Spatial and temporal analysis of dust storms in Saudi Arabia and associated impacts, using Geographic Information Systems and remote sensing

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Abstract

Dust storm events occur in arid and semi-arid areas around the world. These result from strong surface winds and blow dust and sand from loose, dry soil surfaces into the atmosphere. Such events can have damaging effects on human health, environment, infrastructure and transport. In the first section of this PhD dissertation, focus on the suitability of the existing of five different MODIS-based methods for detecting airborne dust over the Arabian Peninsula are examined. These are the: (a) Normalized Difference Dust Index (NDDI); (b) Brightness Temperature Difference (BTD) (Band 31–32); (c) BTD (Band 20–31); (d) Middle East Dust Index (MEDI) and (e) Reflective Solar Band (RSB). This work also develops dust detection thresholds for each index by comparing observed values for 'dust-present' versus 'dust-free' conditions, taking into account various land cover settings and analysing associated temporal trends. The results suggest the most suitable indices for identifying dust storms over different land cover types across the Arabian Peninsula are $BTD_{31–32}$ and the RSB index. Methods such as NDDI and $BTD_{20 – 31}$ have limitations in detecting dust over multiple land-cover types. In addition, MEDI was found to be an unsuccessful index for detecting dust storms over all types of land cover in the study area. Furthermore, this thesis explores the spatial and temporal variations of dust storms by using monthly meteorological data from 27 observation stations across Saudi Arabia during the period (2000–2016), considering the associations between dust storm frequency and temperature, precipitation and wind variables. In terms of the frequency of dust in Saudi Arabia, the results show significant spatial, seasonal and inter-annual. In the eastern part of the study area, for example, dust storm events have increased over time, especially in Al-Ahsa. There are evident relationships ($p < 0.005$) between dust storm occurrence and wind speed, wind direction and precipitation.

This thesis also describes the impact of dust on health, and specifically on respiratory admissions to King Fahad Medical City (KFMC) for the period (February 2015 – January 2016).This study uses dust data from the World Meteorological Organization (WMO) for comparing and analysing the daily weather conditions and hospital admissions. The findings indicatethat the total number of emergency respiratory admissions during dust events was higher than background levels by 36% per day on average. Numbers of admissions during 'widespread dust' events were 19.62% per day higher than during periods of 'blowing dust' activity. The average number of hospital admissions for lower respiratory tract infections (LRTI) was 11.62 per day during widespread dust events and 10.36 per day during blowing dust. The average number of hospital admissions for upper respiratory tract infections (URTI) was 10.25 per day during widespread dust events and 7.87 per day during blowing dust ones. I found clear seasonal variability with a peak in the number of emergency admissions during the months of February to April. Furthermore, qualitative evidence suggests that there is a significant impact on hospital operations due to the increase in patients and pressure on staffing and hospital consumables in this period.

Taken together, these findings suggest the (BTD_{31-32}) and (RSB) are the most suitable indices of the five different MODIS-based methods for detecting airborne dust over the Arabian Peninsula and over different land cover. There are important spatial and temporal pattern variations, as well as seasonal and inter-annual variability, in the occurrence of dust storms in Saudi Arabia. There is also a seasonal pattern to the number of hospital admissions during dust events. This is research intended to fill the knowledge gap in the dust detection filed. Here I address the knowledge gap by evaluating the identified dust methods over the whole Arabian Peninsula and by considering different land cover. To my knowledge, this is the first study analysed the temporal trends in indices values considering dust and dust-free conditions.

Previous work has only focused on 13 stations for analysing dust storms over Saudi Arabia. Therefore, this study has analysed the seasonal and inter-annual and spatial variation by using data from 27 observations in Saudi Arabia. This study addresses the relationship between dust storm frequency and the three meteorological factors (i.e. temperature, precipitation and wind variables) which have not yet been clarified in previous studies. In addition, this research fills the gap in the literature by investigating the correlation between different types of dust events such as (wide-spread dust and blowing dust) and their effects on the hospital admissions for upper and lower respiratory tract issues for pediatric in Riyadh city.

Dedication

I dedicate this dissertation to my lovely family.

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1. Introduction

This dissertation has been divided into three parts. The first part focuses on evaluating the efficacy of five Moderate Resolution Imaging Spectroradiometer (MODIS) dust detection indices over Saudi Arabia and the surrounding areas of Kuwait, Bahrain, Qatar, United Arab Emirates, Oman and Yemen. The following dust detection indices were considered: (a) Normalized Difference Dust Index (NDDI); (b) Brightness Temperature Difference (BTD) using the MODIS bands 31–32); (c) BTD band 20–band 31); (d) Middle East Dust Index (MEDI) and (e) Reflective Solar Band (RSB). The second part considers the spatial and temporal distribution of dust events over Saudi Arabia and the influence of environmental forces on the occurrence of dust storms by examining the relationships between dust storm frequency and temperature, precipitation, and wind variables. The final section of the study highlights the effect of the two types of dust events (e.g. widespread dust and blowing dust) on health, especially on the incidence of upper respiratory tract infections (URTI) and lower respiratory tract infections (LRTI) in children living in Riyadh city. To gain improved understanding of the dust impact on human health, semi-structured interviews with hospital staff were used in this part of the study.

1.1. Dust Storms: An Overview

1.1.1. Dust storm definition:

Dust storms are mostly defined by visibility level, and are considered to be such when their visibility range is less or equal to one kilometre (Parolari et al., 2017). Parolari et al., (2017) have noted that some dust storms occur with a visibility range of more than one kilometre, defining them as those with a range of up to 11.3km. Rashki et al. (2019) have characterised them as those with visibility of less or equal to 2 km, while Middleton (2019) has suggested a visibility range of 700 metres.

1.1.2. Dust storm mechanisms:

Dust storms are atmospheric phenomena that occur in arid and semi-arid areas when small particles are blown from land surfaces and transported over great distances (Middleton and Kang, 2017). According to Middleton and Kang (2017), they have three stages: (i) the emission of the material from the surface (entrainment); (ii) transportation through the atmosphere; and (iii)_deposition of these materials back on the surface.

Entrainment of particles occurs when wind is exerted on the surface at strengths exceeding the ability of the material to resist detachment (Ravi et al., (2011). Thus, Shepherd et al., (2016) revealed that the degree of erosion of materials in dust storms depends on the amount of cover provided by non-erodible materials such as rocks and plant litter. Therefore, erodibility is dependent on mineral composition and particle size, with fine particles subject to more extensive erosion than coarser particles. On the other hand, Liu and Coulthard (2017) have noted that the dune system depends on sand movements, as opposed to sources that harbour fine-grained dust, and that erodibility is strongly influenced by soil structure and density, which are dependent on soil organic matter and biological activity. Physical characteristics such as gravel and salts or biological crust increase soil's resistance to erosion.

Severe dust storms are aligned with synoptic conditions that differ from region to another (Shepherd et al., 2016; Boloorani et al., 2014). As a result, regions of the Middle East suffer severe dust storms more frequently than the US, for example. These conditions are steep atmospheric pressure gradients, local winds attached to gradients in relief and monsoonal airflows (Middleton & Kang, 2017). Moreover, the synoptic weather conditions (e.g. the Shamal winds) are responsible for severe dust storms in Saudi Arabia (Yu et al., 2016).

The shape and mass of the particles determine the distance of deposition (Alexander et al., 2016). Accordingly, the settling deposition is dependent on gravitational settling during dry depositions, while wet depositions depend on precipitation. For instance, Middleton and Kang (2017) have noted that the Mediterranean, along with interior China, is dominated by dry depositions, whereas wet depositions are noted in Asia and the North Pacific. Most depositions of coarser materials are within tens of kilometres from the source. Other materials, including coarser particles, are capable of being transported for thousands of kilometres. Thus, dust storms have the ability to transport materials over political boundaries, with their effects ending in different countries from the source (Middleton & Kang, 2017). For instance, Saharan dust is mostly transported towards Amazonia, North America and the Middle East (Middleton & Goudie, 2001). That from China end ups in Korea, Japan, and the Pacific Ocean (Lee et al., 2003).

1.1.3. Dust storm dynamics:

Parts of the world affected by dust storms are mainly located in arid and semi-arid regions. Strong winds are required for dust storms to develop in the air. When they do, the loose-surfaced sandy soil is blown around. In arid and semi-arid areas, dust storms are frequently observed in the dry season. Drought significantly increases dust storm frequency because of the loose soil or sand distributed over the surface. In Phoenix, Arizona, for example, dust storms occur more frequently in the summer than any other season (Kim et al., 2017). This is because strong winds associated with outflow of air classified as cold from a thunderstorm are more prominent during the summer. In Australia, dust storms commonly occur during the spring and summer (Baddock et al., 2013). Middleton (2019) has documented that at 3 pm on 8 February 1983, severe dust storms developed in Melbourne, eventually reaching heights of 2800 metres, as reported by an aircraft pilot. Their height was reduced to 320 metres when the approach was made towards Melbourne. As a result, visibility was less than 100 metres, resulting in the closure of air traffic. Due to these specific events, the dust storm was classified as severe.

The largest dust source in the world is the Sahara Desert. It is the source of most dust storms that occur in the west, central and north parts of Africa (Kim et al., 2017) because of winds such as Haboob and Khamsin (Parolari et al., 2016). The Middle East is also a significant source of dust storms because of its climate, which ranges from rainy winters and sweltering dry summers. Such weather conditions cause sand to blow from the surface, resulting in dust storms. Thus, these storms affect Egypt, Iran, Iraq, Bahrain and Saudi Arabia (Rashki et al., 2015).

1.1.4. Dust particle size distributions:

Even though dust storms occur close to the surface, finer dust particles are usually lifted kilometres high into the atmosphere (Killer, Mulsow & Melzer, 2015). As a result, strong winds transport these fine particles over long distances. While EPA, (2004) have reported that larger coarse are more settled than fine particles and comparatively close to the ground or its sources of emission. Further, the (EPA, 2004) claimed that only fine particles are transported over long distances, Hilchenbach et al., (2016) have noted that dust particles larger than 63 microns have been reported thousands of kilometres from their source. Thus, a possibility of coagulation of fine particles during deposition may be seen as a consequence of the formation of such large particles, hence assumed to have travelled over long distances.

Al-Dousari, Doronzo and Ahmed (2017) have revealed that most dust in the Arabian Gulf originates from the Mesopotamian Flood Plain, Ahwaz, Ahwar and the Baluchistan Desert. These dust particles are explicitly characterised as finer, with a trimodal particle distribution size. Additionally, the particles hold more carbonates, with limited quartz and higher particle surface area values when compared to dust settled in terrestrial areas. Killer, Mulsow and Melzer, (2015) have noted that dust deposited in terrestrial areas mostly originated from the western desert of Iraq, the Nafud Desert and the Empty Quarter Desert. As a result, these regions have substantially different dust particle characteristics, with rich quartz sediments forming a significant part thereof. The poor-quartz sediments are found in the Mesopotamian Flood Plain (Garzanti et al., 2016).

1.1.5. The diameter of dust particles:

The classification of dust particles is based on fine sand grains, with diameters of 0.063 mm and above (Bunte & Abt, 2001; Al-Dousari et al., 2017). These sand particles originate locally in the Arabian Gulf, with 58% being deposited in desert areas (Al-Dousari, Doronzo and Ahmed, 2017). Al-Dousari et al., (2017) have reported that dust particles become finer towards the Gulf and coarser towards the deserts. As a result, these particles contain quartz and carbonates, with feldspars noted in considerable amounts. Quartz and carbonate percentages in dust particles function in complementary ways, with quartz increasing while carbonate decreasing in percentage as the desert area is reached (Alexander et al., 2016). Nevertheless, in general, the sand-sized particles are larger than around 0.06 mm (Shepherd et al., 2016).

1.1.6. The vertical distribution of dust in the air:

Dust particles are widespread within the atmosphere, causing multiple and complex interactions within the environment and climate. Guo et al. (2017) have highlighted that the altitude attached to the lifting of aerosols influences their interaction with clouds and radiation, and hence their life limit. Investigations by Du et al. (2018) into the vertical structure of dust in the air, revealed that dust particles are trapped and transported under specific well-structured conditions. Specifically, the dust is enclosed inside well-defined layers that exist in the free troposphere. Consequently, its transportation occurs vertically, and multiple layers with clearly distinct areas develop. These layers are noted to have different altitudes, between 1.5 to 5 km from the surface. The Saharan dust storm topped heights of approximately 4 km, with the maximum heights reached after several days of dust storm collection.

Depending on the origin of the dust storm, different layers, with dust from different origins, may be present. Durán et al. (2017) conducted a study on the origin of dust storms and their composition. They noted that dust storms originating from North Africa and ending in Europe had traces of dust from all regions, including minerals explicitly from the Atlantic Ocean. Temperatures within the vertical distribution of dust, according to Mazar et al., (2016), vary significantly when measured from the ground up. It is noted that the maximum threshold value of 1 degree centigrade is required to ensure the different layers form. Thus, the particles within the vertical dust storm are arranged according to their weight and temperature favourability. Du et al. (2018) provided an alternative look into the mixing rations and size distributions, focussing on the aerosol source. The researchers noted that if the aerosol is above the atmosphere, the size distribution of materials and mixing ratios within the vertical dust storm will form independent of the altitude. Alternatively, aerosol sources in the lower part of the atmosphere form mixing ratios and size distributions varying by altitude. Through this, the vertical distribution of dust may vary as the dust storm travels from one area into another, ending with a different arrangement from its original segments. This view has been supported by an early study by Ahmed and Al Haider (1987), in which they clarified that global distribution during dust storms is difficult to identify, and the distribution may depend on the location and the conditions of the storms.

1.2. Background and Motivation:

This study deals with the phenomenon of dust storms, which are increasingly recognized as serious events in arid and semi-arid areas of the world, causing widespread socio-economic and environmental disruption and affecting human health (Prospero, 1999; Alghamdi et al., 2015; Terradellas et al., 2015; Middleton & Kang, 2017). This natural hazard happens as a result of strong winds which raise dust and sand from deserts and their surrounding areas and carry it over large distances (Middleton, 1986). A generally accepted definition of a dust storm, based on the visibility criteria, is the reduction of visibility to less than 1000 m (Goudie; 1983; Middleton, 1986; McTainsh & Pitblado, 1987). Following the World Meteorological Organization (WMO) protocol, dust presence is classified by visibility, as follows:

1) *Dust haze or widespread dust*: The suspension of dust in the air, causing visibility not greater than 10 km, which is also considered as fine particles that are suspended in the air by the wind (OFCM, 1995).
2) *Blowing dust:* Dust or sand raised by the wind at the time of observation reducing the visibility to between 1 and 10 km, but not to below 1 km. However, in the literature (Ozer, 2002) claimed this dust can reduce horizontal visibility to less than 5 km.

