BIROn - Birkbeck Institutional Research Online

Al Ameri, I.D.S. and Briant, Rebecca and Engels, Stefan (2019) Drought severity and increased dust storm frequency in the Middle East: a case study from the Tigris-Euphrates alluvial plain, Central Iraq. Weather , ISSN 1477-8696. (In Press)

Drought Severity and Increased Dust Storm Frequency in the Middle East: a case study from the Tigris-Euphrates alluvial plain, Central Iraq

Ismael D. S. Al Ameri[1] (*ismaelalameri@gmail.com*), Rebecca M. Briant[2], Stefan Engels[2]

1. Department of Geography, Ibn Rushd, University of Baghdad, Bab Al-Muadham Campus, Iraq
2. Department of Geography, Birkbeck, University of London, Malet Street, London, WC1E 7HX, UK

Abstract

An increase in dust and sand storms has been experienced in Iraq over recent times and seems likely to increase further under future climate change. Iraq is now known as a highly active source region of dust. The impact of dust storms affects most of Iraq and extends to include large parts of Iran, Kuwait, Saudi Arabia, and the Arabian-Persian Gulf. Dust storms are a regional strategic problem for arid and semi-arid regions that have an impact on many different aspects of human life. The problem has been exacerbated by high temperatures and changing precipitation distribution patterns and has resulted in many direct environmental impacts. These include agriculture, food security, rural-urban migration, changes in the pattern of land use, effects on biodiversity and negative health effects of air pollution. It is therefore important to describe dust storm frequency and determine which climatic factors are most significant in driving dust storm fluctuations in order to take the necessary measures to avoid or reduce these negative environmental effects. This paper explores the relationship between drought, wind speed and dust storms in Iraq, including their emergence, frequency and extent. Drought was determined using the Standardized Precipitation Index (SPI) applied to 36-year–long datasets (1977 to 2012) from four locations (Baghdad, Hai in Wasit, Diwaniyah, Nasiriyah in Thi Qar, all in central Iraq). Drought intensities have increased significantly from 2008-2012 in all weather stations, coincident with high dust frequencies. Comparison of monthly wind speed and dust variables for the four weather stations all showed statistically significant relationships, indicating that wind speed is associated with dust storms of all kinds in arid and semi-arid regions such as Central Iraq.

Keywords: Drought, Meteorological Drought, Standardized Precipitation Index (SPI), Suspended dust, Rising dust, Dust storms.

1. Introduction

Dust storms can remove vast amounts of topsoil, destroy crops, grasslands and roads, and can result in rapid desertification of arid and semi-arid regions. As such, dust storms can cause significant environmental and economic damage. Furthermore, dust storms have a negative effect on human health through air pollution (Zou and Zhai, 2004; Liu et al., 2006). The impact of dust storms on public health is likely to increase as extreme weather events are predicted to become more frequent with projected changes in climate throughout the 21st century (Crooks et al., 2016).

Dust storms are a common phenomenon in the Middle East, most frequently occurring across Iraq, Saudi Arabia, and the Persian (Arabian) Gulf (Kutiel and Furman, 2003; Ginoux et al., 2012). One of the major sources of the dust transported during these events is Iraq, where the Mesopotamian plain and areas dominated by dry climate, such as the western plateau and some sections of the sedimentary plain, are especially vulnerable to wind erosion (Figure 1a). Other regional dust sources in the Middle East are the Great African Desert, the Sinai Peninsula, the desert of Sham and the deserts of the Arabian Peninsula.

Iraq is considered one of the region’s most vulnerable countries to climate extremes. It faces a complex set of environmental challenges, including rising environmental degradation and increasing frequency and intensity of extreme weather events, especially sand and dust storms (JAPU, 2014).

Dust and sand storms are a persistent problem in Iraq and other areas in the Middle East, showing distinctly seasonal patterns of recurrence with strong dust activity in spring and summer, and weakened activity in autumn (Prospero et al., 2002). When surface winds are strong, large amounts of sand and dust can be lifted from bare, dry soils into the atmosphere and transported downwind affecting regions hundreds to thousands of kilometres away (Zoljoodi et al., 2013). The fine sediments of the Tigris and Euphrates floodplains provide ample material for massive dust storms and the dust storms affect most of Iraq (e.g. Al-Asadi and Al-Marsoumi, 2010; Figure 1a), as well as large parts of the Middle East (e.g. Middleton, 1986; Figure 2) and beyond (e.g. Galvin et al., 2011). There are two main types of active winds in Iraq:

First, south and southeasterly winds called “sharqi” are dusty winds often accompanied by sand storms. Sharqi are most prevalent during the spring and summer months as their occurrence is linked to the occurrence of strong winds during the winter-spring seasonal transition (Sissakian et al. 2013). Dust storms are most frequent in the periods April-June and September-November as the result of strong turbulent wind systems entraining particles of dust into the air, so that visibility is reduced to less than 1000 m (Qian et al., 2001).

