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Synoptic Analysis of Dust Storms in the Middle East

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Abstract : Dust storm in the Middle East and south-west Asia is a natural hazard and the Tigris-Euphrates alluvial plain has been recognized as the main dust source in this area. In this study, more than 60 dust storms that occurred during the period 2003-2011 are investigated on the basis of MODIS satellite images, and 12 of the dust storms are selected for synoptic analysis using the NCEP-NCAR Reanalysis Data. The potential dust sources in the Middle East and south-west Asian region (20°E to 80°E, 5°N to 50°N) are analyzed and used in the synoptic analysis. Dust storms in the region can be grouped into two main categories, i.e., the Shamal dust storms and the frontal dust storms. Synoptic systems, associated with the two categories, are distinguished and the frequency of the patterns is identified. For 68% of the Shamal dust storms, a high pressure system is situated between 0°E to 30°E and 27°N to 45°N, and a low pressure system between 50°E to 70°E and 23°N to 43°N. For 86% of the frontal dust storms, a high is located between 51°E to 67°E and 18°N to 33°N and a low between 28°E to 48°E and 32°N to 43°N. Three main patterns for Shamal dust storms are identified, which represent about 60% of the Shamal dust storms. This analysis confirms that the Shamal is related to the anticyclones located over northern Africa to Eastern Europe and the monsoon trough over Iraq, southern Iran, Pakistan and the Indian Subcontinent. The analysis also shows that the main dust sink for the frontal dust storms in Tigris and Euphrates alluvial plain extends from center of Iraq to west and center of Iran and, in most severe cases, to northern Iran and the southern coast of the Caspian Sea.

Key words: Shamal and frontal dust storm, MODIS satellite image, NCEP-NCAR reanalysis data, potential dust source, synoptic analysis

1. Introduction:

Mineral dust aerosol is involved in many important processes in Earth's climate system including radiative forcing, nutrient transport, land-use change, and ecosystem health. Dust storms and suspended dust pose serious environmental problems in south-west Asia and natural hazards in the Middle East region. Major dust storms occur over the Middle East region nearly every spring and summer and cause destructive effects in some countries like Iraq, Saudi Arabia and Iran. Model simulations suggest that the dust emission from this region contributes to about 20% of the global total emission. For example, the amount of dust emission in this area is estimated 415 (Tg yr^{-1}) by Zender *et al*. (2003), 496 (Tg yr^{-1}) by Ginoux *et al*. (2004) and 221 (Tg yr^{-1}) by Tanaka *et al*. (2006), which respectively equal to 28%, 24% and 11.8 % of total global dust emission.

The Tigris-Euphrates alluvial plain has been recognized as the main dust source in the Middle East. The dust originating from this area can be transported over large distances because the dust particles from this area mainly consist of fine sediments from the Tigris and Euphrates rivers. Therefore, the dust storms from the Middle East also have important impacts on the neighboring countries like Iran. The dust activities have intensified in the Mesopotamian area in recent years, partly due to the development of the dam construction projects on Tigris and Euphrates rivers. Construction of new dams decrease the humidity and water content of soil in the downstream areas, which consequently lessen the threshold friction velocity of the soil and its resistance against wind erosion. Urbanization in the areas previously devoted to agriculture and shortage of power that prohibits the adequate irrigation of farmlands also enhanced the disaster situation of the area.

The seasonal variation of dust activity in the Middle East is complex and differs for different regions. Over much of the Middle East, dust is active all year long, but it decreases in the winter months. Dust activity increases in March and April, peaks in June and July and weakens in September (Shao, 2008).

Reviewing the previous scientific documents shows that the information about the synoptic pattern of these dust storms is not fully classified. Also, the placements of high and low pressure systems in severe dust storms are not distinguished, quantitatively. Therefore, the main step to brief and suitable analysis of dust storms in this area is having enough information about the synoptic situation of these kinds of dust storms. The result of this study can be useful to make a good overview on dust storm occurrence and investigations in Middle East area.

The MODIS satellite images between 2003 and 2011 show that nearly 60 dust storms occurred in the Middle East, which are reported as natural hazards in the area by NASA. Amongst these, 12 severe dust storms were considered for synoptic analysis of the dust storms in this area. The distinguished feature of these selected dust storms is that, their dust plumes were spread and covered the western to central part of Iran.

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The rest of 48 dust storms were just spread over Iraq and a smaller part of Iran. In four of the selected cases, the dust plumes reached the north-eastern to eastern part of Iran and affected the Caspian Sea region. The analysis of the MODIS satellite images shows that the dust storms from the Tigris-Euphrates alluvial plain may affect more than 10 countries in the Middle East.

This study has three objectives: (a) to provide an overview of potential dust source; (b) to provide an overview of synoptic characteristics of dust events; and (c) to provide a meteorological classification of severe dust storms in Tigris and Euphrates alluvial plain.

