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Characterization of synoptic patterns causing dust outbreaks that affect the Arabian Peninsula

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ABSTRACT

Dust storms pose serious weather hazards in arid and semiarid regions of the earth. Understanding the main synoptic conditions that give rise to dust outbreaks is important for issuing forecasts and warnings to the public in cases of severe storms. The aim of the present study is to determine synoptic patterns that are associated with or even favor dust outbreaks over the Arabian Peninsula. In this respect, red–green–blue dust composite images from the Meteosat Second Generation (MSG) satellite are used to detect dust outbreaks affecting the Arabian Peninsula, with possible influences in southwestern Asia and northeastern Africa, between 2005 and 2013. The Meteosat imagery yielded a sample of 95 dust storm days. Meteorological fields from NCEP/NCAR reanalysis data of wind fields at 10 m and 250 hPa, mean sea level pressure, and geopotential heights at 850 and 500 hPa were obtained for the dust storm days. Using principal component analysis in T-mode and non-hierarchical k-means clustering, we obtained four major atmospheric circulation patterns associated with dust outbreaks during the study days. Cluster 4 had the largest number of days with dust events, which were constrained to summer, and cluster 3 had the fewest. In clusters 1, 2 and 3, the jet stream favored the entry of a low-pressure area or trough that varied in location between the three clusters. Their most northerly location was found in cluster 4, along with an extensive low-pressure area supporting strong winds over the Arabian Peninsula.

The spatial distribution of aerosol optical depth for each cluster obtained was characterized using the Moderate Resolution Imaging Spectroradiometer data. Then, using METAR stations, clusters were also characterized in terms of frequency and visibility.

1. Introduction

Dust is a major type of tropospheric aerosol (Maghrabi et al., 2011), and dust storms are one of the most common weather phenomena in arid and semiarid regions of the earth (Sissakian et al., 2013). They particularly affect the Sahara Desert, Mongolia, and Middle East (Kahn et al., 2009; Rezazadeh et al., 2013; Liu and Liu, 2015). These regions also constitute the primary sources of atmospheric dust and extend from North Africa to China, through the Middle East, to central and southern Asia (Prospero et al., 2002).

The Middle East is not only one of the main dust sources worldwide (Rezazadeh et al., 2013) but also one of the areas most affected by dust storms. The most affected regions are the Syria-Iraqi plains, northern and eastern Saudi Arabia, Arabian Gulf, and southwest and southeast parts of Iran (Kutiel and Furman, 2003; Notaro et al., 2013; Rashki et al., 2013; Najafi et al., 2014; Hamidi et al., 2017). The main dust sources in this region are along a continuous band from the upper reaches of the Tigris and Euphrates rivers to the coast of Oman (Prospero et al., 2002). The Rub' Al Khali, the An-Nafud and the An-Dahna deserts are the major local dust sources in Saudi Arabia. However, there are more distant sources, mainly the Sahara and deserts in Iraq that affect the western, northern, and eastern parts of Saudi Arabia (Notaro et al., 2013; Jish Prakash et al., 2015). These source regions may be active throughout the year or be influenced by seasonal changes (drought, precipitation; UNEP, 2013). The frequency and seasonality of the dust storms vary spatially, as does dust activity in the source regions. Generally, dust is active throughout the year in most of the Middle East. This activity weakens during winter in most parts of this region (Hamidi et al., 2013), although there are peaks of activity depending on the area.

Owing to the natural hazards presented by the dust storms and their potential impacts on human health and ecosystems, various studies have focused on the characterization and forecasting of dust storms in certain periods or cases in the Middle East and surrounding oceanic areas, using the synergy of ground-based measurements, satellite data, model simulations, and reanalyses (e.g., Huang et al., 2007; Badarinath

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et al., 2010; Maghrabi et al., 2011; Alharbi et al., 2013; Kalenderski et al., 2013; Notaro et al., 2013; Prijith et al., 2013; Sannazzaro et al., 2014; Kaskaoutis et al., 2014a; Srivastava et al., 2014; Jish Prakash et al., 2015; Hamidi et al., 2017).

For better understanding of dust storms, one of the fundamental aspects in their study is the examination of atmospheric conditions under which sand or dust storms are triggered (Al-Yahyai and Charabi, 2014) and their displacement or extent (Rodríguez et al., 2015; Kaskaoutis et al., 2016). Discerning synoptic environments are also important to produce the most reliable forecasts possible and issue public weather alerts as necessary. The uplift of dust can occur under different regional and dynamic meteorological conditions. However, certain synoptic conditions can enhance dust activity over the study area (Goudie and Middleton, 2001; Rodríguez et al., 2015; Kaskaoutis et al., 2016). Dust aerosols, in turn, may have an impact on synoptic-scale systems. In this respect, Mohalfi et al. (1998) observed a strong heat low over Saudi Arabia caused by dust aerosol radiative heating, which prevented its dissipation via cold winds from the northwest. In addition, Das et al. (2015) and Jin and Sun (2016) studied dust aerosol radiative heating and related consequences in the enhancement of south Arabian heat lows and precipitation redistribution over the Arabian Sea and India. Dust storms are frequently associated with strong pressure gradients that increase wind speeds over large areas (Zoljoodi et al., 2013; Al-Yahyai and Charabi, 2014). Several indices have been used to study pressure gradients in certain areas and their relationships with dust activity. Kaskaoutis et al. (2015a, 2015b) used the Caspian Sea-Hindu Kush index to associate mean sea level pressure (MSLP) anomalies with dust storms over eastern Iran. Rodríguez et al. (2015) found that Saharan dust outflow to the subtropical Atlantic is linked with the North African dipole composed of 700-hPa geopotential height anomalies between Morocco and Mali. Once dust has been lifted, its transport direction depends on prevailing wind regimes, which are in turn determined by synoptic pressure systems (Badarinath et al., 2010).