Second, northwesterly winds called "shamal" are active in the dry period between June and September (e.g. Rao et al., 2001; 2003). A strong northerly Shamal wind can lift up dust from the Tigris-Euphrates Basin of Iran/Iraq and transport it to the Persian Gulf and Arabian Peninsula (Notaro et al., 2013). Dust can occur in both stable and unstable weather conditions during the ‘Shamal-season’. During stable weather conditions dust is generated at the time of sea-level reversal at 500-1000 metres elevation due to air falling from the upper atmosphere. In unstable weather conditions dust will be trapped by air fronts causing increased wind speed and spreading dust horizontally and vertically.

Besides wind strength and direction, seasonality of precipitation can play an important role in determining the frequency and severity of dust activity (Marsham et al., 2016). Soil moisture increases the cohesion of particles and thus decreases the rate of dust phenomena. Therefore, dust storms occur mainly during periods of strong winds and low precipitation (Dagsson-Waldhauserova et al., 2014) and are most commonly caused by strong pressure gradients which cause an increase in wind velocity over a wide area (Zoljoodi et al., 2013). In general, the probability of dust storms is higher when relatively cold air masses move over relatively warm ground, causing the bottom layers of the air mass to become unstable.

The main type of rainfall in central Iraq is frontal rainfall from systems that originate in the Mediterranean region during the winter, moving east across northern Iraq before changing to a southerly direction (Shubbar et al., 2016). The passage of Mediterranean low pressure systems gives rise to rain during winter and spring, particularly in Baghdad, Tehran and Amman (Babu et al., 2011). Changes in pressure systems between low (Indian monsoon low, Sudan low) and high (Subtropical High and Siberian High Pressure) also play an important role on the climate across the entire Arabian Peninsula (Hasanean and Almazroui, 2015).

Precipitation is one of the most important water resources in arid and semi-arid regions (Huang et al., 2014). Whilst drought has had a significant impact on civilizations throughout history, it is one of the most difficult phenomena to measure or even to define (Heim Jr., 2012). Drought can occur for one year (meteorological drought – Kumar et al., 2009) or for several years. Since the damage caused by drought (e.g. to agriculture, surface and groundwater resources and biodiversity) is dependent on severity, quantification of drought severity should be the first consideration when analysing drought climatology (Kim et al., 2011).

A functional and quantitative definition of drought can be calculated for a certain location using the Standardized Precipitation Index (SPI; McKee et al., 1993), providing a means to track meteorological drought and to objectively determine the severity of this meteorological drought. A location’s SPI can be calculated from the long-term record of precipitation over a period of at least 30 years (Charusombat and Niyogi, 2011). SPI is based solely on precipitation data and is recommended as the standard by the World Meteorological Organization (Hayes, 2011).

Climatic variables such as temperature, precipitation and wind speed are all projected to change under future climate change scenarios (IPCC, 2013). Increased drought is identified as a particular problem for arid and semi-arid regions and the frequency of dust storms is expected to increase as a result. Dust has an important influence on climate at both regional and global scales (Field et al., 2010). At regional scales, dust can have a substantial effect on the atmospheric radiative balance and the concentration of condensation nuclei, both of which can influence climate variability via effects on surface temperatures and precipitation patterns (Yoshioka et al., 2007). Detecting dust phenomena, identifying their sources and surveying their movements and location can help decision makers in planning to reduce damage arising from these phenomena (Samadi et al., 2014).

The response of dust storm frequency to drought severity has not previously been investigated for Central Iraq. Given the disruption described above caused by dust storms, it is important to know which climatic factors are the most significant drivers of dust storm frequency. The aim of the present study is therefore to investigate the long-term weather trends in central Iraq and to assess what the drivers of dust storm frequency are. We present multi-decadal records of weather and dust events for four weather stations located in Central Iraq, a region that is particularly vulnerable to dust storms and show that, besides drought, further climatic variables are required to explain the recent increase in frequency of dust events in arid and semi-arid regions.