2. Potential dust sources

The Middle East, largely made up of the Arabian Plateau and the Tigris-Euphrates Basin, is an area of active wind erosion. The Arabian Plateau slopes down from the southwest high terrains (1,500-3,000 m) bordering the Red Sea towards the northeast flat lands (50-200 m) adjacent to the Persian Gulf. One of the largest sand deserts in the world, the Rub al Khali (or Empty Quarter 582,750 km^2) occupies much of the southern interior of the Arabian Peninsula. The Rub al Khali is connected to the An Nafud sand sea in the north by the Ad Dahna, a sand corridor of 1287 km long. Two dust areas have been identified. The first covers the Tigris-Euphrates River alluvial plain in Iraq and Kuwait, the low-lying flat lands in the east of the peninsula along the Persian Gulf and the Ad Dahna and the Rubal Khali deserts (Shao, 2008). The alluvial plains have the highest frequency of dust storms in the Middle East (Safar, 1980). The second dust area is found off the Oman coast, and the number of daily dust-storms in this area is rather low and thus is eliminated from this study.

In this paper, the land surface is divided into non erodible areas which are not prone for dust emission, and potential dust source regions which can be used for dust emission in numerical models. The potential dust source regions are defined on the basis of remotely sensed leaf area index (LAI), topography (H) and surface type (S). The methodology has been used by Shao *et al*. (2010) and Klose *et al*. (2010). In their study, the critical LAI of 0.3 was found to give the best results for their study area. In the present study, based on modeling with different critical LAIs (0.3, 0.5 and 0.7), critical LAI of 0.3 was found to provide the best approximation for potential dust sources. The LAI data for March which represents the least magnitude of LAI in the year was selected to treat the data. It is expected that the results provides the highly potential areas for dust source, to match our criteria in determination of potential dust source. By this selection, the results of potential dust source may best represent the potential for the whole year. It should be mentioned that alluvial plains as a source of fine sediment for dust are usually placed above the sea level but not very high to face mountains. Therefore, as the most part of the present study area located in Iran and Arabian plateau with high altitude, critical height topography of 500 m, 700 m and 900 m were selected for this investigation, which cover most of the potential dust sources.

By applying some criteria in Geographic Information System, the potential dust sources for the study area are provided. ArcGIS software as a suitable system for designing and managing solutions was used for this application. The criteria consist of $LAI < LAI_c$, $H < H_c$, and $S = S_c$, where LAI_c is a critical LAI (in this study 0.3), H_c is a critical height of topography (in this study 500, 700 and 900 m above sea level), and S_c is a type of surface that is erodible (water surfaces and stony surfaces are not erodible). The results showed three potential dust sources, named Case 1 ($LAI_c = 0.3$, $H_c = 900$), Case 2 ($LAI_c = 0.3$, $H_c = 700$) and Case 3 ($LAI_c = 0.3$, $H_c = 500$), as is observed in Fig. 1.

The required data for topography (H) was obtained from the United State Geological Survey website. Global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (approximately 1 km), developed by U.S. Geological Survey's Center for Earth Resources Observation and Science (EROS) was used for implementing of height criteria (http://eros.usgs.gov/#Find_Data/Products_and_Data_Available/gtopo30_info). The LAI data were obtained from the Climate and Vegetation Research Group, Department of Geography, in Boston University. The data are monthly composite with 4 km spatial resolution, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) TERRA and AQUA products (ftp://primavera.bu.edu/pub/datasets/modis15_bu). The website is disappeared, but similar data is available on https://lpdaac.usgs.gov/products/modis_products_table/mod15a2. The soil types are derived from the Webb-Rosenzweig global soil profile data set (ftp://www.daac.ornl.gov/data/global_soil/Webb-Rosenzweig) for the first meter of soil (Webb *et al*., 2000). The data have a spatial resolution of 1^o and are available from the Oak Ridge National Laboratory Distributed Active Archive Center. The soil data profile gives the percentage of sand, silt, and clay, which are used to regroup the Webb-Rosenzweig soils into the U.S. Department of Agriculture (USDA) soil types for some additional analysis in dust models.

3. Meteorological characteristics of dust storms

The climate in the Middle East is mainly affected by four systems: (a) The Siberian anticyclone in winter over central Asia; (b) The Polar anticyclone in summer over east of Europe and Mediterranean Sea; (c) The monsoon cyclones in summer over the India Subcontinent, south and southeast of Iran and southeast of Arabian peninsula; (d) The depressions travelling from north of Africa and south and east of Mediterranean sea across the Middle East and southwest of Asia in the non-summer seasons (spring and winter).