3) *Dust storm:* Strong winds lifting large amounts of dust particles, which reduce the visibility to between 0.2 km and 1 km.

4) *Severe dust storm:* Very strong winds lifting great quantities of dust particles, causing visibility to less than 0.2 km.

The African and Asian deserts are the major sources of dust in the world (Tsoar & Pye, 1987). The Sahara, in Africa, is one of the world’s largest sources of dust storms (Middleton & Goudie, 2001). Sahara dust can affect the southwestern Arabian Peninsula (Notaro et al., 2013; Prakash et al., 2015); the Peninsula is where major Asian deserts such as Rub' al Khali (The Empty Quarter), An Nafud and Ad-Dahna) are located (Shao, 2008; Yu et al., 2015). Other deserts, including the Gobi, Karakum, Kyzylkum, Taklamakan and Thar, also generate dust storms (McKee et al., 1974).

The Middle East is one of the regions most affected by dust storms (Middleton, 1986; Furman, 2003). An early study by Idso (1976) stated that the Arabian Peninsula is one of the major source areas for dust storms, together with the Sahara, the Sudan, the southern coast of the Mediterranean Sea and parts of the former Soviet Union. However, Tanaka and Chiba (2006) studied the nine potential dust storm sources (Arabian Peninsula, Central Asia, eastern and western China, the North and South of Africa, North and South America and Australia) by using numerical simulation method with a global dust transport model during the period (1990 -1995). Their aim was to investigate the contributions of each dust storm to the global dust load into the atmosphere. They found that the Sahara Desert by 58% is responsible for the total global dust emission. In the Arabian Peninsula, the Rub Al Khali, An Nafud and Ad Dahna deserts are the primary source areas of locally generated dust storms (El-Baz, 1979; Notaro et al., 2013). However, the literature indicates the Sahara desert is also one of the main dust sources for Saudi Arabian dust storm events, as well as those in the desert areas surrounding the Arabian Peninsula (Junge, 1979; Morales, 1979; Ganor & Mamane, 1982; Goudie, 2001; Notaro et al., 2013), such as parts of Syria and Iraq (Bartlett, 2004; Goudie & Middleton, 2006; Yu et al., 2015).

There are several main factors that have been identified as causing dust storms in Saudi Arabia. For instance, the topography and the climatological conditions (e.g. strong wind and the air pressure gradients related to storms) in the region have an influence on the appearance of the dust storm events (Mohammad, 1989; Zhang et al., 2003; Goudie & Middleton, 2001; Akbary, & Farahbakhshi, 2015). In addition, anthropogenic activities are one of the factors that cause dust storms. The latter include overgrazing by cattle and off-road driving, both of which result in the disintegration of the vegetation and soil structure.

Moreover, the loose fine particles in dunes might be a source of dust storms, as Sweeney et al., (2016) have pointed out. In contrast, other studies have shown dune fields are not a major source of dust (Huang et al., 2019; Bakker & Bristow, 2019). Sparse vegetation cover and droughts could be factors in dust storms (Middleton, 2019). Naturally, plants have an important role in soil and sand stabilization, which could reduce blowing dust (Sofue et al., 2018).

1.3. Justification of Research Questions:

Dust events are a regional and global natural problem that affects the health of many human beings living in dust storm areas. Furthermore, they have the potential to cause very large economic impacts. For example, a recent study by Al-Hemoud et al. (2017) has shown that dust events in Kuwait City in the period 2001–2014 have caused total damage to the oil export sector amounting to $824,311 per tanker and flight delays costing $28,180 per day, asocial and environmental damage. For instance, intensive dust storms lead to road closures, airport closures and even frequent school closures (Kutiel & Furman, 2003; Goudie & Middleton, 2006; De Villiers & Heerden, 2007; Maghrabi et al., 2011; Alharbi et al., 2013; Goudie, 2014). Such storms induce soil loss and agricultural productivity decline (Sivakumar, 2005; Goudie & Middleton, 2006). Further, dust emissions increase air pollution and ultimately affect human wellbeing (Tolba & Saab, 2009). The inhalation of airborne particulate can seriously affect the human respiratory system (Keeton & Cooksey, 2012). Dust storms also have an impact on industry and energy. El-Shobokshy and Hussein (1993) tested the impact of the accumulation of airborne dust on the surface of photovoltaic cells in Saudi Arabia. They concluded that the presence of fine particulates on the cells remarkably reduced their performance. In addition, Andreae and Crutzen (1997) and Autrup (2010) concluded that fine particles have a much bigger impact on the performance of photovoltaic cells than coarse particles.

Remote-sensing instruments are useful tools for identifying and detecting dust (Qu et al., 2006) and should be considered an important data source along with in-situ observations (Chen et al., 2014). NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) was developed to provide data for short- and long-term changes on land, water and atmosphere, which is very helpful for studying land cover, natural hazards and climate changes. Dust events were observed at 27 meteorological stations across Saudi Arabia during the period between 2000 and 2016 by the Presidency of Meteorology and Environment (see Figure 12). However, there were incomplete observational records for two years in this period (2002 and 2009). These incomplete data underline the importance of remote-sensing-based dust detection techniques. In that respect, the MODIS multi-spectral sensor, currently operating on the Terra and Aqua satellites, is an ideal tool for detecting dust events, as it can provide instantaneous monitoring of very large areas at a range of wavelengths (i.e. 0.4 μm to 14.4 μm) every one to two days (Xiong et al., 2005; Gu & Wylie, 2015). It is important to note that while there is a lack of knowledge about dust detection analyses in the Arabian Peninsula, this particular area is important because it is commonly affected by dust storms. Therefore, the purpose of this study is to analyse the existing MODIS dust detection methods and evaluate the efficacy of these techniques in the Arabian Peninsula.

In addition, the spatio-temporal variability of dust storms in all the regions of Saudi Arabia is not fully understood, and there have been few, if any, previous studies about the impact of weather variables (e.g. temperature, precipitation, wind speed and wind direction) on the occurrence of dust storms. In this study, I investigate the possible influences of environmental conditions on the temporal variability and spatial distribution of dust storms in Saudi Arabia during the period 2000 to 2016. To the best of my knowledge, very few studies have examined the impact of airborne dust on human health in Saudi Arabia, and especially the impact of different weather conditions on the upper and lower respiratory tract. In an effort to close that gap, I analyse the effects of dust events on daily emergency admissions for respiratory illness at King Fahad Medical City (KFMC) in Riyadh.

1.4. Research Questions:

Given the knowledge gaps outlined above, I have formulated the following research questions:

1. What are the most effective satellite methods for detecting dust storms over the Arabian Peninsula?
2. How did temperature, precipitation and wind speed factors influence the spatial and temporal patterns of dust storms in Saudi Arabia during the period 2000–2016)?
3. Is there a detectable impact of dust storms on numbers of hospital admissions due to respiratory illness during or following those storms?

1.5. Aims and Objectives

In order to address the research questions above, I have designed the following aims and objectives:

Aim 1: To evaluate the suitability and efficacy of existing satellite dust detection methods over the Arabian Peninsula.

Aim 2: To quantify the spatial-temporal variability of atmospheric dust in Saudi Arabia between 2000 and 2016.

Aim 3: To examine the impacts of dust storms on the respiratory system and on hospital admissions.

To achieve these three aims, it is necessary to collate and analyse a combination of remote sensing and in-situ observations related to dust storms in Saudi Arabia. The first point of focus is the evaluation of existing methods for detecting dust storms from MODIS images, and geographic information systems (GIS) form a key element of the present analyses. The outputs of this project will be of interest to national, regional and local planning authorities aiming to combat related threats to society. To make progress towards these aims, I defined the following more specific research objectives:

1. Develop an improved multi-approach method for MODIS detection of dust storms.
    a) Evaluate the suitability of five different MODIS-based methods for detecting airborne dust over the Arabian Peninsula: (a) Normalized Difference Dust Index (NDDI); (b) Brightness Temperature Difference (BTD) (31–32); (c) BTD (20–31); (d) Middle East Dust Index (MEDI); and (e) Reflective Solar Band (RSB).
    b) Identify the index threshold for each of the considered dust detection indices.
    c) Validate the performance of the various dust indices for different land cover types (barren, urban and vegetation).
    d) Quantify the seasonal and inter-annual variability of the dust detection indices and quantify the temporal variability as a function of land-use type.
2. Identify the spatial and temporal variations in the occurrence of dust storms over Saudi Arabia, as well as the temperature, precipitation and wind speed factors, to determine the possible effect of these factors on the patterns of dust storms.
3. Investigate the impact of dust events on the incidence of respiratory tract infections, and the association between dust events and emergency hospital admissions in Riyadh.

1.6. Study Area and Physical Characteristics

The Arabian Peninsula covers a total area 3,237,500 km² (García et al., 2015) and is surrounded by water on all sides, except to the north, where it is connected to mainland Asia. Saudi Arabia, the largest country in the peninsula, covers an area of 2,150,000 km^2 (Yaqub et al., 1991) and is bordered by several other countries, including Yemen, Oman, the United Arab Emirates, Iraq, and Jordan. Unlike most of the Peninsula, which is almost entirely surrounded by water, Saudi Arabia is only bordered by water to the northeast (by the Arabian Gulf) and to the southwest (by the Red Sea). Saudi Arabia is situated to the southwest of the continent of Asia (located between longitudes 35°-56° East and latitudes 16°-32° North). The Arabian Peninsula has a considerable diversity of desert and mountain habitats. Some of its dry lands are covered with drifting sand dunes, while others are more stable flat plains of sand (Edgell, 2006).

Geographical factors, along with the location of Saudi Arabia and the wider Peninsula, have an impact on the meteorological elements that affect the occurrence of dust storms (Mao et al., 2014). The Peninsula's landscapes can be divided into several subfields. For instance, about three quarters of it is covered by desert. The largest deserts are the north-central An Nafud, with an area of 57,000 km^2, and the Empty Quarter (The Rub' al Khali) in the south, which covers more than 650,000 km^2. Moreover, in the eastern part of Saudi Arabia, there is the Ad Dahna desert, which is characterised by a very fine reddish sand and extends about 1,450 km^2.

The Sarawat is the largest mountain range on the Peninsula. It stretches from the north of The Gulf of Aqaba and the Red Sea in the south to the Gulf of Aden, along the Peninsula's western edge. The northern, central and southern parts of this range are called the Hijaz, the Asir and the Sarat al Yemen respectively. Jabal Tuwayq is a prominent mountain ridge in the central part of the Peninsula (Holm, 1960). This mountain ridge is located at an elevation of 705 meters above sea level. The plateau is the dominant geographical feature of the Arabian Peninsula, which rises from the Red Sea and gradually descends toward the Arabian Gulf (Petraglia, 2003). The two longest coastlines of the Arabian Peninsula are the Tihama coast on the west side and the Arabian Gulf coast on the east side. The Tihama coastal plain stretches some 400 km along the Red Sea, from the Asir region in the north to Bab Almandeb near the southern border (Smith, 1985). In the east and along the Arabian Gulf Coast are wide coastal plains. Furthermore, there are various valleys (wadis) distributed across the entire surface of Saudi Arabia. Wadi Al-Rummah is the longest valley in Saudi Arabia, stretching some 600 km from near Madinah to the Al-Khubairat sands. Moreover, the Kingdom of Saudi Arabia has a large diversity of plant species due to its wide range of habitats, which range from mountains, sand seas, deserts, meadows, salt pans (AbuZinada et al., 2001).

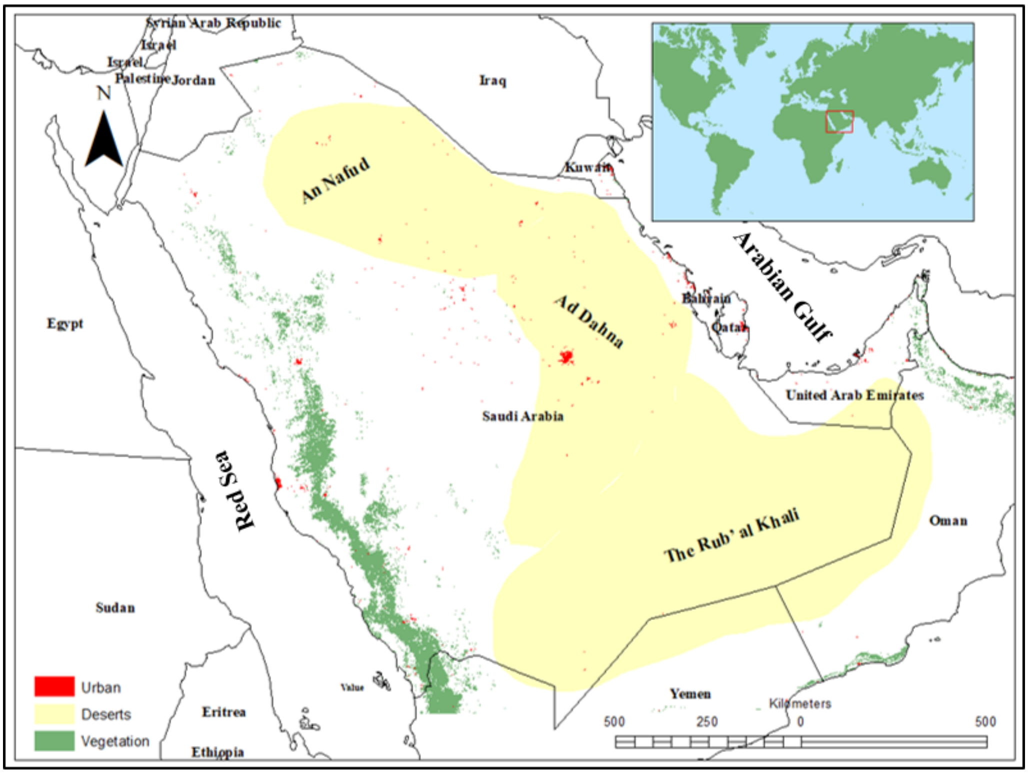


Figure 1 Overview map of the Arabian Peninsula with the approximate extent of the major deserts, cities and vegetated areas.

