in grey.

Mountains (below 850 hPa, Figure 8a), prevented direct transport of the Iraqi dust in the low levels over Iran. Rather, the transport of Iraqi dust to Iran occurred above 3.5 km msl. Dust emission in the QDL region resulted from strong winds blowing over the Dasht-e Kavir desert. The contribution of the different dust source regions to the dust load in Zanjan could be identified using a combination of lidar observations and HYSPLIT back trajectories. The visibility in Tehran decreased significantly (reaching 7 km) on 5 August 2007 only, as air quality was impacted by the low-level transport of dust from the Qom region.

[51] During the 11–13 September 2008 case, dust emission regions were located in Syria/Iraq. Emissions in Syria and Iraq occurred in response to strong Shamal winds. In this case, unlike what was observed in the August case, dust was transported toward the Zagros Mountains at low levels as there was no opposing flow to the west of the Zagros range (Figure 8b). Lidar measurements in Zanjan on 13 September evidenced the presence of a 1–1.5 km thick dust plume from Iraq traveling below 3.5 km msl over northwest Iran. High AOD values and low near surface horizontal visibility were associated with this case. The visibility in Tehran during this case was sometimes reduced to less than 5 km due to the transport of dust at low levels.

[52] Ground-based lidar measurements acquired in Zanjan allowed new insight into the vertical distribution of dust linked to transport over northwest Iran. The analysis of these previously unavailable data highlighted the importance of low-level transport of dust from both Iraq and Iran for air quality issues in a large city such as Tehran. These data also enabled to show that the high-level transport of dust from Iraq only marginally impacted visibility (and hence air quality) in Tehran.

[53] Further investigation is needed to substantiate these findings, in particular the seasonal frequency of dust events from Iraq over northwest Iran as well as the level at which the transport occurs need to be addressed in future studies in order to assess the impact of such events on human health.

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