Summer Shamal and frontal dust storms are the two main kinds of synoptic scale dust storms in this region. Severe dust storms occur in summer and associated with Summer Shamal (for simplicity called Shamal in this study). In non-summer season, frontal dust storm is the most common type. Wilkerson

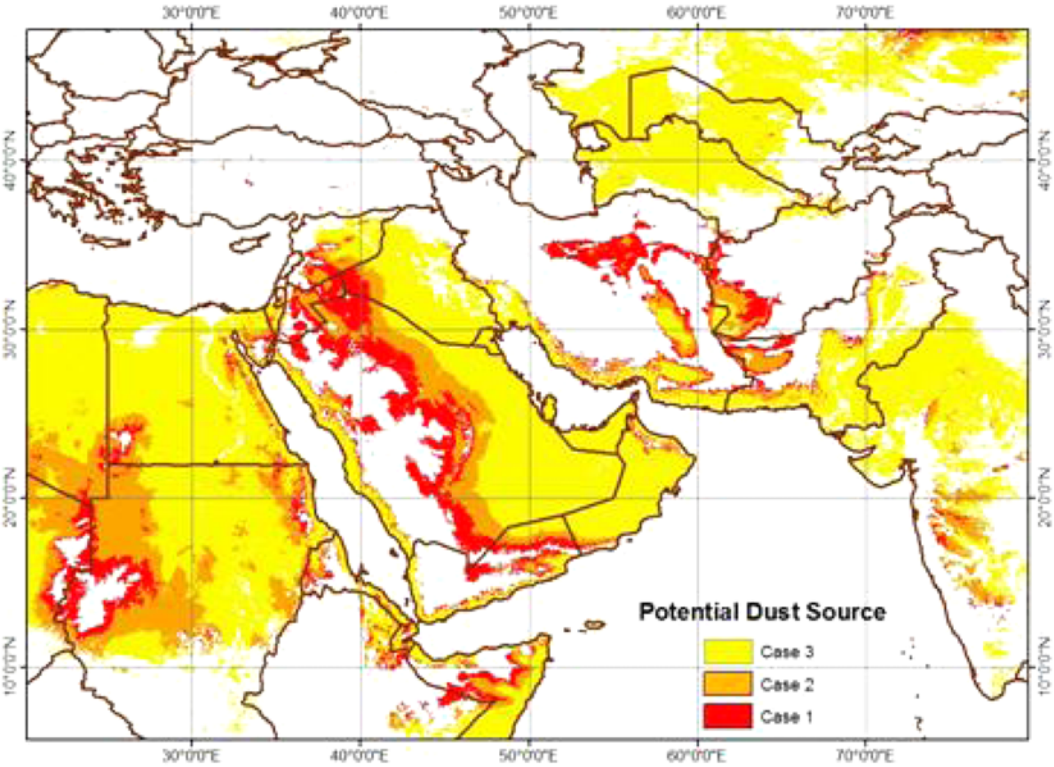

Fig. 1. Potential dust source regions (shaded) specified in Cases 1, 2, and 3. For Case 2 ($LAI_c = 0.3$, $H_c = 700$), the enlarged area with respect to Case 3 ($LAI_c = 0.3$, $H_c = 500$) is orange; for Case 1 ($LAI_c = 0.3$, $H_c = 900$), the enlarged area with respect to Case 2 is red.

(1991) presented a definition for Summer Shamal and frontal dust storms as follows:

(1) Summer Shamal

Shamal (means *north* in Arabic) dust storm occurs across Iraq, Kuwait, western part of Khuzestan plain and some parts of Arabian Peninsula. It blows almost daily during the summer months from June through September. The summer Shamal travels across central and southern Iraq and picking up dust from Tigris and Euphrates rivers alluvial plain. The synoptic feature that creates the potential for the Shamal is a zone of convergence between the subtropical ridge, extending into the northern Arabian Peninsula and Iraq from the Mediterranean Sea and Monsoon Trough across southern Iran and southern Arabian Peninsula. The zone of convergence is caught between the pressure systems and Zagros Mountains of western Iran. It tends to force an acceleration of the northerly low-level winds across southern Iraq, the western Khuzestan Plains of Iran, Kuwait, the northwestern Persian Gulf, and the northeastern Arabian Peninsula.

(2) Frontal dust storm

Frontal dust storms are dynamic synoptic systems that mix the dust in the air and carry it for great distances in non-summer seasons. The two main types of frontal dust storms in Tigris and Euphrates rivers alluvial plain are prefrontal and postfrontal dust storm; each (has own local name) occurs at a specific time in the life-cycle of migratory low-pressure area with a frontal system. Prefrontal dust storms occur across Jordan, Israel, the northern Arabian Peninsula, Iraq and western Khuzestan Plains of Iran, as low-pressure area move across the region. The polar jet stream (PJ) behind the front and the subtropical jet stream (STJ) in the front often converge into a single jet maximum that translate to the surface northeast of the upper-level maximum. These prefrontal winds are known as Sharki in Iraq and Kaus in Saudi Arabia (Middleton, 1986). In Baghdad, the Sharki and Kaus winds cause more than a third of all instances of blowing dust; easterly to southerly are the favored directions from October to April. Postfrontal dust storms are referred as a winter Shamal across most of Middle East. Locally, it is called Belat (Middleton, 1986) in southern Saudi Arabia. Since a front is a density current, vertical motions like in density current surges are also generated along the frontal zone. These horizontal and vertical vortices lift and suspend dust and sand particles.