1.7. Climate and Dust Storm Sources

Saudi Arabia's climate is extremely, dry with an average annual precipitation of less than 100 mm per year (De Pauw, 2002). The temperature can rise to 50°C in the summer. The average maximum temperature drops to 8–17°C during the winter season (Kamel et al., 2006).

1.7.1. Dust storm sources:

According to Middleton (1986), dust storms typically occur on fine-grained material, particularly silt, clay, and other outwash sediments. Boloorani et al., (2014) conducted a study to make sense of the geomorphology of dust sources in the region. They observed that dust storms are formed because of intense pressure gradients between low pressure and high-pressure systems. Boloorani et al.'s explanation is perhaps best clarified by Awad and Mashat (2014), who have explained that the low-pressure belt located over Northern Africa facilitates the northward movement of the low-pressure belt over the southern part of the Sahara. This and similar movements over the region lead to the formation of pressure gradients. Strong pressure gradients lead to the movement of great quantities of dust transported from North-East Africa to Asia (Awad & Mashat, 2014). Dust sources can either be categorised as 'remote ' or ' local':

The primary remote sources of dust in Saudi Arabia, include the Saharan Desert and the Iraqi deserts Al-Hajarah and Al-Dibdibah (Notaro et al., 2013). The Saharan Desert brings dust to the western region of the country, while the Iraqi deserts bring dust to the north. Prospero et al. (2002) have added that the dust activity in this region can be linked to the dust belt in the Northern Hemisphere. This dust belt starts on the west coast of North Africa and extends eastwards though the Middle East and central Asia, terminating in China (Prospero et al., 2002) (Fig. 2).

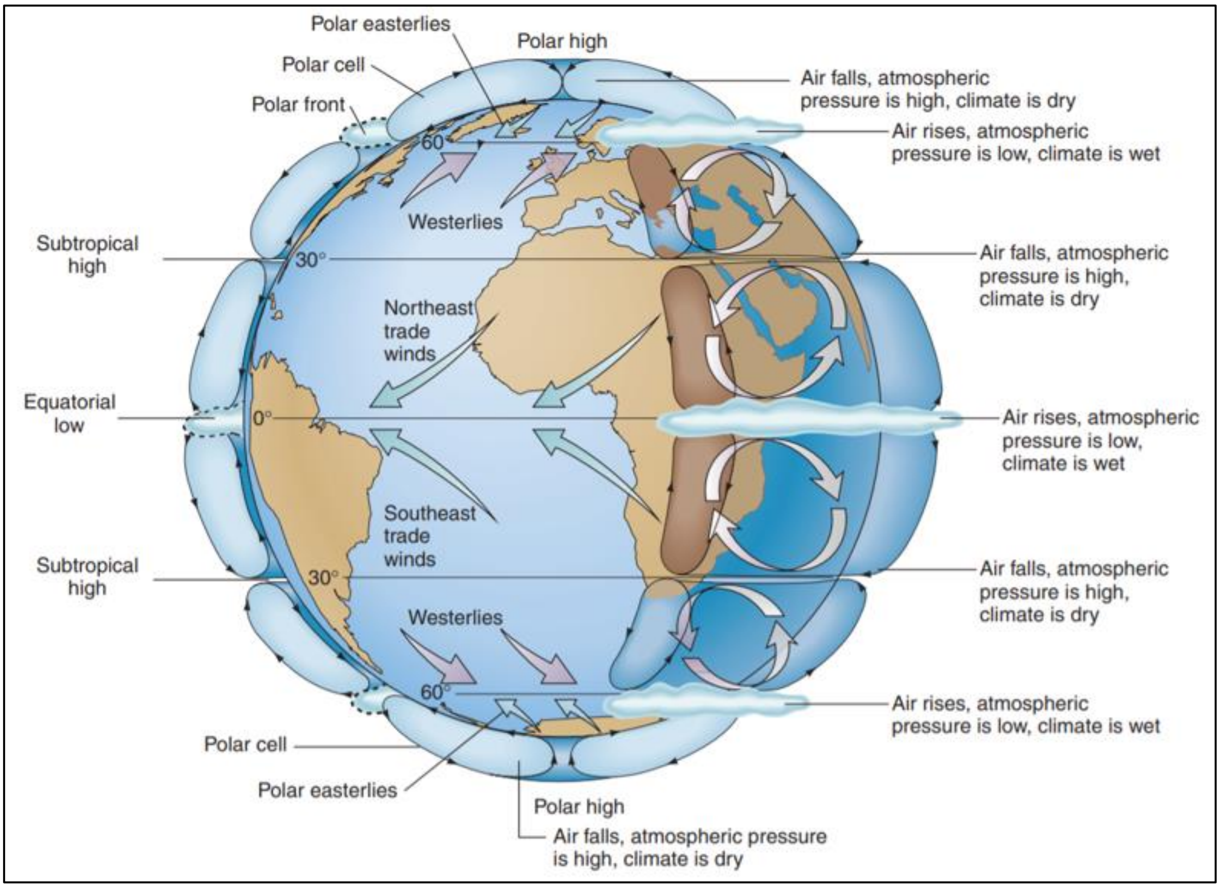


Figure 2 The global atmospheric circulation pattern (Gabler et al. 2008)

The factors in the transport of dust to Saudi Arabia are (i) temporal changes in height above the ground of the air parcels; (ii) the relative humidity; and (iii) the vertical motion (Notaro et al., 2013). In the case of the north-westerly trajectories at Al-Ahsa, air parcels that originate over the Mediterranean Sea are found at altitudes of 2–4 km at t-84 (Notaro et al., 2013; Holm, 1960). The parcels descend rapidly as they cross the Iraqi deserts, leading to dust storms. Mashat et al. (2008) on the other hand, have observed that dust storms most frequently occur in the eastern part of the Arabian Peninsula during spring. The Shamal winds occur in the north during the summer, with speeds above 40–50 km/h, causing reduced visibility for several days due to the high amount of dust which has been transported (Vincent, 2008).

Saudi Arabia's airborne dust is produced mostly locally across the deserts, especially the Rub Al Khali Desert, which is the primary source of local dust (Notaro et al., 2013; Yu et al., 2013).

1.8. Outline of the Thesis:

In this work, I aim to evaluate the suitability and efficiency of existing satellite dust detection indices over the Arabian Peninsula. In addition, I aim to quantify how well these different tests perform on a range of land-use types. This approach allows for the comprehensive characterisation of the seasonal variation in the frequency and spatial distribution of dust storms over different regions of Saudi Arabia. Furthermore, I consider dust's impact on health by examining the effects of dust storms on hospital admissions and operations in Riyadh using statistical and qualitative evidence. This thesis contains seven chapters which cover the main elements of the research. They are as follows:

Chapter One provides the background and motivation of the study, and identifies the problem statement and research objectives. Chapter Two starts by providing the material and methods for the dust storm detection indices, dust storm and climate variable data and the impact of dust storms on human health. Chapter Three highlights the previous work addressing the areas of focus of this study. This analysis is followed by, an overview of previous dust storm detection indices, previous work that used MODIS satellite images, previous work on dust storm spatial and temporal variations and previous work on dust storm impact.

Chapter Four has been published with the following citation: Albugami, S., Palmer, S., Meersmans, J., Waine, T. 2018. Evaluating MODIS dust detection indices over the Arabian Peninsula. *Remote Sensing*, 10, 1993.

Chapter Five has been published with the flowing citation: Albugami, S., Palmer, S., Cinnamon, J., Meersmans, J. 2019. Spatial and temporal variations in the incidence of dust storms in Saudi Arabia revealed from in-situ observations. *Geosciences*, 9, 162.

Chapter 6 has been submitted for publication with the following citation: Albugami, S., Cinnamon, J., Meersmans, J., Palmer, S. 2019. Impact of dust storms on daily emergency admissions for respiratory infections in children in Riyadh city, Saudi Arabia, *International Journal of Environmental Research and Public Health* (Under review).

Chapter 7 presents a synthesis and conclusions, outlines the contributions of this study and offers suggestions for further work.

2. Previous Work

2.1. Overview of the History of Dust Storm Studies:

The modern study of dust storms began in the 1930s because of the intense and widespread dust storms that affected the northern Great Plains of the USA. A cloud of severe dust occurred in May 1934 and transported dust to the southeast, which resulted in the increase of dust across the Atlantic Coast of the United States between Maine and Georgia (Hand 1934; Kellog, 1935; Mattice, 1935). During this period, agricultural activities in the country were severely disrupted. The storm lasted for approximately 60 days in 1934 (Mattice, 1935; Langham et al., 1938). Shortly after this damaging dust storm, another large dust storm occurred in the western desert of Egypt at Borg Al Arab. It lasted for a period of six years, from October 1939 to September 1945. In Oliver’s (1945) study of this storm, he demonstrated that the most frequently occurring wind storm, ‘Khamsin', ranges from two to 50 km, and it transports a vast amount of dust in the year it occurs. Swalim and Swowelin (1960) identified the hot Khamsin storms as the possible cause of sand deposition in Cairo.

Other studies concentrated on detection, monitoring and mapping meteorological conditions using different tools. For instance, TIROS was the first weather satellite to be introduced, in April 1960. Although TIROS was designed to collect information on cloud formations and other weather conditions, there is evidence that TIROS images can detect dust. For instance, the satellite observed the dust storms in the Balkan Peninsula (Beresford, 1960). Vinogradov et al. (1972) conducted a study on satellite imagery to investigate the dust storms in the northern part of the Arabian Gulf. The study found the dust storms were caused by strong north winds. These winds are known as ‘Al-Shamal' winds. They are 1-15 km high in the atmosphere and have a speed of 40 m/s. Wicoishen et al. (1977) conducted a study on the satellite imagery and concluded that it could play a significant role in offering a definitive detection approach for the start time, location and magnitude of dust storm development. The NOAA-7satellite images were used by Wolfson and Matson (1986) to detect storms of dust across northeast Saudi Arabia, specifically in Al Qaisumah, where storms reached a height of 1.8 km.

Satellite imagery was used by Moulin et al. (1977) to conduct dust variability surveillance from the Atlantic Ocean and the Mediterranean Sea on the Sahara and the surrounding areas. The Total Ozone Mapping Spectrometer (TOMS) is a useful instrument for detecting dust (Prospero et al., 2002). Prospero et al. (2002) identified nine potential dust sources regions around the globe and named them according to the source regions. According to Shao and Dong (2006), much progress has been made in the monitoring, modelling and prediction of Saudi Arabian dust storms.

Other studies have explored the frequency and distribution of dust storms around the world. The studies use the World Meteorological Organisation protocol, which has classified dust storms by visibility into ‘dust in suspension’, ‘blowing dust’, ‘dust storm’, and ‘severe dust storm’ (Sun et al., 2001). The distribution and frequency studies were well developed in Asia for over fifty years. However, according to Sun et al. (2001) the classification is subjective, and observers may make varied determinations. The authors analysed the synoptic reports over the 40 years between 1960 and 1999 and concluded that the Gobi in Mongolia and North China are major dust sources. Zhou (2001) found that the Tarim Basin and the adjacent areas and the Alashan, Ordos, and Hexi Corridor regions are main dust centres in China. Natsagdorj et al., (2003) conducted a study on Mongolia by analysing the distribution of influential dust events using a composite of synaptic data acquired between 1937 and 1999. The study concluded that the most affected area in Mongolia is its southern part and the Great Lakes Depression. These findings are consistent with the findings of Prospero et al. (2002).

In addition, other studies have been conducted to analyse the effects of dust storms on human health. Kellog and Griffin (2006) concluded that dust storms contain various microorganisms, including mycobacterium, Brucella, and Bacillus and many others. Several other studies demonstrated the same finding of microorganisms (Chen et al., 2010; Griffin, 2007; Goudie; 2014). The incidences and distances affected by dust storms have been studied by Crooks et al., (2014). According to this study, the incidences of dust storms in the Middle East have increased, and the dust now travels a longer distance than before. For instance, southern, western, and southwestern Iran have been frequently affected by Middle Eastern dust (Goudie, 2014; Griffin, 2007). Kanatani, (2010) found that in Japan, dust storms worsen diseases such as asthma in children, and Khaniabadi et al., (2017) analysed the effects of sand dust storms on human health. The study examined the impacts of Middle East Dust events that occur in Illam. The researchers concluded that there is a rise in the hospitalization of individuals with chronic obstructive pulmonary disease (COPD) during the Middle East dust storms.

2.1.1. **Previous work that Used Moderate Resolution Imaging Spectroradiometer (MODIS) Satellite Images to Detect Dust Storms**

2.1.1.1. **Early studies that used MODIS products.**

Kaufman et al. (2005) developed a method to differentiate dust from other different types of aerosol by using the MODIS measurements, which were used to derive the dust transport and deposition. The findings of the study showed that 230 Tg of dust were transported annually to the Atlantic from the Sahara. This agrees with research by Kalashnikov and Kahn (2008) that demonstrated how the Sahara dust fluxes travelled over the Atlantic Ocean using MODIS and Multi-angle Imaging SpectroRadiometer (MISR). Another study by Li and Zhuang (2003) focused on using Terra/MODIS images to study sand dust storms' quantitative retrieval method. The researchers concluded that MODIS images can be used to study the quantitative retrieval.

Miller (2003) proposed a method that used two algorithms (over land and water) and high spatial and spectral resolution images from the Moderate Imaging Spectroradiometer (MODIS) in order to enhance the detection of dust crossing coastlines in Southeast Asia. El-Askary and Kafatos (2005) used MODIS and MISR sensors for detecting dust storms and applied them over Saudi Arabia and the Gulf area, both major dust storm regions.

Mei (2008) explained that dust storms have serious effects on climate change as well as on people's health. In their study, they monitored the dust storm which occurred in China in April 2006 by using satellite images, mainly derived from MODIS products. While previous studies have considered MODIS effective in detecting dust storms, they have do not gone further to identify specific MODIS combinations that can help in proper identification. Baddock, Bullard and Bryant (2009) have addressed this gap, examining the drawbacks of MODIS and providing suggestions about the best combination. They have argued that the MODIS Deep Blue is influenced by dust mineralogy or the reflectivity of the ground surface. Consequently, it is impossible to rely on only one MODIS L1B or L2 data type to examine all dust events. Zhao et al. (2010) concentrated on MODIS observations and how they are used to test dust and the operation and performance of the algorithm. The algorithm they used can capture heavy dust over land and ocean, so it could be deployed as a global detection algorithm. Li et al. (2010) analysed the massive dust storm which swept over Sydney on 23 September 2009 by using MODIS images and the BTD index. Li et al.'s (2010) findings were validated by Zhang et al. (2015), who demonstrated that MODIS level 1B images can be used to locate dust hotspots, which increases researchers' ability to understand dust events and to improve the dust model.