2. Materials and Methods

2.1. Dust and weather observations

Dust storm occurrences in Central Iraq are reported by the Iraqi Meteorological Organization and Seismology (IMOAS) on the basis of measurements of horizontal visibility and wind speed. Visibility is defined as the greatest distance in a given direction at which an object can be visually identified with unaided eyesight (Wark et al., 1998). Visibility as a standard meteorological parameter is regularly measured at synoptic meteorological stations worldwide. It is determined mostly by the extinction of light by aerosol particles and a reduction of horizontal visibility might occur because of atmospheric phenomena such as dust, fog or heavy rain (Miri et al., 2010). The dust data used in this study consist of monthly data of frequency of dust (in number of days per month for three different dust types) for the period from 1977 to 2012 for four weather stations in the study area of the governorates in central Iraq (Figure 1b; Table 1): Baghdad, Hai in Wasit, Diwaniyah, and Nasiriyah in Thi Qar.

The dust observations are classified in three categories: first 'dust storms' are severe natural disaster events that frequently occur in arid and semi-arid regions (Yang et al., 2007). Dust storms occur when small particles are lifted up by winds of more than 8 m/s, reducing horizontal visibility to less than 1 km (IMOAS, 1987). Second, 'rising dust' is defined by IMOAS (1987) as consisting of small particles with diameters ranging from 1-10 micrometres and a range of horizontal visibility from 1 to less than 10 kilometres (IMOAS, 1987). These dusty winds result from the disintegration of surface soils in arid and semi-arid areas due to a lack of natural vegetation and a lack of rainfall. This type of dust occurs when changes in the strength of the pressure gradient lead to air vortexes that lift dust particles upward. Rising dust can also be caused by convection activity, occurring when two currents with different thermal properties meet, leading to wind turbulence. The continuity of rising dust is related to the ongoing instability of the air. Our third category of dust, 'suspended dust', appears after dust storms. Particles of less than 1 micrometre diameter remain in the air for several hours or days with winds of less than 8 m/s and horizontal visibility ranging from 0 to less than 10 km (IMOAS, 1987). Most of the particles in suspended dust are mud and silt which remain suspended in the air from several hours to several days, depending on the severity of the preceding dust storm. The effect of gravity on these small particles is weak even when winds are light or non-existent. Suspended dust affects ecosystems through the amount of sunlight that is reflected and absorbed by it.

Monthly average precipitation and wind speed data were also obtained from the Iraqi Meteorological Organization and Seismology (IMOAS) for the period from 1977 to 2012 from the same four weather stations from which the dust data was collected.

2.2. Numerical analysis

SPI was calculated for each weather station by fitting a gamma distribution function to the frequency distribution of precipitation totals, and then transforming the gamma distribution to a normal distribution (Charusombat and Niyogi, 2011). A drought event is defined here as a period in which the SPI is continuously negative, reaching a value of -1.0 or less. Drought begins when the SPI first falls below zero and ends with a positive value of SPI (Table 2). Pearson correlation coefficients were calculated for the relationship between wind speed and dust type frequency for each weather station. The calculations were all performed in SPSS Statistics version 23, and Microsoft Excel 2010.

3. Results and interpretation

3.1. Dust and weather observations

3.1.1. Monitoring data

The annual rainfall rates and totals from the four weather stations (Figure 3) show that rainfall in central Iraq is concentrated in the winter months. The rainy season runs from mid-October to mid-May and reaches its peak in January or February. Most of the rain that reaches Iraq comes from the Mediterranean climate zone, although absolute amounts of precipitation are low. Most of Iraq is characterized by low rainfall and close to a desert climate or a desert steppe climate.

3.1.2. SPI analysis

SPI analysis on our 36-year-long rainfall dataset shows that the number of wet years was considerably lower in Baghdad (9 seasons, 25%) than at Hai (15 seasons, 41%), Diwaniyah (14 seasons, 39%), and Nasiriyah (16 seasons, 45%). This is mirrored in the number of dry years at each station, which was also higher in Baghdad (27 seasons, 75%) than at Hai, Diwaniyah, and Nasiriyah. Whilst dry years are more frequent than wet years the most frequent drought severity class is mild drought, while severe drought and severe humidity are very rare (0-6%; Table 2; Figure 4).