Shear lines are another kind of frontal dust storm in Middle East, which is very frequent in winter and occur over west of Arabian Peninsula, the red sea and equatorial Africa. This kind of dust storm rarely occurs in Tigris and Euphrates River alluvial plain and cannot be a main type of dust storm in this area.

4. Results of synoptic analysis

There are nearly 60 major dust storms recorded between

2003 and 2011, with the Tigris and Euphrates River alluvial plain as the primary dust sources. These dust events are reported as natural hazards in Tigris and Euphrates River alluvial plain and are observed by MODIS (Moderate Resolution Imaging Spectroradiometer) as listed by NASA Earth Observatory (data available from http://earthobservatory.nasa.gov/NaturalHazards). The MODIS images are captured by Aqua and Terra satellite every day and are suitable data for our investigation. Among the 60 dust events, 12 representative cases have been selected for the synoptic analysis. The main reason for this selection is that, the affected areas by these dust storms are larger than Mesopotamian area. The dust plume propagated to the neighboring countries or to the Caspian Sea and some countries in its south, southeast and southwest coast. Amongst the 12 cases, 8 occurred between June and September and 4 in March and April.

Satellite images (listed by NASA Earth Observatory) show the worst situations of every dust storm. Therefore, the reported images are due to a certain date and time and is named natural hazard. Thus, 7 days before and 7 days after the dust storm image were selected to analysis and identify the active days of dust emission, which is important for this study. GRADS software and NCEP-NCAR (National Centers for Environmental Prediction/ National Center for Atmospheric Research) data were used to study the meteorological conditions and to determine the 10-m wind velocity during the dust storms. The NCEP/NCAR assimilated data are available from the NOAA website: http://www.esrl.noaa.gov. The results were used to identify the active days of dust emission. Then the situation for high and low pressure was investigated for those active dust emission days. In total, 180 daily data were used, in which each dust storm covers 7 days before and 7 days after the satellite image.

A composite analysis was carried out by averaging the flow field for all dust events in a given category to identifying the corresponding synoptic patterns. They are represented by using the mean sea-level pressure and 10 m wind (to characterize the surface pattern) and the geo-potential heights and wind vectors (to characterize 850 hpa patterns). In addition, the 2 m temperature data are used for supporting the analysis of frontal dust storms. Regardless of the type of dust storm (Shamal or frontal), the active dust sources in Tigris-Euphrates River alluvial plain (in dusty days) are defined when the 10 m wind speed exceeds the threshold velocity on predefined potential dust source areas (in this study, case 2). Based on Wilkerson (1991) investigations on dust storm in Middle East, the threshold velocity for fine materials and deserts can be assigned to 20-25 MPH (9-11 m s^{-1}). Therefore, the velocity of 10 m s^{-1} was selected as the mean threshold velocity.

GRADS software was used to display 850 hpa wind streamlines and then, those wind trajectories passing over the Tigris and Euphrates alluvial plain dust sources were identified. Backward and forward tracing of the wind trajectories for each dusty day helped to identify the high and low pressure areas, respectively. Additionally, the identified high and low pressure areas were also confirmed by the geopotential height shaded contours. Also, the 2 m temperature data were used to distinguish the frontal edge (considering the sharp changes in surface temperature) of the frontal dust storms.

a. Shamal dust storm

More than 72 days of Shamal dust storm with active emission in the Tigris and Euphrates alluvial plain are examined. The results lead to a map of highest frequency of high and low pressure systems, as shown in Fig. 2, which is involved in the Shamal dust storms. About 86% of the high pressure systems are located in three main regions and the rest of %14 in other areas. These 14% consist of places of anticyclones which are far from the mentioned region and their coordinates do not exist in the selected range. The high pressure systems extended from northern Africa to central Europe. These main areas consist of:

· SHP1: The region is located between 5°E to 30°E and 27°N to 37°N. Of the 86% high pressure systems, 43% is located in SHP1, placed in the north of Africa and south of Mediterranean Sea. The SHP1 region is the main place of anticyclones, which are centered in north of Libya. This area extends from north of Egypt to south of Tunisia and center of Libya to center of Mediterranean Sea.

· SHP2: Of the 86% high pressure systems, 25% of the high pressure system is positioned in SHP2, placed between 0°E to 25°E and 37°N to 45°N. This area extends from south of Bulgaria and east of Greece to east of Spain and south of France (east to west) and from south to north of Italy (south to north).

· SHP3: The third region of high pressure system in Shamal dusty days, SHP3, is located between 13°E to 38°E and 47°N to 55°N. In 18% Shamal dusty days, the high pressure system is placed on SHP3, which is centered on west of Ukraine. This area extended from east of Ukraine to east of Germany (east to west) and from Hungary to north of Poland (south to north).