2.1.1.2. **More recent studies using MODIS satellite images.**

Kunte and Aswini (2015) explained the approaches to using MODIS images and geospatial techniques in order to detect and monitor dust events over land and ocean. The researchers used MODIS data to analyse temporal variations in dust events that occurred over a period of weeks in March 2012 in the Arabian Sea. They relied on a dust detection procedure to demarcate or identify the movement of the dust event. They also studied dust formation, source, path and dissipation using different methods, including source back-tracking and remote sensing. They observed that geospatial and remote sensing data techniques were effective in detecting as well as mapping dust events coupled with monitoring of their transportation paths (Kunte & Aswini, 2015).

In recent years, Farahat et al. (2016) used MODIS, CALIPSO and AERONET data to analyse aerosol size distribution characteristics and their role in the rainfall during dust storms over Saudi Arabia. The researchers revealed that a combination of different space-borne sensors can help the distribution of aerosols and the effect they have on distribution of dust storms.

MODIS has been used by Di et al. (2016) and Xie et al. (2017) to detect Asian dust storms. Xie et al. (2017) used measurements of MODIS reflective solar bands, together with the thermal emission band, to develop an algorithm to detect dust aerosols. As they indicated, MODIS true-colour images offer qualitative ways of validating detection results. Quantitatively, Ozone Monitoring Instrument products provide a more objective way of validating results. However, as the researchers confirmed, the multi-spectral detection algorithm that was developed based on the MODIS offers an effective way of monitoring dust aerosols.

Considering the Sahara Desert, Madhavana et al., (2017) used dust detection techniques by MODIS Thermal channels. In addition, they investigated the aerosol optical depth (AOD) variability over the Arabian Peninsula using MODIS infrared satellite data. They confirmed that a combination of MODIS and Ozone Monitoring Instrument provided an effective way of detecting dust. They observed that MODIS overcame the previous limitations and thereby provided a better dust detection algorithm than other schemes. It offered an enhanced dust radiometry with a higher resolution. Su et al., (2017) validated the work of Madhavana et al., (2017) by indicating that the MODIS is a dynamic remote-sensing method that makes it possible to accurately monitor dust storms. It helps to accurately identify the area affected by a dust storm, as well the storm’s strength, and duration. According to the reviewed literature, the MODIS satellite images can be used to detect dust storms.

2.1.2. **Dust Detection Indices.**

2.1.2.1. **The normalized difference dust index (NDDI).**

The NDDI was introduced by Qu et al. (2006), who applied it to detect dust storms over the north of China using MODIS solar reflectance bands. They concluded that this method was successful in detecting dust over bright (barren) surfaces and offered the ability to identify dust storms and clouds. This method was based on the reflective solar bands 3 and 7 of MODIS images. Moreover, this index has been used in several subsequent studies. For example, Li and Song (2009) proved that the NDDI index is suitable for detecting dust storms with a threshold of 0.26 over the Inner Mongolia Badain Jaran Desert (badanjilin) and Minqin county of Gansu province, China. Furthermore, Samadi et al. (2014) found that the NDDI index was able to differentiate dust from clouds. In addition, Khamooshi et al. (2016) examined the movement of dust storms over the south of Iran by using the NDDI method, which was suitable for monitoring and detecting dust events. Due to the high sensitivity of MODIS (band 7), NDDI has advantages in detecting dust storms and soil moisture content (Xie et al., 2017)

2.1.2.2. **Brightness Temperature Difference (BTD) indices.**

The BTD method was first employed by Ackerman (1989) in demonstrating the correlation between the BTD bands and dust storm outbreaks. In addition, Ackerman (1997) highlighted that BTD bands between 11 and 12 µm were sensitive to dust events. Most importantly, the latter study showed that BT_{11} - BT_{12} was a useful index for detecting dust storms over the Arabian Peninsula, Africa and the southwest United States. This index uses the brightness temperature difference (between 12 µm and 11 µm) to identify airborne dust. It has been also demonstrated that the BTD values are used in this index can detect temperature differences which exist between the surface and the mineral aerosol and is not influenced by other absorptions in the atmosphere, such as gases (Darmenov & Sokolik, 2005). The BTD methods use differences between multiple thermal emissive bands, for example BT_{20}, BT_{31} and BT_{32}, which are characterized by a wavelength range of 3.66–3.84 μm, 10.78–11.28 μm and 11.77–12.27 μm, respectively, and a spatial resolution of 1000 m. In addition, Huang et al. (2007) revealed that using the BTD channels 11–12 μm is an effective method for detecting dust storms. According to Yue et al. (2017), the $BTD_{32\text{-}31}$ test is a suitable approach to detecting the spatial magnitude and intensity of a dust storm. This index was applied over northeast Asia in a study of the period between 2000 and 2011. BTD (11–12) has certain drawbacks because this index can detect ash particles of a volcano at high altitudes, according to (Prata 1989) and sulfate aerosol can also be detected (Watson et al., 2004), which may possibly lead to false dust detection (Park et al., 2014).

2.1.2.3. **The Middle East Dust Index**

As Karimi et al. (2012) found that bands 31 and 32 have issues in distinguishing airborne dust from the desert surface, they presented a new method called the Middle East Dust Index (MEDI) (Karimi et al., 2012; Komeilian et al., 2014; Moridnejad et al., 2015). This index is based on Ackerman's dust detection technique, but also includes band 29. Hence, the MEDI is calculated using thermal emissive bands BT_{29}, BT_{31} and BT_{32}, with wavelength ranges of 8.40–8.70 μm, 10.78–11.28 μm, and 11.77–12.27 μm, respectively, at a spatial resolution of 1000 m. It has the specific purpose of differentiating airborne dust and desert surfaces. The MEDI approach was applied over Middle East regions such as Saudi Arabia, Syria and Iraq. Researchers concluded that this method was successful in identifying dust storms over desert areas. However, this index has a limitation: it cannot differentiate airborne dust from clouds (Karimi et al., 2012).

2.1.2.4. **The Reflective Solar Band-derived index.**

The MODIS reflective solar bands B2 (841-876 nm), at a spatial resolution of 250 m, and B18 (931-941 nm), at a spatial resolution of 1000 m, have been considered by Samadi et al. (2014) when developing a new index. This index has been used over the eastern part of Iran to detect dust over bright and dark surfaces (Samadi et al., 2014) (Table 1, Fig. 3).

Table 1: The equations of the dust detection indices

Dust indices		Units
NDDI	$(B_{7-3})/(B_{7+3})$	Dimensionless
BTD	$(31–32) = BT_{31-32}$	Kelvin
	$(20–31) = BT_{20-31}$	Kelvin
MEDI	$(BT_{31-29})/(BT_{32-29})$	Dimensionless
RSB	$(2–18) = B_{2-18}$	Dimensionless

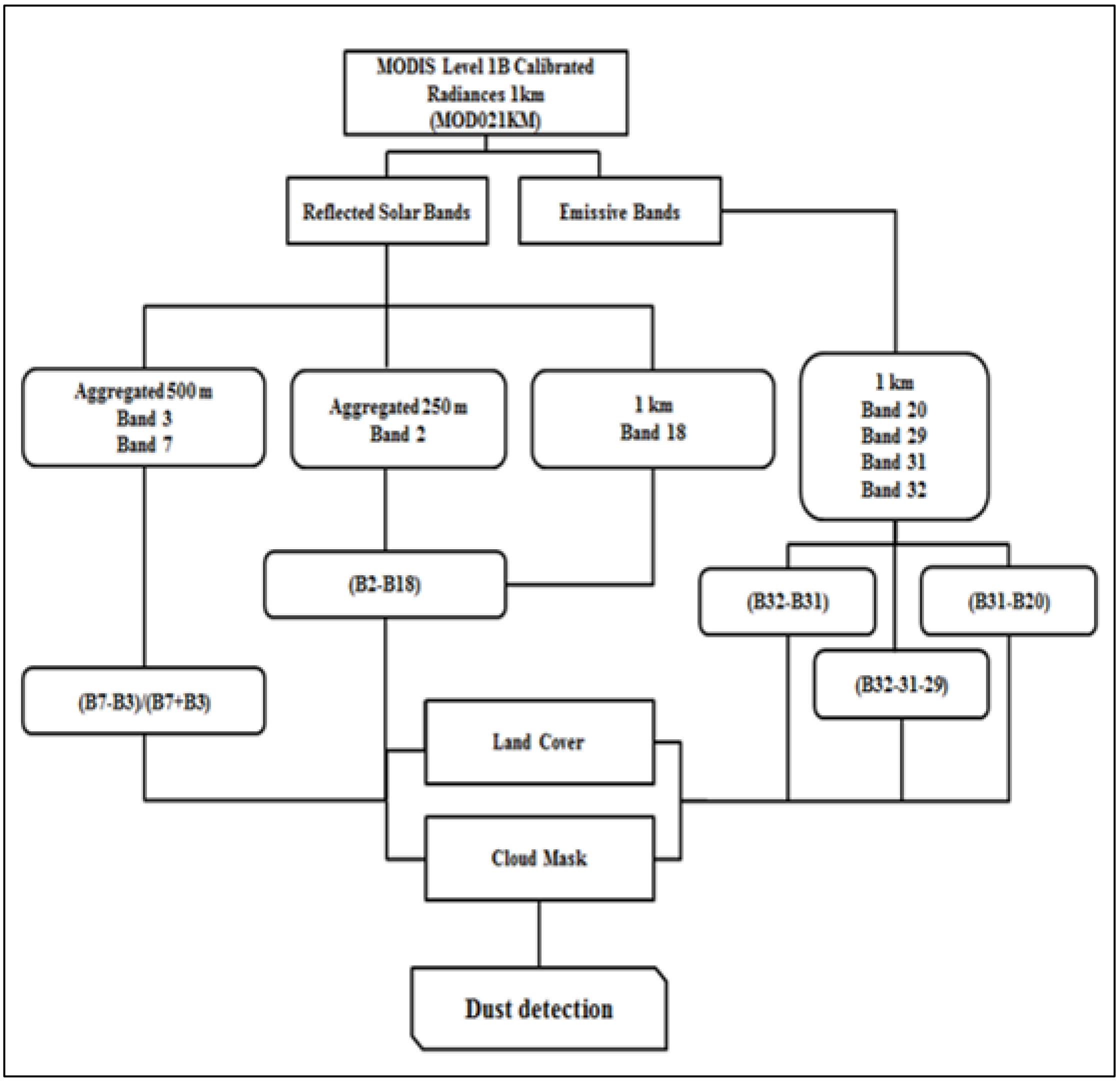


Figure 3 Flowchart of MODIS dust detection indices

2.1.3. **Absorption spectra of dust particles**

The scattering of light by the dust is affected by the particle size, shape, the dust chemical composition and the light scatter direction (Li, 2008). A study by Chiapello et al., (1999) established that the dust particles from the storm are known to cause a cooling effect on the earth's surface as the particles in the atmosphere scatter incoming radiation from the sun back to space.

It has been also demonstrated that the BTD values are used in this index can detect temperature differences which exist between the surface and the mineral aerosol and is not influenced by other absorptions in the atmosphere, such as gases

(Darmenov & Sokolik, 2005). MODIS infrared band 20, band 31 and band 32 are used to detect dust and differentiate it from other ground objects. Band 20 has a greater scattering than band 31 for pixels of dust, this can tell us the dust intensity and its extension from the subtraction of these two bands BTD20-31 (figure 4) (Mei et al., 2008; Yue et al., 2017).

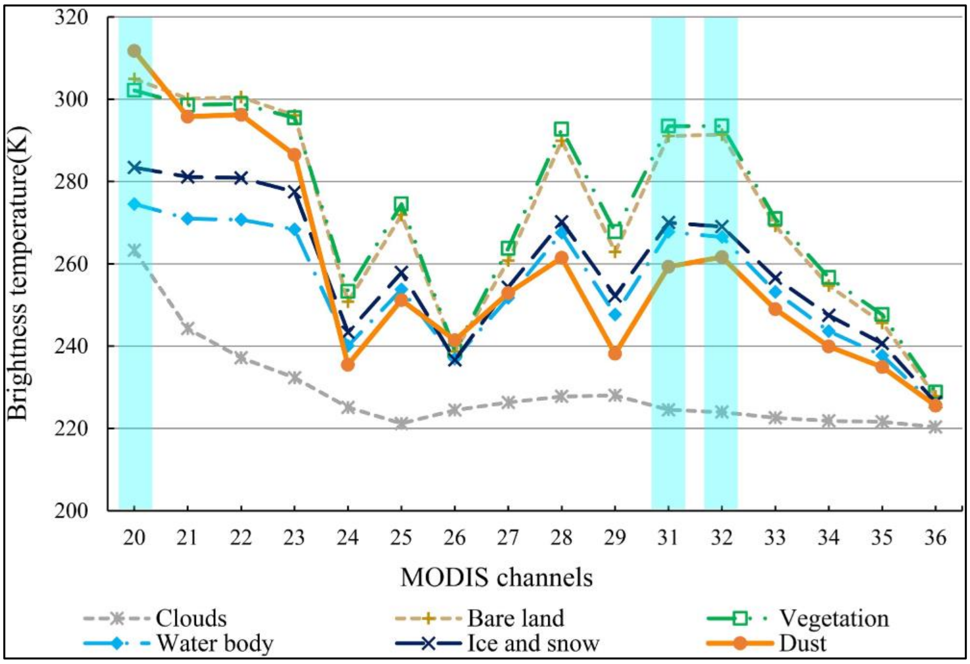


Figure 4 MODIS brightness temperature bands (Yue et al., 2017)

Sun and Ming (2019) findings indicated that cloud and snow/ice have high visibility and NIR band reflectance, and that the reflectance of dust is higher than that of vegetation. The only challenge in this exercise is that most pixels contain a spectrum of information about other land objects, which means the radiation difference of one pixel is a function of other objects and their respective proportions. Unknown surface characteristics make it difficult to determine the precise detection of dust without relying on existing surface reflectance data. When identifying clouds from dust pixels in a dust storm, the dynamic threshold method is employed to distinguish possible cloud pixels (figure 5).