At all stations (Table 3 to 6), dust events of all types are more common when SPI values are more negative. The results also show that drought intensities have increased significantly, with the most recent 5 years (2008-2012) recorded as dry in all four weather stations. This drought severity coincided with high frequencies in different observed dust types. However, since all stations in the study area are dominated by drought conditions for the full 36 year period, a further driving factor such as wind activity must be involved to explain the detailed patterns of changes in incidence of rising dust, suspended dust and dust storms.

3.2. Relationship between dust types and wind speed

To compare dust event frequency and wind speed, scatter plots of monthly dust event frequency and average wind speeds (Figures 4-16) were constructed and Pearson correlation coefficients calculated (Table 7). There is a statistically significant positive correlation between wind speed and dust storms at Baghdad weather station (Table 7, Figures 5-7), with correlation coefficients of 0.785, 0.963 and 0.805 for dust storms, rising dust and suspended dust, respectively. There also is a positive correlation between all dust types. The strong correlation between rising dust and wind speed shows that the area is vulnerable to drought and will be an active source for rising dust if drier conditions occur in the region in future.
At Hai weather station, there is a statistically significant positive correlation between wind speed and all three types of dust (Table 7, Figures 8-10). The correlation coefficient was 0.578 for dust storms, 0.963 for rising dust and 0.784 for suspended dust. Rising dust shows a strong correlation with wind speed, confirming that the region is affected by dryness and little vegetation cover, and that it is an effective exporter of rising dust. The correlation coefficient for dust storms was lower than those for other types of dust, suggesting reasons other than wind speed as a driving factor.
At Diwaniyah weather station, there is a statistically significant positive correlation between wind speed and rising dust (0.924) and wind speed and suspended dust (0.803) only (Table 7, Figures 11-13). The correlation between dust storms and wind speed was much lower at 0.371. This clearly shows that the occurrence of dust storms at Diwaniyah weather station is

affected by regional anticyclones and depressions, whereas the occurrences of rising and suspended dust are affected by local factors such as wind speed.

The Nasiriyah weather station data shows statistically significant strong positive correlations between wind speed and all dust types (Table 7, Figures 14-16). The correlation coefficients were 0.983, 0.980 and 0.897 for dust storms, rising dust and suspended dust, respectively. All dust types are higher in Nasiriyah than in the other stations because of the strong influence of northwesterly winds, particularly during the hot season. These winds often come from areas where the soil is dry and easily transported from these source regions towards our study area. In addition, the existence of two ranges of sand dunes in the western and southern sections of the province of Dhi Qar probably increases the frequency of dust phenomena, especially with northwest and southwest winds. Our results clearly show the effect of wind speed on all types of dust occurrence. Vegetation degradation in this drought-dominated region with dry, fragile, unstable soil makes this area an effective source of dust because the soil does not have the strength to resist the erosive effects of wind.

4. Discussion

4.1. Wind dynamics and dust events in Central Iraq

An important reason for the occurrence of dust storms in Iraq, whose land is characterized by surface dryness due to a lack of rainfall, is the passage of depressions in late winter. The movement of these depressions and cold fronts, accompanied by strong cooling in the upper atmosphere, cause dust and sand to be carried across a number of countries in the Middle East. The intensity of the storms depends on the depth of the atmospheric depression, which affects the speed of the cold front. Three main conditions are identified as drivers of dust storms: high wind speeds, instability in the lower troposphere, and a dry land surface to provide a dust source (Zou and Zhai, 2004). All the weather stations studied in central Iraq showed positive statistically significant correlations between wind speed and dust frequency, indicating that wind speed is associated with all kinds of dust in arid and semi-arid regions characterized by repeated droughts.

The most common type of dust in our dataset is rising dust (Tables 3 to 6). Dust rises when two currents with different thermal properties meet, leading to turbulence in the air column that causes dust to rise. Alternatively, dust can rise due to high temperatures creating low atmospheric pressure, leading to convection activity in arid and semi-arid areas where there is dry soil, poor vegetation cover, and erodible sediments. Rising dust had a strong positive correlation with wind speed (0.924-0.980) in all our records, indicating that in Central Iraq wind speed is indeed a strong forcing factor of rising dust.