Along with the high pressure systems, low pressure systems also play an important role in dust transport. About 90% of low pressure systems associated with the dust events are located in four areas. The remaining 10% are located outside of the study domain. The low pressure areas extend from north-west of the Persian Gulf to the Indian subcontinent. Figure 2 shows the areas of low pressure systems associated with the Shamal dust storms, which are:

· SLP1: The region with the highest frequency of low pressure system is located in central to southern Iran between 50°E to 60°E and 27°N to 35°N. This area extends from Sistan-Bluchestan to Khuzestan of Iran (east to west) and from north of Persian Gulf and Hormuz strait to center of Iran (south to north). In 44% of Shamal dusty days, the cyclone is positioned in SLP1.

· SLP2: In 19% of Shamal dusty days, the cyclone is positioned in SLP2. It is placed between 62°E to 68°E and 25°N to 32°N. This region consist of some parts of south-east

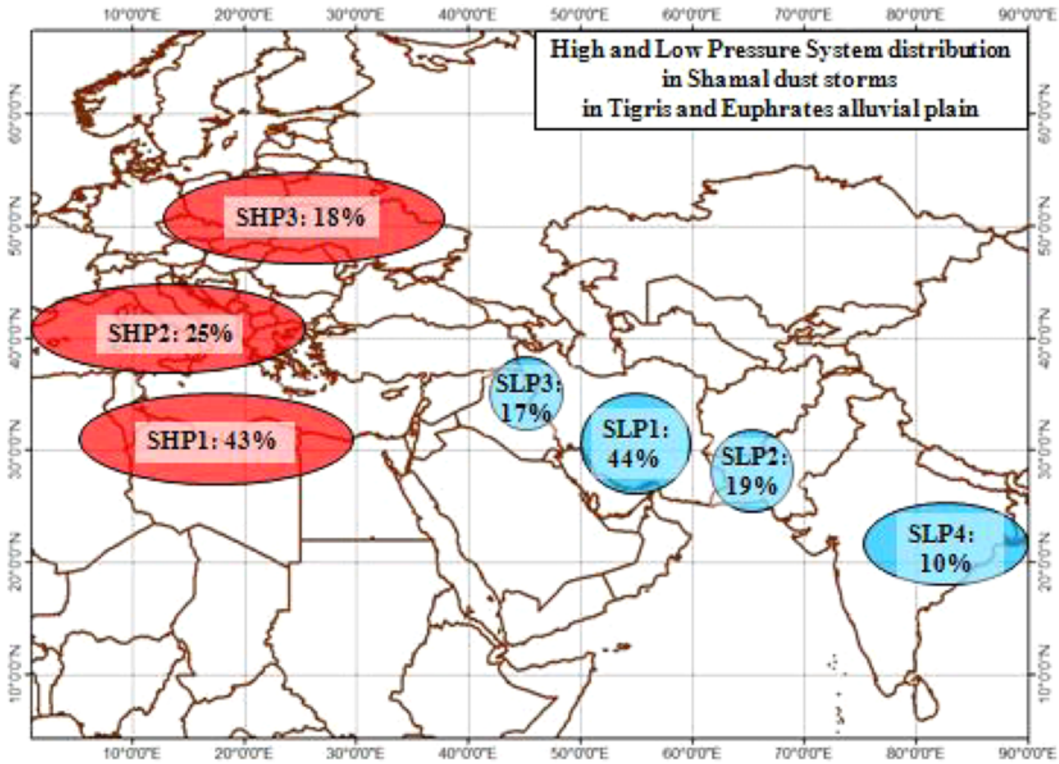

Fig. 2. High and low Pressure System distribution in Shamal dust storms in Tigris and Euphrates alluvial plain, Red areas show high pressure systems and Blue areas shows low pressure systems.

of Iran, south-west of Pakistan and south of Afghanistan.

· SLP3: It is the third region of low pressure system in Shamal dusty days, which is positioned between 43°E to 48°E and 33°N to 38°N. In 17% of Shamal dusty days, the low pressure system is placed on SLP3 area, which extends from west of Iran and north-east of Iraq to the center of Iraq.

· SLP4: In 10% of Shamal dusty days, the low pressure system is positioned in SLP4. It is placed between 75°E to 90°E and 18°N to 25°N. This region extends on north-east of India subcontinent with less frequency of occurrence.

Figure 3 depicts the three different types of synoptic pattern that lead to Shamal dust storms. On the left, the flow pattern and dust source regions are shown. Blue and red shaded area show respectively the position of low and high pressure systems and the orange shaded areas represent the possible dust source region in Tigris and Euphrates alluvial plain. Black shaded arrows show the basic flow fields. Occurrence frequency is also shown in the top-right side. Dust plumes are represented by yellow ellipses. On the right, the geopotential height of 850 hpa is shown. White vectors show the velocity magnitude of wind and its direction. The color bar presents geopotential height of 850 hpa in deka meter.