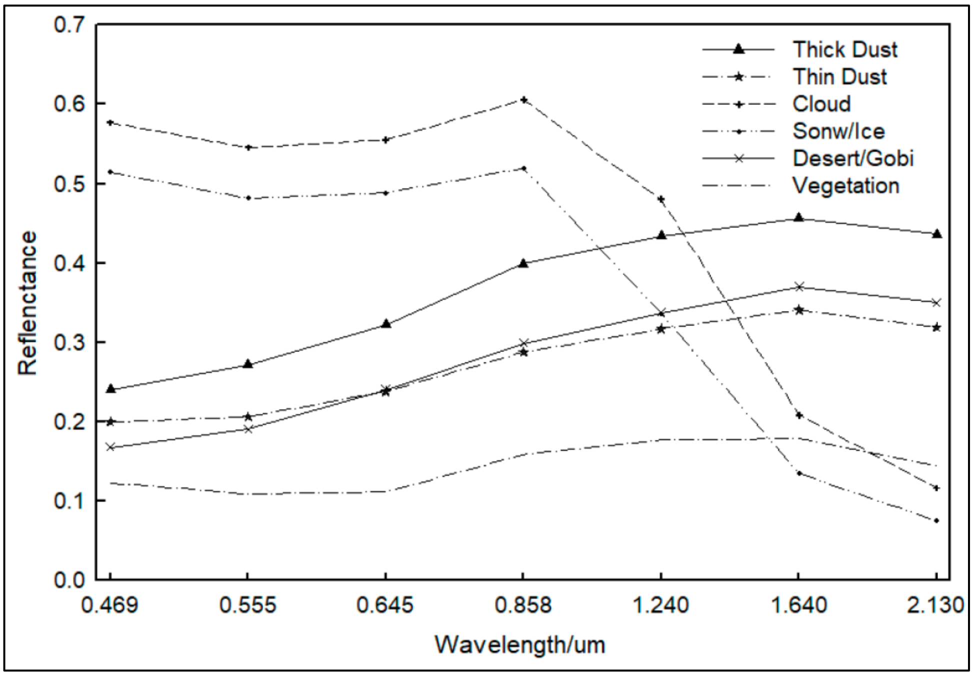


Figure 5 The spectrum of distinct targets at MODIS bands 1–7 (Sun & Ming (2019).

Ge et al. (2010) investigated the optical characteristics of dust aerosol in semi-arid regions and concluded that the single-scattering albedo (SSA) values increase with wavelength, from 0.76 ± 0.02 at the wavelength of 0.415 μm to 0.86 ± 0.01 at the wavelength of 0.870 μm during dust storms. This suggests that dust aerosol is absorbed at shorter wavelengths. Kunte and Aswini (2015) claimed that the spectral characteristics of dust aerosols are different on land and water; some specified thresholds of a variety of linear combinations may clearly make dust visible. Their result demonstrates that NDDI and BTD (11, 12) are successful methods for detecting dust storms over ground surface and water. In addition, the radiation absorbed by dust is greater at 12 μm than 11 μm, which is the reason for the negative values in the BTD (11, 12) index (Li & Song, 2009).

2.2. Previous Work on Dust Storm Spatial and Temporal Variations

Back trajectories were used to identify sources of dust storms using HYSPLIT modelling programs (Mattice,1935). Dust storms cause a significant change to the atmosphere and even instability in weather conditions (Mattice, 1935). They are also known to cause ENSO cycle and rainfall variation over the Arabian Peninsula. Ackerman and Cox (1989) conducted a study on temporal and spatial distribution of dust storms in Saudi Arabia, which is located in the southwest monsoon region. They concluded that dust storms in Saudi Arabia were at their peak during the spring and winter. Ali-Mohamed (1991) examined the various characteristics of the spatial and temporal dust storm activity in Saudi Arabia between 1989 and 1992 using the dust concentration monitoring method. He concluded that the highest number of days with dust storms in Saudi Arabia happen in the city of Riyadh during March and August. In addition, he explained that dust storms can be transported from Saudi Arabia toward Bahrain by the Arabian Gulf (Ali-Mohamed, 1991). Swap et al. (1996) established that the temporal and spatial Saharan storm dust had a characteristic of being at its peak during the months of February and April, with frequent dust aerosols in the first six months of the year.

In addition, Chiapello et al. (1999) stated that the dust particles from a storm are known to cause a cooling effect on the earth’s surface, as the particles in the atmosphere scatter incoming radiation from the sun back to the space. The dust is also known to alter the optical properties of the clouds, causing condensation and finally rainfall in the area. In Australia, the dust storms are characterised by a high frequency of occurrence in the Lake Eyre Basin region (Goudie & Middleton, 2000). Kutiel and Furman (2003) claimed that the temporal and spatial Saharan storm dust had a characteristic of being at its peak during the months of February and April, with frequent dust aerosols in the first six months of the year. According to Alfaro et al. (2004), arid and semi-arid places are the main sources of dust storms in Africa and the USA. A study done by Qian and Quan (2004) on the temporal and spatial characteristics of storms in China showed that the frequency of storm dust increases as storms move northwest. Further, Indoitu et al. (2012) underlined that the frequency of storm dust in Middle Asia has been showing a significant decline in recent decades. This is in good agreement with Wyrwoll et al. (2016), who noted a declining trend in northern China's dust storms. According to Lyu et al. (2017), dust storms are transported from north-western, arid areas of China to eastern regions. They noted that this trend has contributed to the Beijing annual dust fall. However, there was a downward trend of dust from Taklamakan Desert in China from r 2000 to 2012 (Luo et al., 2017). Additionally, a recent study by An et al. (2018) mentioned that dust storms significantly decreased in East Asia during the period 2007–2016).

Yu et al. (2013) found that dust activity peaked between April and June, and that dust storms were correlated with strong surface winds across the north-central Saudi desert areas during February to March, and through the southwestern areas from July to August, owing to dust transport from the Sahara. This result has a number of similarities with the research of Notaro et al. (2013), who stated that Saudi Arabian dust storm activity occurs in the spring and summer. According to Rezazadeh et al. (2013), dust events occur frequently in the northern parts of Saudi Arabia and other regions in the Middle East (e.g. Sudan). Gherboudj and Ghedira (2014) mentioned that dust storms have a significant spatial variation over the United Arab Emirates.

On the other hand, Alizadeh-Choobari et al. (2016) found five regions in Iran where dust storms are more frequent. These are Khuzestan Plain, the west of

Iran, the coastal plain of the Arabian Gulf, Tabas and Sistan. Recent studies by Mashat et al. (2017) and Yassin et al. (2017) investigated the inter-annual variability in dust events over the Arabian Peninsula. The dust storms were found to cause a significant change to the atmosphere, even producing instability in weather conditions (Mashat et al. 2017).

2.3. Overall Dust Impacts

Mitchell (1971) argued that dust storms damage soil fertility and crop productivity, in addition to reducing solar radiation on the surface. Wasson and Nanninga (1986) stated that dust storms significantly contribute to the reduction of vegetated surfaces, while Modaihsh (1997) showed that the dust fallout sediments in Riyadh, Saudi Arabia, mainly consist of loam and silt loam. Washington et. al. (2003) mentioned that dust storms have deleterious impacts on the environment, such as deflation, abrasion and erosion, notwithstanding their role in desert loess formation. Nonetheless, Maghrabi et al. (2011) chose as an example one of the massive dust storms in Riyadh, which occurred on 10 March 2009. This widespread event triggered a heavy dust storm leading to zero visibility, and resulted in the shutdown of the Riyadh airport. Recent studies like that by Al-Hemoud et al. (2017) have reported on the economic implications of dust, focusing on its effects on oil exports and flight cancellations. However, positive effects of dust storms have been reported on the Red Sea. These include the maintenance of energy balance, the circulation and the distribution of the sea (Stenchikov and Osipov, 2018). Another study by Stefanski and Sivakumar (2009) showed that fertilizing soil minerals in the ecosystems is one of the positive impacts of dust storms. Despite the positive impact of dust storms and implications, this part of the study will entirely focus on the health repercussions associated with dust storms. The exploration analyses those studies carried out in dust-storm-prone areas.

2.3.1. Dust's effects on health.

Korenyi-Both et al. (1992) found a relationship between dust storms and several diseases, including pneumonitis and Al Eskan disease, from a research exploration in Saudi Arabia. The same conclusion has been supported by empirical exploration, especially in earlier studies like that by Nickling and Gillies (1993), which illustrated how dust storms might have a long-term health risk. Kwaasi el al. (1998) found that dust storms contain a variety of allergens and antigens; hence, they trigger allergy and respiratory diseases in humans. Likewise, Rutherford et al. (1999) found that the occurrence of dust storms contributed to increases in the number of patients admitted to hospitals with severe asthma in Brisbane, Australia. The same phenomenon has been noted by Al Frayh et al. (2001), who reported that asthma admissions in Saudi Arabia increased during dust-storm seasons, while Taylor (2002) demonstrated that larger dust particles can cause tracheobronchial irritation. This has been supported by Kwon et al. (2002), who have highlighted the strong relationship between Asian dust storms and mortality in Seoul, Korea. Negative health implications have also been established by Wiggs et al. (2003), who observed that there is a relationship between dust storm events and paediatric respiratory diseases.

Dust contains microbial particulate matter with profound health implications. For example, Griffin and Kellogg (2004) focused on the effect of transport of marine microbial communities by dust storms and their impact on human health. Gyan et al. (2005) claimed that hospital visits for children with asthma symptoms were increasing, a trend they attributed to the stronger African dust storms. Meng and Lu (2007), meanwhile, focused on the daily cases of hospital admissions in Minqin (China) due to respiratory and cardiovascular illnesses diseases during the period 1994–2003. Another study by Ozer (2008) illustrated higher dust-induced respiratory diseases in Mauritania. Kanatani et al. (2010) showed that there was a significant increase in the prevalence of asthma in children, which led to an increase in hospitalization in Japan, due to Asian dust storms. Hashizume et al. (2010) presented an epidemiologic review concerning the possible health impacts of the Asian dust storms in Japan. Furthermore, Al-Dabbas et al. (2011) studied the mineralogical and microorganism effects of regional dust storm effects in Iraq and the Middle East region. They showed the effects of these dust storms on human health, demonstrating that the storms caused diseases including breathing problems, asthma, bronchitis and lung diseases. In addition, smaller dust particles were shown to be able to affect the respiratory system by inhalation, which immediately affects the epithelium of the airways (Watanabe et al., 2011). The increase in the number of respiratory diseases has been reported by Thalib and Al-Taiar (2012), who have examined the effect of dust event on hospital admissions from asthma and every respiratory disease. Tam et al. (2012) claimed that the increase visits to respiratory emergency hospital departments is associated with widespread dust presence. As reported by Barnett et al. (2012), there was an increase of 39% of hospital admissions due to dust events in Brisbane, Australia during 2009.

Gupta et al. (2012) investigated the role of dust storms in the worsening of respiratory diseases, especially in individuals with asthma. They established that the smaller the particles in a dust storm, the greater its potential to aggravate asthma. Meo et al. (2013) intended to research the intense respiratory and general health objections in subjects exposed to dust storm in Riyadh, Saudi Arabia. The same has been confirmed by Al-Ghazawy (2013), who documented that 24% of people are affected by asthma in Saudi Arabia, and that the presence of dust storms is one of the main reasons for augmented asthmatic diseases in this region. This was also explained by De Longueville et al. (2013), who focused on how dust events have an adverse impact on human health, leading to respiratory, cardiovascular and cardiopulmonary illnesses. In this respect, it is evident that dust storms should be considered a public health problem, especially in desert regions. The relationship between dust storms and respiratory diseases has been subject to extensive research, with some researchers identifying serious health implications including wheezing, runny nose, cough, headache, sleep and most seriously, psychological problems (Meo et al., 2013). Dust storms have been associated with serious health implications and, therefore, should be studied and considered as a serious risk factor for general ailments and respiratory conditions. Accordingly, the present research recommends avoiding excessive exposure to dust storms. The problem has been reported in regions prone to dust storms like the Middle East, especially by Al-Ghazawy (2013), who has associated sandstorms or dust with higher rates of asthma in Saudi Arabia.

3. Materials and Methods

3.1. Introduction

The purpose of this chapter is to introduce the research materials, methods and to highlight the key approaches of this thesis. I began my study by investigating the satellite multispectral observations – more precisely, 17 Moderate Resolution Imaging Spectroradiometer (MODIS) bands – of dust and non-dust images between 2000 and 2015 to compare and evaluate the suitability of dust events detection indices over the Arabian Peninsula. Another approach focused on the spatiotemporal distribution. This analysis was performed in order to describe and identify the spatial and temporal patterns of dust storms in Saudi Arabia by using the in-situ weather and climate observations for 2000 and 2016. In addition, it is important to consider dust storm impacts on human health. For that purpose, I used the hospital admissions data and dust events data from the World Meteorological Organization (WMO) over the period February 2015 – January 2016 in Riyadh, Saudi Arabia. Furthermore, I did interviews with hospital personnel to aid interpretation.

The three approaches in this thesis are: (i) evaluating the suitability of dust detection methods by remote sensing and MODIS images over the Arabian Peninsula; (ii) analysing the spatial and temporal variations of dust storms over Saudi Arabia; and (iii) investigating dust's impact on health. These three aspects will be discussed in-depth using the data, analysis methods and tools discussed in this chapter. The methodology offers us an insight into the suitability of the five dust detection indices (i.e. NDD, BTD [31–32], BTD [20–31], MEDI and RSB) and the temporal trends in indices values considering dust and non-dust conditions. I also carried out more detailed analysis in order to understand the frequency and occurrence of dust events, as well as the extent to which these dust storms are associated with other weather variables when determining spatial patterns as well as seasonal and inter-annual variations. Furthermore, I focused on identifying dust's impact on the respiratory system by assessing which type of dust storm event has a negative influence on upper respiratory tract infection (URTI) and/or lower respiratory tract infection (LRTI).

3.2. Moderate Resolution Imaging Spectroradiometer (MODIS) Images

MODIS is the primary sensor on the NASA Earth Observing System (EOS) satellites Terra and Aqua, which launched in December 1999 and May 2002, respectively (Ichoku et al., 2005). The MODIS instrument produces daily worldwide coverage; it can monitor location and vegetation abundance, ocean surface and atmosphere. The spectral channel's role is to improve the atmospheric layer and characterisation of clouds, including by removing any atmospheric effects on the earth observations (Justice et al., 1998). The MODIS data uses the Hierarchical Data Format (HDF), which is the standard data format for all NASA (EOS) data products (Meng et al., 2008).