Suspended dust may be the result of dust storms occurring elsewhere as well as close to the weather station, since these fine dust particles (consisting mainly of clay and silt - less than 2 µm and less than 0.1 mm in diameter) can be transported significant distances from their source (UNEP, 2013), even by low wind speeds for up to 1-15 hours. Fine particles (particulate matter smaller than 2.5 µm in diameter) can travel further than coarser dust (particulate matter between 2.5 µm and 10 µm in diameter) (Araujo et al., 2014). Suspended dust also showed a strong positive correlation (0.784-0.897) with wind speed in our records. Dust storms showed a weaker correlation with wind speeds than that observed for the other dust types, with results ranging from 0.371 at Diwaniyah to 0.983 at Nasiriyah. This is likely because the pressure systems that generate dust storms are not always characterised by high wind speeds. The climate of Iraq is affected by a range of pressure systems, including low pressure systems such as Mediterranean Frontal Depressions, the Sudan Low, the

Combined or Incorporated Depression, the Indian Monsoon Low, and thermal depressions. Dust storms in the summer are associated most commonly with the Indian Monsoon Low, the Sudanese low and domestic systems. Dust storms can also be generated by high pressure systems (anticyclones), such as the Azorean High, Siberian High, and European High. Anticyclones are associated with frequent stillness, because the pressure gradient is usually low, which can reduce wind speeds and thus reduce the correlation between dust storms and wind speed.

There is a particularly low correlation between wind speed and dust storms in the Diwaniyah weather station, which is characterized by abundant surface water suitable for agriculture from sources such as the Euphrates, Shatt Diwaniyah, Shatt Daghara, Shatt Shamiya and Shatt Kufa. The large areas of agricultural land irrigated by these rivers and streams result in low availability of sediment for transportation, and thus lower dust storm frequency. This is despite the strong correlation between wind speed and rising dust, and between wind speed and suspended dust at this meteorological station because these two types of dust come from areas adjacent to the station rather than the station itself.

In contrast, Nasiriyah, which lies on the fringes of the desert region, is characterized by a large number of mobile sand dune belts north of Nasiriyah and the neighbouring province of Samawah, and these dunes provide a large amount of sediment available for transportation, which likely accounts for the strong correlation between wind speed and dust storms at this station.

The strong correlation between dust storms and wind speed at the Baghdad station is also due to the local presence of large sources of dust. This includes the Anbar province, which covers the largest deserts in Iraq, as well as the other provinces surrounding the capital, which are characterized by the existence of large areas of mud deposits and alluvium from river origin (Figure 1a).

Hai weather station showed only an average correlation between wind speed and dust storms, which is most likely due to the presence of marshes as well as large areas of agricultural land surrounding the province. Indeed, the area is characterized by a large number of streams branching out of the Tigris River, as well as by the existence of the Dalmaj and Shuwayja marshes. The availability of these water resources increases the number of agricultural areas, as well as presence natural dense of trees and shrubs on the banks of rivers and streams.

4.2. Drought events and dust events

Drought events, referring to the condition of an insufficient supply of water necessary to meet the demand, are believed to increase dust events, especially in sand and dust storm source areas (Zoljoodi, 2013). However, this study has shown that in central Iraq, drought is an insufficient explanation for the changes that are observed in dust storm frequency. The SPI results clearly show that most of the years in the 36 year long records are classified as drought years and that the wetter periods are never more than four years long. Such relatively short wet periods will not fundamentally affect the growth of natural plants and soil moisture content. In addition, in arid and semi-arid areas such as Iraq, all wet seasons are short in duration, and combined with high temperatures and evapotranspiration rates, do not have any significant effect on natural plant growth or soil moisture. Due to the high evaporation rate, especially if precipitation is not effective, mild and moderate humidity seasons become similar to seasons of mild drought.

Therefore, as the water balance in this region is probably always negative, even during 'wet' years sediment will be available to be transported as dust. This is a problem with regard to projections of future increases in aridity as projected by climate models, because vegetation cover is one of the most important factors for the reduction of dust storm occurrence (Ishizuka et al., 2005) and sparsely vegetated dry lands are an important source of dust emissions (Sofue et al., 2009).

4.3. Outlook

Arid and semi-arid areas in Iraq and the whole of the Middle East are characterised by dry climate, low rainfall, low natural vegetation, vast desertified areas, and soil degradation. They all contain large areas of land that are identified as river bed sediments, alluvial fans, marsh sediments and deserts. These can all serve as potential dust source regions, especially in the long dry summer which is characterized by high temperatures and increased evaporation rates. In such areas, dust storms cannot be prevented, but their atmospheric and terrestrial effects can be reduced through the development of strict environmental regulations aimed at protecting the natural environment. Dust emissions from human activities can be reduced using temporary mechanical methods such as concrete barriers, tree belts and increased vegetation that helps stabilize the soil and sand dunes. Windbreak trees can reduce the speed of wind, sand and drifts that impact the soil due to wind intensity. Controlled use of surface water, wastewater treatment, prevention of logging and a change of agricultural and pastoral areas to residential areas can further help to reduce dust emissions.