The synoptic patterns are classified into three types. The synoptic patterns classification is based on positioning of high and low pressure systems. We introduce 4 areas of low pressure systems, covering 90 percent of low system in shamal dust storms. Introducing the types of dust storm using three high pressure areas (SHP1, SHP2 and SHP3) and four low pressure areas (SLP1, SLP2, SLP3 and SLP4) provides 12 types of shamal dust storm. Therefore, it was decided to use one low pressure system and present just 3 main type of shamal dust storm to prevent any confusion. In other words, SLP1, SLP2, SLP3, SLP4 are combined and formed SLPM. The three types of synoptic pattern are as follows:

· Type 1: 29% of the Shamal dust storms belongs to this category. The main feature of Type 1 is the extension of a high pressure system over northern Africa and Libya (described in SHP1). The wind direction over the Tigris and Euphrates alluvial plain is northwesterly and westerly over Syria and Iraq and the emitted dust is transported to west and center of Iran by the westerly winds associated with the low and high-pressure systems. Because of the position of the cyclone, dust can be transported to east and north-east of Iran. The most destructive dust storms observed in Iran are associated with this synoptic pattern, e.g., the dust storm of July 2009.

· Type 2: 17% of the Shamal dust storms belongs to this category. The main feature of Type 2 is the extension of a high pressure system from south to south-east of Europe (described in SHP2). The wind direction over the Tigris and Euphrates alluvial plain is northwesterly and northerly over Syria and north of Iraq. The wind direction changes from north-westerly to westerly in west of Iran and dust may be transport to west and center of Iran by the westerly winds. A portion of the emitted dust may be transported to the southeast of the Arabian