In the research described in this thesis, I used the MODIS Level 1B, which contains a collection of calibrated and geolocated radiances for 36 spectral bands covering wavelengths from 0.4 µm to 14.4 µm (Justice et al., 1998; Barnes et al., 2003; Xiong et al., 2003; Isaacman et al., 2003). The Level 1B algorithm produces three radiance products based on spatial resolution (i.e. 250 m [bands 1-2], 500 m [bands 3-7] and 1km [bands 8-36]) (Table 2). Every granular file of MODIS data contains five-minute day- and night-time observations. The MODIS Level 1B products are as follows:

1) Earth View Radiance Product (MYD02QKM): This product covers Reflective Solar Bands 1 and 2 and contains calibrated Earth View data at 250m resolution.

2) Earth View Radiance Data Product (MOD02 HKM): This product covers Reflective Solar Bands 3, 4, 5, 6 and 7 and contains calibrated Earth View data at 500m resolution, including 250m resolution bands aggregated to appear at 500m resolution.
3) Earth View Radiance Data Product (MOD021KM): This product covers Reflective Solar Bands 8, 19 and 26 and it combines 250m and 500m resolution bands to appear at 1km resolution. Moreover, it contains thermal emissive bands 20–25 and 27–36 (Ahmad et al., 2002a).

In this project, indices and algorithms based on the multi-spectral technique were used to detect dust aerosols. I used a combined measurement of (MODIS) reflective solar bands and thermal emissive bands. The temporal resolution of this MODIS product is 5 minutes (Nasagov, 2019). The bands which were used in this study are shown in the table below:

Table 2: MODIS Level 1B Calibrated Radiance bands

Band name	Resolution	# bands	Spectral bands
Reflective Solar Band	250 m	2	1, 2
	500 m	5	3,4,5,6,7
	1 km	15	8-19, 26
Thermal emissive bands	1 km	16	20-25, 27-36

3.3. The MODIS Cloud Mask Product

Clouds can affect the detection of dust storms (e.g. Ackerman et al. 1998). Therefore, the cloud mask was used in the present study to identify cloudy pixels that might affect the dust storm detection. It tends to give false detections and to misclassify the thick dust as cloud (Frey et al., 2008). Martins et al. (2002) revealed that pixels with heavy aerosols, such as dust, could be misclassified as clouds. The MODIS Cloud

Mask product is a Level 2 product at a resolution of 1km and 250 m (Ackerman, 2015). The temporal resolution for this product is 5 minutes (Ahmad et al., 2002b). Moreover, the cloud mask product is able to identify pixels if they are water or land pixels (Remer et al., 2005). The MODIS Cloud Mask data have two product files (Savtchenko et al., 2004):

1) MOD35_L2 containing data from the Terra satellite.
2) MYD35_L2 containing data from the Aqua satellite.

The MODIS level 1 data, geolocation, cloud mask, and atmosphere products can be downloaded from this website: http://ladsweb.nascom.nasa.gov/ (Fig. 6 & 7).

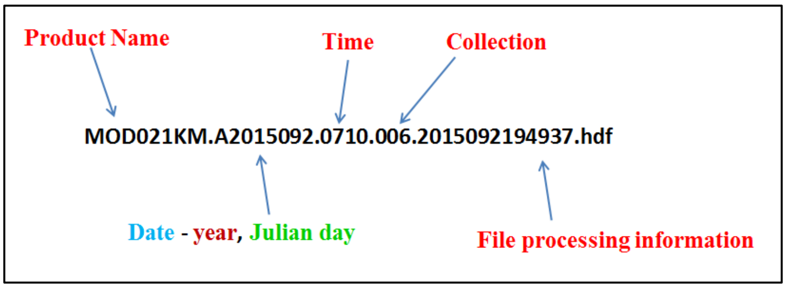


Figure 6 MODIS Level 1B, Hierarchical Data Format (HDF) product file.

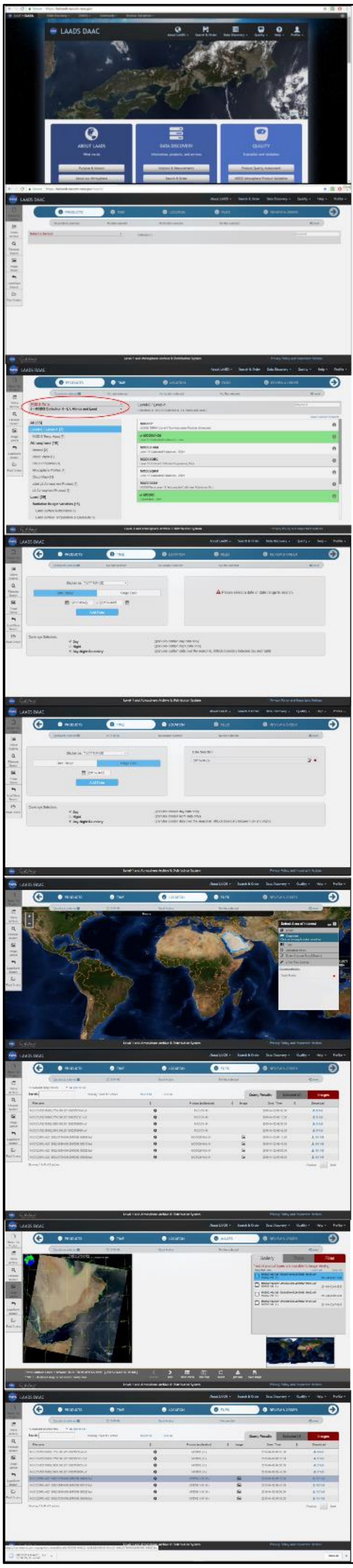
In my analysis as I mentioned above that I downloaded these two products:

- MODIS Level 1B Calibrated MOD021KM
- Geo-located Radiances MOD03

Note: the files should be in the same time for example:

MOD03.A2015092.0710.006.2015092130351.hdf

MOD021KM.A2015092.0710.006.2015092194937.hdf



Downloading data from the web address: https://ladsweb.nascom.nasa.gov/

Searching for the images and order

Selecting the product

Selecting a date: You can select a range of dates or a single date.

Selecting a location

Selecting the image

- You can choose which image you want to download.
- Go back to files and start downloading

Figure 7 Downloading MODIS data from the Web http://ladsweb.nascom.nasa.gov/

3.4. The MODIS Land Cover Type Product (MCD12Q1)

I chose this product in order to gain a better understanding of aerosol values over different types of land cover on the Arabian Peninsula. The surface reflectance provides a value based on land-cover type. The MCD12Q1 has five global land-cover classifications with a resolution of 500m, which has been updated annually since 2001 (Friedl et al., 2010; Cai et al., 2014). The land cover is projected into geographic coordinates of latitude and longitudes on the WGS 1984 coordinate reference system. These land cover data are available as GeoTIFF format files (*.tif) I used these data for the evaluation of the effectiveness of the dust detection indices over different land cover types, namely the urban, barren and vegetated areas in the study area. Huang et al. (2015) have described the use of the MODIS land-cover data to determine and predict the impact of different covers (e.g. barren, cropland and open shrubland) on the occurrence of dust activity.

3.5. Top of the atmosphere (TOA)

Before using the MODIS bands to develop the dust indices, I calibrated the images to convert the pixel values to spectral radiance at top-of-atmosphere, which is an atmospheric correction (Zhou et al., 2008; Jiménez-Muñoz et al., 2010). The radiance, reflectance, and top-of-atmosphere (TOA) were calculated to correct the atmospheric inaccuracies, and solar angle effects were removed accurately for each band of the MODIS image. It was used by converting the top-of-atmosphere (TOA) reflectance calibration for the reflective bands and the TOA brightness temperature calibration for the thermal emissive bands (White, 2007; Zhang et al., 2014; Mousivand et al., 2015). These MODIS-calibrated reflectance data were computed using the MCTK: the MODIS Conversion Toolkit plugin for ENVI (White, 2007).

3.6. Dust events images.

In this thesis, I analysed 17 MODIS images capturing major dust storm events that occurred between 2000 and 2015 in Saudi Arabia and the surrounding areas. The dust storm in the METAR data is reported if the visibility is reduced to between 1 and 0.5 km, and if the visibility is less than 1 km, it is reported as a heavy dust storm (Steenburgh et al., 2012). The table below shows the level of visibility for each dust event that was used in the dust detection analysis (Table 3). These dust storms were described in the media as massive events that had several negative implications. For example, schools in Riyadh were closed on 26 March 2011 as a result of a huge dust storm.

Table 3 Dust events visibility level

Dust events	Visibility in km
July 20, 2000	1
February 21, 2001	0.6
July 11, 2002	1
March 26, 2003	0.1
January 24, 2004	1
June 6, 2005	0.09
March 2, 2007	0.4
February 2, 2008	1
February 20, 2008	0.5
September 10, 2008	0.5
March 10, 2009	0.09
June 8, 2010	0.4
March 26, 2011	0
March 18, 2012	0.1
January 8, 2013	0.9
May 8, 2013	0.04
April 2, 2015	0.4

3.7. Dust Storm and Climate Variable Data

This subsection will describe the dust storm data and the essential climate variable (e.g. temperature, rain, wind speed and direction) data that might be associated with the occurrence of dust storms. Furthermore, it will highlight the usefulness of the Meteorological Terminal Aviation Routine (METAR) data from World Meteorological Organization when detecting dust storms and analysing their spatial and temporal variability, as well as their impacts on human health.

To understand the dynamics of dust events and other climate variables, I used meteorological variables collected from 27 in-situ stations. These included a record of monthly observations of temperature, precipitation and wind speed for the period 2000–2016 which was available through the Presidency of Meteorology and Environment (PME) of Saudi Arabia, launched in 2001 (Almasoud & Gandayh, 2015). These in-situ stations cover most of the study area, which is situated across the 13 regions of Saudi Arabia (i.e., Riyadh, Makkah, Madinah, AlQassim, Eastern Province, Asir, Tabuk, Hail, Northern Borders, Jizan, Najran, Baha and Al-Jouf). However, the Empty Quarter desert has no weather station.

The main goal of this phase of my research was to investigate the seasonal and inter-annual average dust frequency distributions in Saudi Arabia. Monthly dust storm data from the Presidency of Meteorology and Environment (PME), Saudi Arabia for the period 2000–2016 were used for that purpose. These types of data were used in many studies about Saudi Arabia analysing any climate variables, including dust storms, rainfall, temperature and wind (Maghrabi et al., 2011; Almazroui et al., 2012; Alharbi et al., 2013; Munir et al., 2013). The data have shown that there are incomplete observational records available for two years in this period (i.e. 2002 and 2009); thus, these records were omitted from the analysis. The analysed data included monthly average climate data provided by PME for 27 in-situ meteorological stations for the period 2000–2016. These data were examined in order to determine the association between the occurrence of dust events and specific climate variables. The relevant variables were the average temperature (°C), the average numbers of rain events per station and the wind speed.

3.7.1. METAR data:

I used additional daily in-situ observation data obtained from the METAR (Meteorological Terminal Aviation Routine) aviation routine weather report at hourly or half-hourly intervals. These reports contain observations of meteorological elements such as surface wind, visibility and present weather (e.g., dust storm, haze, mist and thunderstorm), clouds of operational significance, air temperature, dew-point temperature and atmospheric pressure. They are based on the coding of the present weather, which is observed and forecasted by the World Meteorological Organization (WMO, 1995; Papadopoulos & Katsafados, 2009). The purpose of using these data was: (i) to validate the dust detection analysis; (ii) to investigate the wind speed and direction at each in situ station; and (iii) to examine the association between daily dust events and the number of hospital admissions.

The main aim of the validation method exercise was to obtain a general understanding of the effectiveness and suitability of the MODIS dust-detection results. Therefore, it has only been applied to one sample dust storm event, which occurred over the Arabian Peninsula on 2 February 2012. This dust event covered 10 sites in the Arabian Peninsula (see Chapter 4).

In order to identify the relationship between the prevailing wind directions, the wind speed and the occurrence of the dust storms in the study area (Kurosaki & Mikami, 2003; De Villiers & Heerden, 2007; Lee & Sohn, 2009) I used the daily METAR data to create the wind rose diagram. The wind rose describes the direction the wind blows from each of the five monitoring stations; I compared wind patterns for the period

2005–2017 under dust-free weather conditions versus dust storm conditions (see Chapter 5).

For the health impact analysis, I focused on two categories of dust presence (i.e. widespread dust and blowing dust) and dust-free days covering the period Feb 2015–Jan 2016. The World Meteorological Organization (WMO) has emphasized the classification of the presence of dust event by the level of visibility (Shao, 2006) as follows: (a) Widespread dust; (b) Blowing dust; (c) Slight or moderate dust storm or sandstorm; and (d) Severe dust storm or sandstorm. Several researchers have attempted to define these categories as follows: the 'widespread dust' is dust in suspension in the air with a visibility of less than 1 km (Middleton, 1986) or not greater than 10 km (Shao, 2006; Rezazadeh et al., 2013). This airborne suspended particulate matter is described as fine dust of $PM_{2.5}$ (WMO, 1995; OFCM, 1995; Todhunter & Cihacek, 1999). 'Blowing dust' is defined as dust or sand raised by the wind at the time of observation, causing a visibility range of less than 11 km (Hinds et al., 1975) but not below 1 km (Middleton, 1986; WMO, 1995; Todhunter & Cihacek, 1999; Shao, 2006; Rezazadeh et al., 2013) (Table 4).

Table 4 The two-dust events code (SYNOP)

Code figure	
06	Widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation.
07	Dust or sand raised by the wind at or near the station at the time of the observation, but no well-developed dust whirl(s), and no sandstorm seen: or, in the case of ships, blowing spray at the station

Code number 06, above, is dust in suspension or floating dust, and code number 07 is blowing dust (Camino et al., 2015; Minamoto et al., 2018; Kawai et al., 2019).

3.8. Statistical Analysis

This section will discuss the statistical analysis and tools that were used in this thesis for the dust detection methods and to determine the spatio-temporal variability of dust and the dust health impact.

3.8.1. Dust detection analysis.

Statistical analysis was pursued for dust and non-dust values. Following the Kolmogrov-Smirnov test, the dust and dust free indices values were found to be distributed abnormally; accordingly, non-parametric statistical analysis was carried out. In this study, I have evaluated the differences in the indices between dust and non-dust conditions by considering two pairs of images with a temporal separation, and as such, I had to consider these as dependent samples. Hence, the non-parametric alternative for the paired t-test, i.e. the Wilcoxon signed-rank test for paired samples, has been considered. I applied that statistical method to test the differences in index values between the pairs of dust and associated non-dust images closest in time. Moreover, I investigated the possible existence of temporal trends across the 17 MODIS between 2000 and 2015 by conducting regression analyses to obtain a better understanding of the variability in index values under both dust and dust-free conditions. The regression analysis method provides researchers with the ability to identify any significant systematic changes in the considered index over time, and to estimate the difference in the dust detection index value between dust and dust-free images in a temporal context.