Drought, desertification, soil degradation and dust storms are the most prominent features of climate change in the Middle East. The West Asia Region, especially the Tigris-Euphrates alluvial plain, has been recognized as one of the most important dust source areas in the world (Cao et al., 2015) due to its high temperatures, low rainfall, drought and the deterioration of the agricultural sector. Dust storms are a transboundary problem, and the affected countries in the Middle East should build regional cooperation to review the environmental components and try to rehabilitate the region through a focus on comprehensive assessment of the causes and effects of dust storms at national and regional levels.

5. Conclusions

Standardized Precipitation Index (SPI) values for four weather stations (Baghdad, Hai in Wasit, Diwaniyah, Nasiriyah in Thi Qar) in Central Iraq spanning a period of 36 years, from 1977 to 2012, are presented. The results show that drought intensities have increased significantly, with 5 dry years (2008-2012) recorded in all weather stations. This drought severity coincided with high frequencies in different observed dust types. The percentage of dry years in the study area for the period from 1971 to 2012 was high, reaching 75%, 59%, 61%, and 55% in the weather stations at Baghdad, Hai, Diwaniyah, and Nasiriyah respectively. All weather stations in the study area therefore showed a permanent deficit in their water budget, which is associated with an acceleration in desertification and land degradation.

A statistical comparison of the three dust types used in this study (rising dust, suspended dust and dust storms) and wind speed shows that:

A. There is a strong, statistically significant, positive correlation coefficient between suspended dust and wind speed for all four weather stations: Baghdad (0.805), Hai (0.784), Diwaniyah (0.803) and Nasiriyah (0.897).

B. There are strong positive correlation coefficients between rising dust and wind speed at all four weather stations: Baghdad (0.963), Hai (0.963), Diwaniyah (0.924) and Nasiriyah (0.980).

C. Whilst positive correlation coefficients were also found when comparing dust storms and wind speed, these varied in their strength: Baghdad (0.785), Hai (0.578), Diwaniyah (0.371) and Nasiriyah (0.983).

The variation between correlation coefficients occurs because of the varying impact of synoptic-scale and regional anticyclones and depressions. Local factors associated with wind speed and vegetation cover will impact the correlation coefficients as well, because regions with dry soils and poor vegetation are more sensitive to wind movement. Iraq has substantial sources of dust, including areas such as river bed sediments, alluvial fans, marsh sediments and deserts. Dust emissions are dependent on the soil erodibility by wind erosion. For this reason, dust emission variability is mainly dominated by wind speed.

Acknowledgments

The authors wish to thank two anonymous reviewers for their constructive comments, which greatly improved this manuscript. We thank Dr Aideen Foley, Department of Geography, Birkbeck, University of London, whose useful comments on an early draft of the paper helped to improve the manuscript.

References

Al-Asadi M, Al-Marsoumi A. 2010. Dust Storms and their environmental impacts at the North West Part of Arabian Gulf. *J. Iraqi Desert Studies*, **2**: 43-53.

Araujo I, Costa D, Moraes R. 2014. Identification and Characterization of Particulate Matter Concentrations at Construction Jobsites. *Sustainability*, **6:** 7666-7688.

Babu C, Samah A, Varikoden H. 2011. Rainfall Climatology over Middle East Region and its Variability. *Internat. J. Water Resources Arid Environm.,* **1**: 180-192.

Cao H, Amiraslani F, Liu J, Zhou N. 2015. Identification of dust storm source areas in West Asia using multiple environmental datasets. *Sci. Total Environm.*, **502**: 224–235.

Charusombat U, Niyogi D. 2011. A Hydroclimatological Assessment of Regional Drought vulnerability: A Case Study of Indiana Droughts. *Earth Interact.*, **15**: 1-65.

Crooks J, Cascio W, Percy M, Reyes J, Neas L, Hilborn E. 2016. The Association between Dust Storms and Daily Non-Accidental Mortality in the United States, 1993–2005. *Environm. Health Persp.* **124**: 1735–1743.