The summer Shamal and both pre-frontal and post-frontal dust storms are the two main types of synoptic-scale dust storms on the Arabian Peninsula (Hamidi et al., 2013). The Shamal is a strong northwesterly wind with gusts up to 100 km/h (Garzanti et al., 2013), which causes dust storms throughout Iraq, Kuwait, and the Arabian Peninsula (Fattahi et al., 2012; Bou Karam Francis et al., 2017). The seasonal tendency of the Shamal is attributable to combination of the subtropical and polar jet streams (Sissakian et al., 2013). Onset and termination of the Shamal season are typically associated with La Niña (El Niño) conditions (Yu et al., 2016).

Several studies have analyzed synoptic conditions associated with dust storms in various parts of the Middle East. Fattahi et al. (2012) studied and classified synoptic patterns during dust storms in southwest Iran through principal component analysis (PCA). Al-Jumaily and Ibrahim (2013) analyzed synoptic patterns conducive to the formation of various dust events in Iraq. They observed that a low-pressure system that formed over Iran generated Shamal winds, which were responsible for the lifting of dust. Hamidi et al. (2013) studied major synoptic patterns associated with dust events between 2003 and 2011 in the Middle East, defined by the locations of their high and low pressure systems. Awad and Mashat (2014) examined synoptic characteristics associated with cases of widespread dust during spring in central and eastern Saudi Arabia as well as its southwest, with the most notable pattern (Awad et al., 2015) being a strong low-pressure system over the eastern Arabia peninsula or strong high-pressure system over western Arabia. Kaskaoutis et al. (2015a) examined synoptic meteorological patterns associated with summer dust storms over Sistan, eastern Iran, which is one of the most active dust source areas in the Middle East and southwestern Asia. They found a strong ridge over the Arabian Peninsula (at 700 hPa) associated with a trough over India, resulting in intensification of the northern Levar wind over Sistan. In the Sahara, Barkan and Alpert (2008) analyzed differences in synoptic patterns associated with years in which dust was present or not during various seasons of 1979–1992.

Therefore, analysis of the synoptic meteorological conditions favorable to the development of dust storms is very important to improve forecasting and determine affected areas and potential impacts on the environment and humans. As mentioned above, the vast majority of such studies in the Middle East have focused on specific events or analyzed synoptic weather patterns in certain countries. The present study classifies and analyzes synoptic atmospheric conditions (weather clusters) that determine the onset of dust-storm events over the Arabian Peninsula. The results can potentially be used to improve dust prediction and determine its potential impacts. Many forecast tools, such as statistical analog models, use past event analysis to furnish estimates based on similar atmospheric patterns. To that end, we characterized such patterns using METAR data and aerosol optical depth (AOD) retrievals. The method of this study allows the classification of weather conditions into clusters associated with dust outbreaks over the Arabian Peninsula. This method is very novel for that study area. There was only one analogous work in a neighboring region (India) by Kaskaoutis et al. (2014b), who classified into six clusters weather conditions associated with aerosol extremes over the Ganges Basin. This paper is organized as follows. Sections 2 and 3 present the study area and methodology, respectively. Section 4 gives results of the synoptic analysis and a characterization of each synoptic pattern (weather cluster). Finally, Section 5 contains a discussion and conclusions.

2. Study area

Saudi Arabia has the largest continuous stretch of sand on earth, with nearly one-third of the country covered by active dune fields (Garzanti et al., 2013). The Arabian Desert covers most of the Arabian Peninsula (Rezazadeh et al., 2013), with sand accumulated mostly in two large basins, the Great Nafud in northern Saudi Arabia and Rub' al-Khali (or Empty Quarter) in the south (Garzanti et al., 2013). The latter is one of the largest desert areas in the world (Prospero et al., 2002). The two basins are connected by the Ad Dahna corridor of sandy terrain in the east (Notaro et al., 2013); in the west lie the Sarawat Mountains, which may contribute to the lifting of air parcels in southwestern Saudi Arabia (Notaro et al., 2013). Extensive deposits along the coast with high salt content, known as *sabkhas,* are found in the east (Shehata and Amin, 1997). The Tigris–Euphrates floodplain is also one of the main sources of dust in the study area (Hamidi et al., 2013).

Desert areas continue in the interior of Iran to the west of Pakistan and Afghanistan, and are mostly associated with low-topography basins with drainage characteristics and/or dry salty lakes, such as Sistan and Jazmurian in southeastern Iran, and the Dasht-e-Kavir, Dasht-e-Lut and Registan deserts (Kaskaoutis et al., 2015b; Rashki et al., 2015, 2017). Other deserts around the Arabian Peninsula include the Sinai Desert on the Sinai Peninsula and Negev Desert in the north of that peninsula (Warner, 2004), the Libyan desert, which is partially within our study area, and the Nubian Desert in northeastern Sudan.

For the analysis of synoptic weather conditions that give rise to dust outbreaks, we considered the area from 5°N–50°N and 20°E–70°E, spanning southwestern Asia, northeastern Africa, and the eastern Mediterranean (Fig. 1).

3. Methodology and database

3.1. Satellite: Meteosat RGB and MODIS

Satellite images are especially useful for the detection, monitoring, and characterization of dust storm events and identification of source regions, because their coverage permits tracking over large areas (Sannazzaro et al., 2014).

In the present study, we used a database of 95 days over 2005–2013, during which dust storms formed on the Arabian Peninsula. These days were chosen from an initial database created