The confidence interval and the model uncertainty allowed us to identify significant differences between the dust and non-dust values temporal trends in both datasets. This model uncertainty, as well as the uncertainty on the slope parameter of the linear regression model, was used to evaluate the goodness of fit of the regression lines and to draw conclusions regarding the suitability of the indices in a temporal context. Furthermore, the threshold value for dust-storm detection determined whether the dust and non-dust observations values differed significantly from each other, which enabled evaluation of the suitability of the considered index as a function of time. More specifically, I defined the threshold value as either the upper or the lower 95% confidence interval line of the model error bound of the trend line fitted through the non-dust observations, and whichever is closest to the trend line fitted through the dust storm observations. Further, the Wilcoxon signed rank test was used with the temporal regression analysis over the dust and non-dust observation considering all the pixels as well as considering the land land-cover type pixels (i.e. urban, barren and vegetation).

3.8.2. The spatio-temporal variability of dust

Data were analysed and correlated with regression analysis, which is an important method for the understanding of the variability in the observed occurrence of the dust storm events. Further, this statistical analysis allows for the identification and characterisation of the correlations among multiple variables. I also used the regression analysis to assess the possible existence of temporal trends across the study area stations between 2000 and 2016 (Rao, 1973; Schneider et al., 2010). Coefficients of determination (R2) and model uncertainty were calculated to evaluate the goodness of these fits. Furthermore, a Pearson correlation coefficient (r) analysis was used to investigate the potential existence of significant relations between the weather variables (e.g. temperature, rainfall and wind speed) and the frequency of dust storm occurrence.

Data were analysed in Microsoft Excel. Temporal linear trend fitting and five-pass filtering was completed for each observation station. Furthermore, I used an established technique, namely Python (WinPython-64bit-3.5.2.3) Pandas package (McKinney, 2011), to analyse the seasonal variation in the frequency of dust storms, as well as meteorological conditions (precipitation, temperature and wind).

The “Spline with barrier” interpolation method was applied by ArcGIS 10.5.1. This method estimates values using a mathematical algorithm which minimizes the surface curvature with a barrier of a chosen area. This method allows the researcher to generate a smooth surface based on a set of input points (Samanta et al., 2012). Here, it was used to interpolate each station dust value in order to provide continuous raster layers representing the spatio-temporal variability of dust storms across the entire study area. The interpolation was employed to detect the changes in the occurrence and frequency of dust events for the period of the study area.

3.8.3. Dust’s impact on health.

3.8.3.1. Medical data and interview data.

I analysed the data collected from King Fahad Medical City (KFMC) in Riyadh, a specialised centre that provides medical and surgical treatments and critical care. The centre, which opened on 5 October 2004, is a leader in health education, research and specialised medical training programs (KFMC, 2015). The daily data on paediatric emergency admissions for conditions of the respiratory system, categorised as upper respiratory tract infections (URTI), and lower respiratory tract infections (LRTI), for the study period 1 February 2015–31 January 2016 were analysed in MS Excel. In this study, I will explore whether the upper respiratory tract or lower respiratory tract is most vulnerable to the dust exposure.

To provide further contextual information on the wider impacts of dust, I used a qualitative analysis method of semi-structured interviews which were done with participants from the medical administrative staff in different hospitals in three cities across Saudi Arabia (i.e. Riyadh, Al-Ahsa and Al-Khobar). I sought the opinions of seven participating emergency physicians on the impacts of dust storms on population health and hospital operations. Participants were interviewed by phone at times convenient for them. The interviews were recorded, then transcribed. Ethics approval was granted by King Fahad Medical City (KFMC) hospital and the University of Exeter prior to the beginning of the study. The interview questions were:

1. What effects do dust storms have on your operations (department)?
2. What is the estimated financial impact of dust storms on your operations? Overall? For each event?
3. What is the estimated impact on human resources (e.g. staffing)?
4. Do you see an increase in patient admissions during and after dust storms? If so, how many, and with what health conditions? Is the severity of illness increased as a result of dust exposure?
5. Do respiratory diseases increase depending on age and gender?
6. What is the estimated rate of asthma in the region (e.g. Riyadh, Jeddah, Al-Ahsa, etc.)?
7. Do you have any further information about the effects of dust storms on health?

3.8.3.2. Statistical analysis of the dust impact

I started by giving overall descriptive statistics of patients admitted to KFMC hospital with respiratory problems (URTI and LRTI combined) during the study period, followed by a more detailed analysis of the data that considered patients admitted to the emergency department for each weather condition separately (widespread dust, blowing dust and non-dust).

I applied the Pearson correlation coefficient analysis to investigate the potential existence of a correlation between upper respiratory tract infection (URTI) and lower respiratory tract infection (LRTI) during the three weather conditions (widespread dust, blowing dust and non-dust) by using RStudio (The R Foundation for Statistical Computing).

To quantify hospital admissions for the two respiratory symptoms (upper and lower respiratory tract infections) during widespread dust, blowing dust and non-dust, I used a cumulative graphing technique that calculates the number of patients at hospital admissions. I also investigated the delayed effect of dust events on hospital admission by selecting multiple dust events and the days after each one, which might reveal a consistent pattern of either an increase or decrease in the number of patients at the hospital admissions. For more understanding, the cross-correlation was applied to detect if there was an increase in admissions days after a dust storm. Cross-relationship is a technique that compares the two-time series and finds objectively how they coincide and especially where the best match is made. This method is a useful statistical tool in order for determining the time lag between variables (Olden & Neff, 2001) (see Chapter 6).

4. Evaluating MODIS Dust-Detection Indices over the Arabian Penninsula[1]

4.1. Abstract

Sand and dust storm events (SDEs), which result from strong surface winds in arid and semi-arid areas exhibiting loose dry soil surfaces, are detrimental to human health, agricultural land, infrastructure and transport. The accurate detection of near-surface dust is crucial for quantifying the spatial and temporal occurrence of SDEs globally. The Arabian Peninsula is an important source region for global dust due to the presence of extensive deserts. This paper evaluates the suitability of five different MODIS-based methods for detecting airborne dust over the Arabian Peninsula: (a) Normalized Difference Dust Index (NDDI), (b) Brightness Temperature Difference (BTD) (31-32), (c) BTD (20-31), (d) Middle East Dust Index (MEDI) and (e) Reflective Solar Band (RSB). We derive detection thresholds for each index by comparing observed values for 'dust-present' versus 'dust-free' conditions, taking into account various land cover settings and analysing associated temporal trends. Our results suggest that the BTD (31-32) method and the RSB index are the most suitable indices for detecting dust storms over different land-cover types across the Arabian Peninsula. The NDDI and BTD (20-31) methods have limitations in identifying dust over multiple land-cover types. Furthermore, the MEDI has been found to be unsuitable for detecting dust in the study area across all land-cover types.

4.2. Introduction

Dust storms and sandstorms are defined as events during which constituent particles of dust and sand are raised to altitudes of up to 3000 m by strong winds (Goudie,

[1] This chapter has been published as a peer-reviewed journal article, as: Albugami, S., Palmer, S., Meersmans, J., Waine, T. 2018. Evaluating MODIS dust detection indices over the Arabian Peninsula. Remote Sensing (IF 3.4), 10, 1993. Waine's contribution was technical advice on the top of the Atmosphere (TOA) correction.

2009; Goudie & Middleton, 2006; WMO, 2005). Dust storms have been shown to have direct detrimental effects on human health, the economy and the environment (Baddock el al., 2013; Goudie & Middleton, 2001; Middleton, 2017). An example of their negative impact on health is the associated increase in instances of respiratory diseases (Furman, 2003). Dust storms may also cause an assortment of other issues, such as reduced visibility, which limits different activities and raises the risk of fatal transport crashes.

The Arabian Peninsula, classified as an arid and semi-arid climate (Alsharhan et al., 2001; Edgell, 2006), is characterised by vast sand and gravel deserts located at high-elevation plateaus. These factors mean that sand and dust storms constitute a significant natural hazard to communities across the Arabian Peninsula. One of the most damaging dust storms in the last decade swept over Riyadh city on the 10th of March 2009, resulting in dense airborne dust, causing zero visibility and a shutdown of the airport. In addition, buildings, vehicles, electricity poles and trees were damaged during this event (Alharbi et al., 2013; Maghrabi et al., 2011; WMO, 2013). During another event, on the 18th of March 2012, a dust storm swept over the Arabian Peninsula, closing schools across Saudi Arabia and sending many people to hospitals with breathing problems (Yu et al., 2013).

Despite the large detrimental effects these airborne dust events have on the region, a comprehensive study of the spatio-temporal incidence of dust storms required to understand their key drivers has yet to be undertaken. Therefore, the main aim of this paper is to evaluate the suitability and efficiency of extant satellite dust methods over the Arabian Peninsula. In addition, we aim to quantify how well these different tests perform considering a range of land-use type.

4.2.1. Previous Work

Traditionally, dust storms have been detected using observations made at fixed monitoring stations (Chavez et al., 2002). However, the discrete locations of these in-situ observations result in sparsely sampled records, especially because large areas of the Arabian Peninsula such as the Rub'al Khali desert, which covers approximately 560,000 km^2 (Edgell, 2006), do not contain monitoring stations. Where these stations do exist, records are made at high temporal resolution, typically every three hours and, in recent years, every hour, but, in practice, the archives tend to be incomplete due to technical failures and/or when the observing system is being updated or maintained. Hence, there is keen interest in using satellite images to identify dust storms, because such images have the potential for providing regularly repeated, consistent observations of airborne dust events over the entire Arabian Peninsula. As a consequence, satellite observations can provide observations of the instantaneous extent of a dust storm, which in-situ measurements cannot.

Satellite observations are a powerful tool for examining the characteristics of large-scale dust storms. More precisely, the application of indices and algorithms for detecting airborne dust at the time the satellite passes over provides instantaneous information about the location and extent of individual dust storms. Previous studies have used a range of satellite observations to remotely detect airborne dust such as the TOMS aerosol index to monitor dust storms (Alpert & Ganor, 2001; Barkan et al., 2004; Chiapello et al., 1999; Herman et al., 1997; Prospero et al., 2002). Other studies have used the SEVIRI instrument to detect and identify dust sources (Brindley & Russell 2006; Schepanski et al., 2007; Schmetz et al., 2002). While this instrument provides observations at very high temporal resolution (15 mins), the high-altitude geostationary orbit and fixed acquisition geometry result in insufficient spatial resolution required to understand spatial variations in airborne dust and its drivers. Due to its lower orbit, wide swath and broad spectral bandwidth, the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, on board NASA's Terra and Aqua satellites, is particularly well-suited for detecting and monitoring airborne dust. Moderate Resolution Imaging Spectroradiometer (MODIS) was launched on the 18th of December 1999. The satellites follow polar orbit with a repeat period of 16 days and have north-to-south equator crossing times of about 10:30 am and 1:30 pm respectively. While MODIS gives almost full worldwide coverage each day, they do not provide the same level of high temporal sampling as e.g., the SEVIRI instrument on board the Geostationary orbiting Meteosat. This means MODIS observations of individual dust storm events are discontinuous, limiting the ability to observe how individual events evolve over time. However, this is compensated by the much higher spatial and spectral resolution of MODIS, which has 36 spectral channels and generates imagery at spatial resolutions 250 m, 500m and 1km, depending on the channel (Turner et al., 2003). Hence, several previous studies have developed and described dust-detection tests based on MODIS data (Karimi et al., 2012; Kaufman et al., 2005; Miller, 2003; Samadi et al., 2014; Yue et al., 2017). Consequently, the aim of this study is to evaluate which of the existing MODIS dust detection methods are most effective over the Arabian Peninsula.

4.2.2. Study Area

Figure 1 (see chapter 1) presents the location and the elevation map of the study area. Most of the Arabian Peninsula lies within a wide band of deserts; some of these dry lands are covered with drifting sand dunes (Mallon, 2011). The high-elevation plateaus of the Arabian Peninsula are intersected by numerous shallow valleys, while the southern part of the peninsula is dominated by the Rub' al Khali (Empty Quarter) desert, the largest sand desert in the world, covering an area of approximately 560, 000 km^2 and characterised by an average total annual precipitation of less than 100 mm (De Pauw, 2002). In addition, the large An Nafud desert is situated in the northern part of the peninsula with an area of 70, 000 km^2 (Faulkender, 1986), while, in the east of Saudi Arabia, there is the Ad Dahna desert, which is about 1,450 km^2 (Vincent, 2008) (Figure, 1). The dominance of sand-covered areas makes the Arabian Peninsula a challenging region to detect airborne dust.

4.3. Materials and Methods

In this paper, we analysed seventeen MODIS images capturing major dust storm events that occurred over the Arabian Peninsula between 2000 and 2015. More precisely, Saudi Arabia and the surrounding area covered by the bordering states located on the Arabian Peninsula were considered (as indicated in Figure 8). The a priori extent of these events were defined using visual interpretation of the MODIS true colour (RGB) images (Figure 9), which was then validated using in-situ observations METAR (Meteorological Terminal Aviation Routine) observations issued at hourly or half-hourly intervals (Baltaci, 2017). Moreover, the same method was applied to the dust-free observations we used in-situ measurements to validate dust-free images. We compared each 'dust storm' image with a 'dust-free' MODIS image from a nearby point in time and in the same location with the exact extent of the dust storm as shown in (figure 8) in order to evaluate the various MODIS dust-detection approaches. Moreover, we evaluated the suitability of dust-detection indices for each land-cover type. We used MODIS Level 1B Calibrated Radiances 1km (MOD021KM) observations for our analysis. Once downloaded, we converted the pixel values using the Top of Atmosphere

(TOA) reflectance calibration for the reflective bands, and the TOA brightness temperature calibration for the thermal emissive bands. Hence, each MODIS image was corrected after the atmospheric and solar angle effects were removed accurately (but not atmospheric distortions or dust). These MODIS-calibrated reflectance data were computed using the MCTK: the MODIS Conversion Toolkit plugin for ENVI (White, 2007).