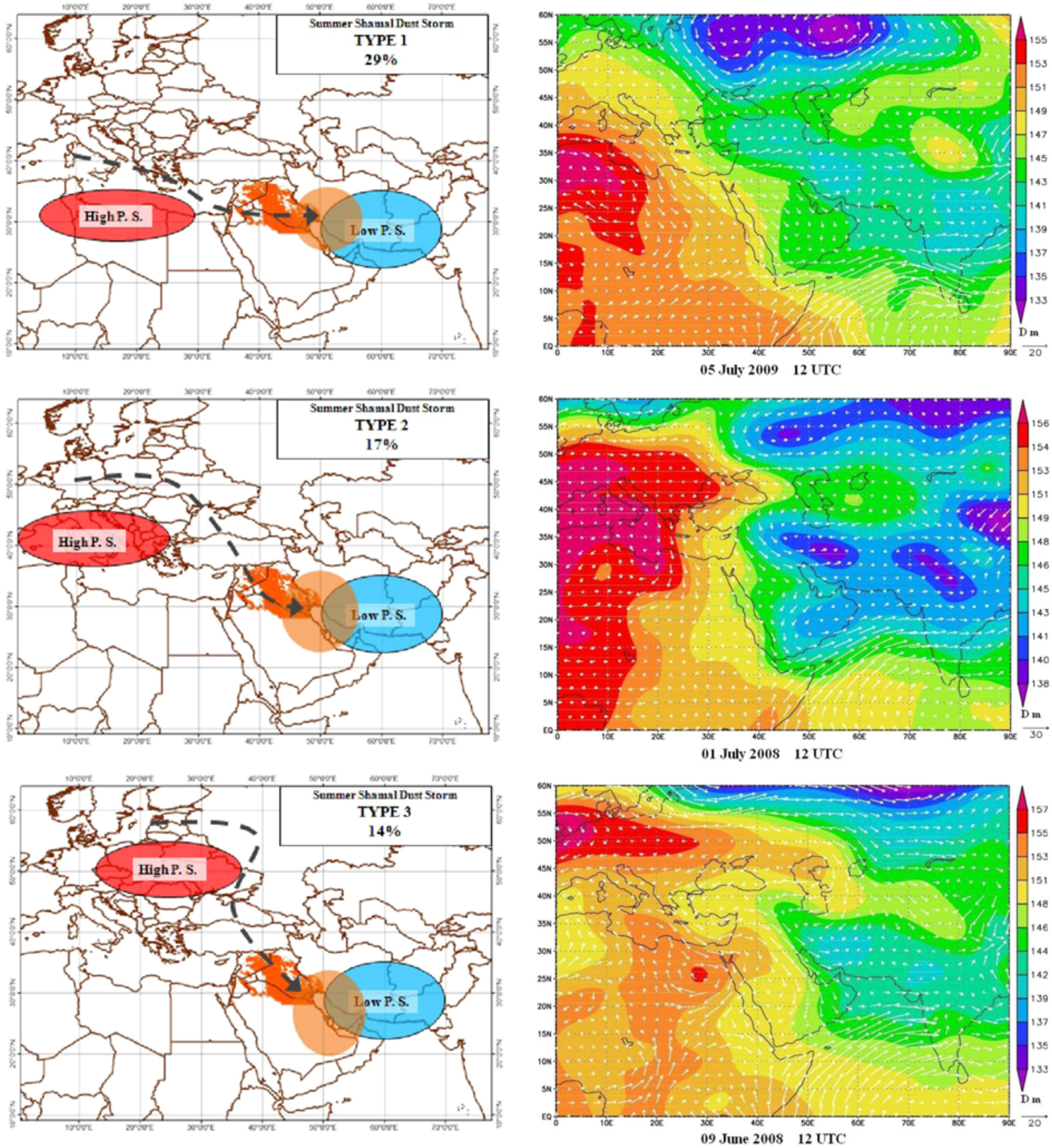

Fig. 3. Illustration of the different types of synoptic pattern, lead to Shamal dust storm, 5th July 2009 (Type 1), 1st July 2008 (Type 2), 9th June 2008 (Type 3). (Left): Flow pattern and dust source regions. Red and blue areas show respectively the high and low pressure systems. Orange area shows the dust source in Tigris and Euphrates alluvial plain and black shaded arrows show the flow fields. The resulted dust plume is represented by yellow ellipses. Occurrence frequency is shown in the top-right side. (Right): The geopotential height of 850 hpa and wind vectors. The color bar presents the 850 hpa geopotential height in deka meter. White vectors show the velocity magnitude of wind in m s^{-1} and its direction.

Peninsula and southern Iran by the north-westerly winds.

· Type 3: 14% of the Shamal dust storms belongs to this category. The main feature of Type 3 is the extension of a high pressure system from center to east of Europe (described in SHP3). The wind direction over Tigris and Euphrates alluvial plain is northwesterly and northerly over northern Iraq and dust is transported to the west, south-west and south of Iran by the north-westerly winds.

b. Frontal dust storm

More than 25 days of frontal dust storms with active dust emission from the Tigris and Euphrates alluvial plain are investigated and the areas of the highest frequencies of high

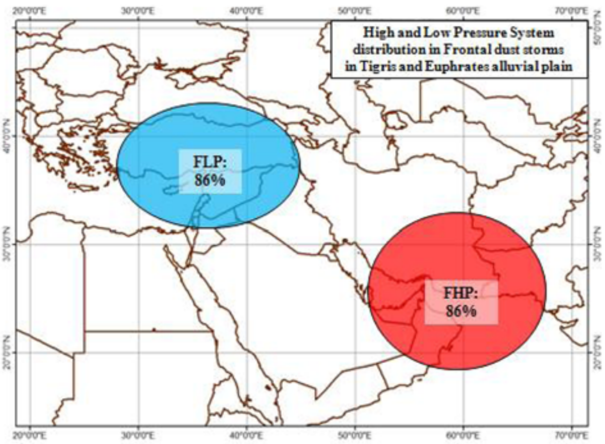

Fig. 4. High and low pressure system distribution in frontal dust storms in Tigris and Euphrates alluvial plain. Red areas show high pressure systems and Blue areas shows low pressure systems.

and low pressure systems associated with this type of dust storms are shown in Fig. 4. About 86% of the high and low pressure systems are grouped into a distinct region. The rest 14% are located outside of the study domain. The low pressure system is placed between 28°E to 48°E and 32°N to 43°N (FLP). This region extends east to west from north-west of Iran to west of Turkey and south to north from north of Jordan and east of Mediterranean Sea to center of Black Sea. The corresponding high pressure system is placed between 51°E to 67°E and 18°N to 33°N (FHP). This region extends east to west from south and south-west of Pakistan to west of Qatar and south to north from east of Oman to west of Afghanistan and east of Iran. About 82% of the frontal dust storms are associated with this distinct synoptic pattern.

Figure 5 shows a schematic illustration of the synoptic pattern together with a real example on 25th March 2003. On the left, the flow pattern and dust source regions are shown. Red and blue areas show respectively the high and low pressure systems. Orange area shows the dust source and black shaded arrows show the flow fields. The resulted dust plume is represented by yellow ellipses. Occurrence frequency is also shown in the top-right side. On the right, the geopotential height of 850 hpa is shown. White vectors show the velocity magnitude of wind and its direction. The color bar presents geopotential height of 850 hpa in deka meter. This pattern generates prefrontal dust storms in southern Iraq, Kuwait and the Khuzestan Plain of Iran. The most famous postfrontal dust storm is a Winter Shamal dust storm that occurs in central and northern Iraq. Due to the direction of frontal winds, the emitted dust can be transported north-eastwards to western and central Iran and in some severe cases; the dust plume reaches the south coast of the Caspian Sea. According to the synoptic analysis, the frontal edge extends from south-east of Red Sea to north-west of Persian Gulf in 68% of the analyzed frontal dust storms.