Dagsson-Waldhauserova P, Arnalds O, Olafsson H. 2014. Long-term variability of dust events in Iceland (1949–2011). *Atmos. Chem. Phys.,* **14**: 13411–13422.

Field J, Belnap J, Breshears D, Neff J, Okin G, Whicker J, Painter T, Ravi S, Reheis M, Reynolds R. 2010. The ecology of dust, Front Ecol Environ, **8:** 423–430.

Galvin J, Black I, Priestley D. 2011. Mesoscale weather features over the Mediterranean: Part 1. *Weather*, **66**: 72-78.

Ginoux P, Prospero J, Gill T, Hsu N, Zhao M. 2012. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Rev. Geophys*., **50**: RG3005.

Hasanean H, Almazroui M. 2015. Rainfall: Features and Variations over Saudi Arabia, A Review. *Climate*, **3**: 578-626.

Hayes M, Svoboda M, Wall N, Widhalm M. 2011. The Lincoln Declaration on Drought Indices: universal Meteorological drought index recommended. *Bull. Am. Meteorol. Soc.*, **92:** 485-488.

Heim J, Brewer M. 2012. The Global Drought Monitor Portal: The Foundation for a Global Drought Information System. *Earth Interact.*, **16**: 1-28.

Huang J, Wang T, Wang W, Li Z, Yan H. 2014. Climate effects of dust aerosols over East Asian arid and semi arid regions, *J. Geophys. Res. Atmosph.*, **119**: 11,398–11,416.

Iraqi Meteorological Organization and Seismology (IMOAS). 1987. Dust phenomena, Baghdad, Iraq.

Intergovermental Panel on Climate Change. 2013. *Climate Change 2013: The Physical*

Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge (UK).

Ishizuka M, Mikami M, Yamada Y, Zeng F, Gao W. 2005. An observational study of soil moisture effects on wind erosion at a Gobi site in the Taklimakan Desert. *J. Geophys. Res*., **110**: D18S03.

Joint Analysis and Policy Unit JAPU. 2014. *Sand and Dust Storms Fact Sheet*. UN: Iraq.

Kim D, Byun H, Choi K, Oh S. 2011. A Spatiotemporal Analysis of Historical Droughts in Korea. *Am. Meteorol. Soc.*, **50:** 1895-1912.

Kumar M, Murthy C, Sai M, Roy P. 2009. On the use of Standardized Precipitation Index SPI for drought intensity assessment. *Meteorol. Appl.*, **16**: 381–389.

Kutiel H, Furman J. 2003. Dust storms in the Middle East: Sources of origin and their temporal characteristics. *Indoor and Built Environm.*, **12**: 419–426.

Liu M, Westphal D, Walker A, Holt T, Richardson K, Miller S. 2006. COAMPS Real-Time Dust Storm Forecasting during Operation Iraqi Freedom. *Weather Forecasting*, **22**: 192-206.

Marsham H, Parker D, Todd M, Banks J, Brindley H, Carreras L, Roberts A, Ryder C. 2016. The contrasting roles of water and dust in controlling daily variations in radiative heating of the summertime Saharan heat low. *Atmos. Chem. Phys.,* **16**: 3563–3575.

McKee T, Doesken N, Kleist J. 1993. The relationship of Drought Frequency and duration to time scales. *Eight Conf. Applied Climatol*., 17-22 January 1993, California.

Middleton N. 1986. Dust Storms in the Middle East. *J. Arid Environm*., **10**: 83-96.

Miri A, Moghaddamnia A, Pahlavanravi A, Panjehkeh N. 2010. Dust storm frequency after the 1999 drought in the Sistan region, Iran. *Clim. Res*., **41**: 83–90.

Notaro M, Alkolibi F, Fadda E, Bakhrjy F. 2013. Trajectory analysis of Saudi Arabian dust storms*. J. Geophys. Res. Atmosph.,* **118**: 6028-6043.

Prospero J, Ginoux P, Torres O. 2002. Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Rev. Geophys*.,**40**: 1–31.

Qian W, Quan L, Shi S. 2001. Variations of the Dust Storm in China and its Climatic Control. *J. Clim.,* **15**: 1216-1229.

Rao P, Hatwar H, Al-Sulaiti M, Al-Mulla A. 2003. Summer shamals over the Arabian Gulf.

Weather, **58**: 472-477.

Rao P, Hatwar H, Al-Sulaiti M, Al-Mulla A. 2001. Winter shamals in Quatar, Arabian Gulf. *Weather*, **56**: 444 - 451.