5. Summery and conclusions

This study presents a climatological analysis and synoptic classification of dust pattern in the Middle East, with a focus on the Tigris and Euphrates alluvial plain. Analysis was done by using the NCEP-NCAR Reanalysis Data, based on 12 severe dust storms in the region from 2003 to 2011. These severe cases were selected from 60 major dust activities, reported by NASA. Additionally, potential dust sources in the Middle East and south-west of Asia (20°E to 80°E longitude and 5°N to 50°N latitude) were presented and used in the synoptic analysis. Synoptic scale dust storms in the Middle East were classified in two main categories: Shamal (Summer Shamal) and frontal dust storms.

Shamal is the main type of synoptic dust storms in this region. The highest frequency of Shamal is in June and July. High and low pressure system placement has been analyzed in

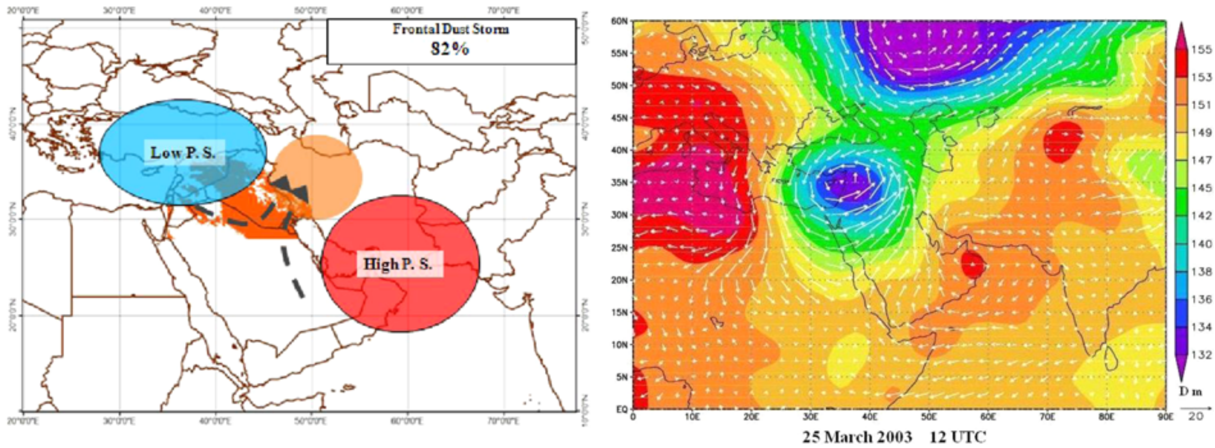

Fig. 5. Illustration of the different types of synoptic pattern, lead to frontal dust storm, 1200 UTC, 25th March 2003. (Left): Flow pattern and dust source regions. Red and blue areas show respectively the high and low pressure systems. Orange area shows the dust source in Tigris and Euphrates alluvial plain and black shaded arrows show the flow fields. The resulted dust plume is represented by yellow ellipses. Occurrence frequency is shown in the top-right side. (Right): The geopotential height of 850 hpa and wind vectors. The color bar presents the 850 hpa geopotential height in deka meter. White vectors show the velocity magnitude of wind in m s^{-1} and its direction.

this study and the regions with 86% of the high pressure system and 90% of the low pressure system positioning was distinguished. The high pressure systems associated with 68% of the dust storms are located between 0°E to 30°E and 27°N to 45°N extending east to west from north of Egypt to east of Spain and south of France and south to north from center of Libya to north of Italy. Also, low pressure systems in 67% of dust storms located between 50°E to 70°E and 23°N to 43°N (SLPM) extending from center of Pakistan to north-west of Persian Gulf (east to west) and from north-east of Oman to north-east of Iran and south-east of Turkmenistan (south to north). Three main patterns for Shamal dust storm were identified. About 60% of Shamal dust storms can be classified in these three main types. This analysis confirms that the Shamal dust storm incorporates with Anticyclones over north of Africa to east of Europe and Monsoon trough over Iraq, south of Iran and Pakistan and India subcontinent. In other words, the Monsoon trough is the main low pressure systems with special affects in formation of destructive dust storms. The main region of dust sink of Tigris and Euphrates alluvial plain extends from center of Iraq and south-west of Iran to south and center of Pakistan.

The highest frequency of frontal dust storm is in March and April. High and low pressure system placement in frontal dust storm was analyzed and regions with 86% of high and low Pressure system positioning were distinguished. Due to this classification, high pressure systems in 86% of frontal dust storms are located between 51°E to 67°E longitude and 18°N to 33°N latitude (FHP) extending from south and south-west of Pakistan to west of Qatar (east to west) and from east of Oman to west of Afghanistan and east of Iran (south to north). Also, the low pressure systems in 86% of dust storms located between 28°E to 48°E longitude and 32°N to 43°N latitude (FLP). This region extends from north-west of Iran to west of Turkey (east to west) and from north of Jordan and east of Mediterranean Sea to center of Black sea (south to north). The main pattern for frontal dust storm was identified, which is able to classify 82% of these dust storms. The analysis shows the main dust sink for frontal dust storms in Tigris and Euphrates alluvial plain is extended from center of Iraq to west, center and north of Iran and south coast of Caspian Sea.

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