Samadi M, Boloorani A, Alavipanah S, Mohamadi H, Najafi M. 2014. Global dust Detection Index (GDDI); a new remotely sensed methodology for dust storms detection. *J. Environ. Health Sci. Eng.,* **12:** 20-33.

Shubbar R, Salman H, Lee D. 2016. Characteristics of climate variation indices in Iraq using a statistical factor analysis, *Int. J. Climatol*., **37**: 918-927.

Sissakian V, Al-Ansari N, Knutsson S. 2013. Sand and dust storm events in Iraq. *Natural Sci.*, **5**: 1084-1094.

Sofue Y, Hoshino B, Demura Y, Nduati E, Kondoh A. 2017. The Interactions Between Precipitation, Vegetation and Dust Emission Over Semi-Arid Mongolia. *Atmos. Chem. Phys. Discuss.,* https://doi.org/10.5194/acp-2017-83.

United Nations Environment Programme. 2013. *Establishing a WMO Sand and Dust Storm Warning Advisory and Assessment System Regional Node for West Asia: Current Capabilities and Needs.* World Meteorological Organisation (WMO): Switzerland

Wark K, Warner C, Davis W. 1998. *Air pollution its origin and control, third edition*. Addison Wesley: USA.

Yang B, Brauning A, Zhang Z, Dong Z, Esper J. 2007. Dust storm frequency and its relation to climate changes in Northern China during the past 1000 years. *Atmosph. Environm.*, **41:** 9288-9299.

Yoshioka M, Mahowald N, Conley A, Collins W, Fillmore D, Zender C, Coleman D. 2007. Impact of desert dust radiative forcing on sahel precipitation: Relative importance of dust compared to sea surface temperature variations, vegetation changes, and greenhouse gas warming, J.of Climate, **20:** 1445-1467.

Zoljoodi M, Didevarasl A, Ranjba A. 2013. Dust Events in the Western Parts of Iran and the Relationship with Drought Expansion over the Dust-Source Areas in Iraq and Syria. *Atmosph. Clim. Sci.,* **3**: article ID 33894.

Zou X, Zhai P. 2004. Relationship between vegetation coverage and spring dust storms over northern China. *J. Geophys. Res.*, **109:** D03104

Figure captions

Figure 1: (a) Map of soil grain sizes in Iraq and surrounding areas, showing the dust source regions; (b) Map of Iraq, showing the study areas in beige.

Figure 2: (a) Massive dust storm over most of Iraq on July 3, 2009 - this true-colour image shows thick dust between Syria and the Iraq-Iran border; (b) July 4, 2009 - the dust storm has spread toward the east and southeast, over Iran and the Arabian-Persian Gulf; (c, d) July 5-7 2009 - satellite images show the dust storm continuing to spread toward the east and southeast, covering most of Iran west of the Caspian Sea, Kuwait and the Arabian-Persian Gulf. (e) July 31, 2009 – the same dust storm extended over eastern Iran, Kuwait, Bahrain, Qatar, the Arabian-Persian Gulf, the United Arab Emirates and Oman.

Figure 3: Monthly rainfall values (mm) reported from the meteorological stations in the study area (Baghdad, Hai, Diwaniyah, Nasiriyah), averaged over the 36 year period 1977-2012.

Figure 4: Annual SPI values between 1977 and 2012 from the meteorological stations in the study area (Baghdad, Hai, Diwaniyah, Nasiriyah).

Figures 5-7: Scatter plots of monthly frequency of different dust types (days / month) against monthly average wind speed (m/s) at Baghdad weather station over the full 36 year period (1977 – 2012). Pearson correlation coefficient values (R^2) and the linear regression equation are shown.

Figures 8-10: Scatter plots of monthly frequency of different dust types (days / month) against monthly average wind speed (m/s) at Hai weather station over the full 36 year period (1977 – 2012). Pearson correlation coefficient values (R^2) and the linear regression equation are shown.

Figures 11-13: Scatter plots of monthly frequency of different dust types (days / month) against monthly average wind speed (m/s) at Diwaniyah weather station over the full 36 year period (1977 – 2012). Pearson correlation coefficient values (R^2) and the linear regression equation are shown.

Figures 14-16: Scatter plots of monthly frequency of different dust types (days / month) against monthly average wind speed (m/s) at Nasiriyah weather station over the full 36 year period (1977 – 2012). Pearson correlation coefficient values (R^2) and the linear regression equation are shown.