The present study aims to define the suitability and threshold for each of the considered dust detection indices. In this context, we also aim to reveal the possible existence of temporal trends. Moreover, we compared the results with in-situ observations of airborne dust from Saudi Arabia meteorological observation stations as reported in METAR aviation weather reports issued at hourly or half-hourly intervals. The main aim of this validation exercise is to obtain a general understanding of the effectiveness and suitability of the studied dust-detection indices, and therefore, it has only been applied to one major dust storm event as an example. The MEDI index was unable to make a distinction between dust and non-dust circumstances, therefore, it was omitted from the validation analysis.

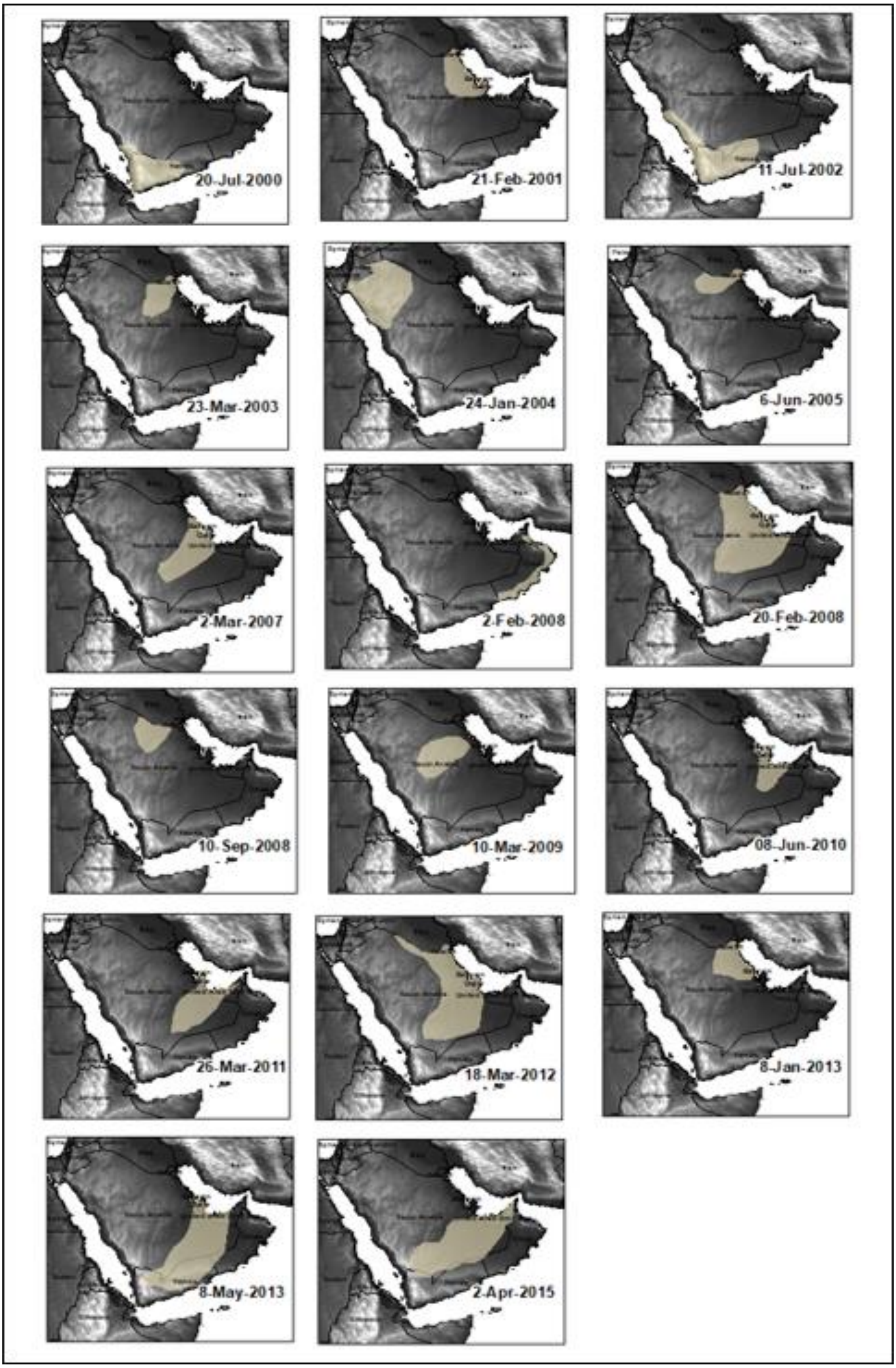


Figure 8 The extent of the 17 dust storms over the Arabian Peninsula as indicated by light grey-coloured polygons with a topographic map (grey scaled) as background.

4.3.1. Moderate Resolution Imaging Spectroradiometer (MODIS) images

MODIS satellite observations have been used to detect airborne dust in previous studies. In 1997, Ackerman introduced the combination of the Brightness Temperature (BT) method for multiple channels. As this method considers the emissive properties of dust, it is sensitive to variations in chemical structure and size distribution (Merchant et al., 2006; Sokolik, 2002). Multiple studies have attempted to further develop this index by introducing more robust versions based on the Brightness Temperature Difference (BTD) between two wavelength channels (e.g. Darmenov & Sokolik, 2005; Roskovensky & Liou, 2005). However, during recent years, researchers have considered more advanced techniques focusing on dust storm detection through the use of various indices, such as the Normalized Difference Dust Index (NDDI) (Miller, 2003; Qu et al.,2006) and the Middle East Dust Index (MEDI) (Karimi et al., 2012; Moridnejad et al., 2015).

4.3.2. MODIS Cloud Mask

As clouds affect the successful detection of dust storms, we used the MODIS cloud mask Level 2 product (MOD35) to indicate the presence of cloudy pixels. The reason for using the MODIS cloud mask is to restrict the analysis to areas free of clouds (Ackerman et al., 1998). However, the cloud mask tends to misclassify thick dust storms as clouds. This might affect dust detection (Martins et al., 2002).

4.3.3. MODIS Land Cover

Most previous work has only distinguished between bright land cover and dark land cover (Barren–Vegetation); however, the performances of the observation in reflective bands are different over various land cover types (Samadi et al., 2014). In this study, we go further by evaluating how the effectiveness of the various dust detection tests varies between urban, barren and vegetated areas within each region. We used the MODIS Land Cover Type product, MCD12Q1 at 500 m resolution (Friedl et al., 2010) in order to evaluate which of the considered indices is the most effective test for detecting airborne dust over these different land-cover types.

4.3.4. MODIS

We evaluated the following existing MODIS dust detection approaches:

- **The normalised difference dust index:**

The NDDI, used in several previous studies (Miller, 2003; Qu et al., 2006; Samadi et al., 2014), is calculated using reflective solar bands 3 and 7 of MODIS (eq. 1). The spatial resolution of these bands is 500 m and is characterised by a spectral reflectance at a wavelength range of 459 – 479 µm for band 3 and 2105 – 2155 µm for band 7. These bands are often used for land surface studies, for detection of aerosols and to obtain information on clouds' optical thickness, phase and effective radius.

$$NDDI = (B7-B3) / (B7+B3), \qquad (1)$$

- **Brightness Temperature Difference (BTD) indices:**

BTD methods utilise differences between multiple thermal emissive bands and have been used successfully across a wide range of regions (Ackerman, 1997; Karimi et al., 2011; Legrand et al., 2001; Samadi et al., 2014). The most commonly used thermal emissive bands are BT20, BT31 and BT 32, which are characterised by a wavelength range of 3.66 – 3.84 µm, 10.78-11.28 µm and 11.77-12.27 µm, respectively, and a spatial resolution of 1000 m. The equations for the existing BTD-related indices considered in this study are given by equations eq. 2 and 3. The unit of these indices is Kelvin (K).

$$BTD\ (31\text{-}32) = BT31 - BT32, \quad (2)$$

$$BTD\ (20\text{-}31) = BT20 - BT31, \quad (3)$$

- **The Middle East Dust Index:**

As Karimi et al. (2012) found that bands 31 and 32 are having issues in distinguishing airborne dust from the desert surface, they presented a new method called the Middle East Dust Index (MEDI) (Karimi et al., 2012; Komeilian et al., 2014; Moridnejad et al., 2015). This index is based on Ackerman's dust detection technique but includes also band 29. Hence, the MEDI is calculated using thermal emissive bands BT29, BT31 and BT32 (eq. 2) with wavelength ranges of respectively 8.40 - 8.70 µm, 10.78 - 11.28 µm, 11.77 - 12.27 µm at a spatial resolution of 1000 m, and has the specific purpose of differentiating airborne dust and desert surfaces.

$$MEDI = (BT31 – BT29) / (BT32 – BT29), \quad (4)$$

- **The Reflective Solar Band-derived index:**

Finally, we also consider an index derived from the MODIS reflective solar bands B2 (841-876 nm) at a spatial resolution of 250 m and B18 (931-941 nm) at a spatial resolution of 1000 m (eq. 5) as developed by Samadi et al. (2014). This index has been used over the western part of Iran to detect dust over bright and dark surfaces (Samadi et al., 2014).

$$RSB\ (2\text{-}18) = B2 - B18, \quad (5)$$

4.4. Statistical Analysis

We have analysed differences in index values between pairs of dust and associated non-dust images closest in time via the Wilcoxon signed rank test for paired samples. More precisely, as the Kolmogorov-Smirnov test indicated that most of the considered datasets were non-normally distributed, we chose the Wilcoxon signed rank test for paired samples to conduct this analysis, as it is the non-parametric alternative of the more commonly used paired t-test.

To obtain a more profound understanding of the variability in index values under both dust and dust-free conditions, we also investigated the potential existence of temporal trends across the 17 observations between 2000 and 2015 by conducting regression analyses. This regression analyses allowed us to (i) detect any significant systematic changes in the considered index over time and (ii) assess the difference in the index value between dust and dust-free conditions in a temporal context. Model uncertainty, as well as the uncertainty on the slope parameter of the linear regression model, were used to evaluate the goodness of fit of the regression lines and to draw conclusions regarding the suitability of the indices in a temporal context. The threshold value for dust-storm detection determined whether the dust and non-dust observations are significantly different, enabling an evaluation of the suitability of the considered method as a function of time. More precisely, the threshold value was defined as either the upper or the lower 95% confidence interval line of the model error bound of the trend line fitted through the non-dust observations, whichever is closest to the trend line fitted through the dust storm observations. We applied the Wilcoxon tests and temporal regression analysis across the entire selected dust storm-affected areas considering the pixels regardless of their land-cover classification as well as separately stratified by land-cover type (i.e. urban, barren and vegetation).

4.5. Results

4.5.1. Dust detection validation

We used in-situ observations of a dust storm over the Arabian Peninsula on the 2nd of February 2012 to validate the MODIS dust-detection results. This intense dust storm initially occurred in the northeast of the peninsula and moved later further towards the southwest (Figure 3). The in-situ observations from 10 sites over the Arabian Peninsula (e.g. Riyadh - Wadi al-Dawasir - Al-Ahsa -Dammam - Jubail - Al-Kharj- Qassim - Dawadmi - Manama - Doha) were used to validate the results obtained by applying the various MODIS dust-detection indices. In essence, by comparing the dust detection results with the observation data the effectiveness of the threshold in identifying dust was tested. Note that the cloud mask was used to eliminate the pixels for which the presence of cloud might affect the detection result. Figure 3 shows a MODIS true-colour image illustrating the total extent of this particular dust storm event. Table 5 presents the outcome of the dust detection by using the threshold values determined in this paper. We compared the dust detection results with the observation data to test the effectiveness of the threshold in identifying the dust. Figure 4 presents the area within the total extent of the dust storm for which a given index indicated the presence of dust. Sub-panel (a) shows the result of the land cover independent dust detection index, whereas sub-panel (b) shows the outcome of the land cover specific dust detection indices. Within the latter, only the land use pixels of which the considered index is able to detect dust are displayed.

Table 5 the Validation of Index Performance over Different Land Cover (Dust Event February 2, 2012)

Stations	in situ	NDDI	BTD(31-32)	BTD(20-31)	RSB
		Barren			
Riyadh	*	✓	✓	✓	X
Wadi al-Dawasir	*	✓	X	X	✓
Al-Ahsa	*	✓	✓	✓	✓
Dammam	*	✓	✓	✓	✓
Jubail	*	✓	✓	✓	✓
Al-Kharj	*	✓	✓	✓	X
Qassim	*	✓	✓	✓	X
Dawadmi	*	✓	✓	✓	X

Manama	*	✓	✓	✓	✓
Doha	-	X	✓	✓	✓
Urban					
Riyadh	*	+	✓	✓	X
Wadi al-Dawasir	*	+	X	X	X
Al-Ahsa	*	+	✓	✓	✓
Dammam	*	+	✓	✓	✓
Jubail	*	+	✓	✓	✓
Al-Kharj	*	+	✓	✓	✓
Qassim	*	+	✓	✓	✓
Dawadmi	*	+	✓	✓	✓
Manama	*	+	✓	✓	✓
Doha	-	+	✓	✓	✓

* *In-situ* Dust recorded, - No *in-situ* dust records, ✓ The MODIS dust detection index indicates the same outcome as the in-situ observations, X The dust detection index indicates a different outcome to the *in-situ* observations, + Test not suitable.

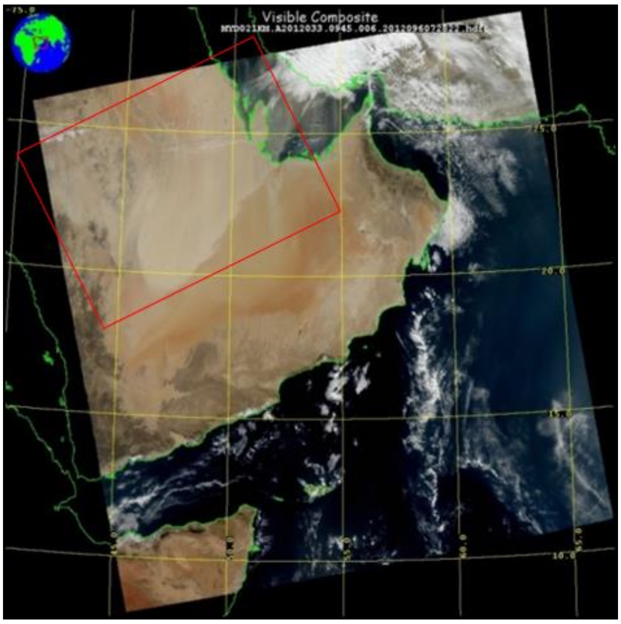


Figure 9 An RGB true colour image of MODIS observation indicating the extent of the dust storm over the Arabian Peninsula on the 2nd of February 2012.

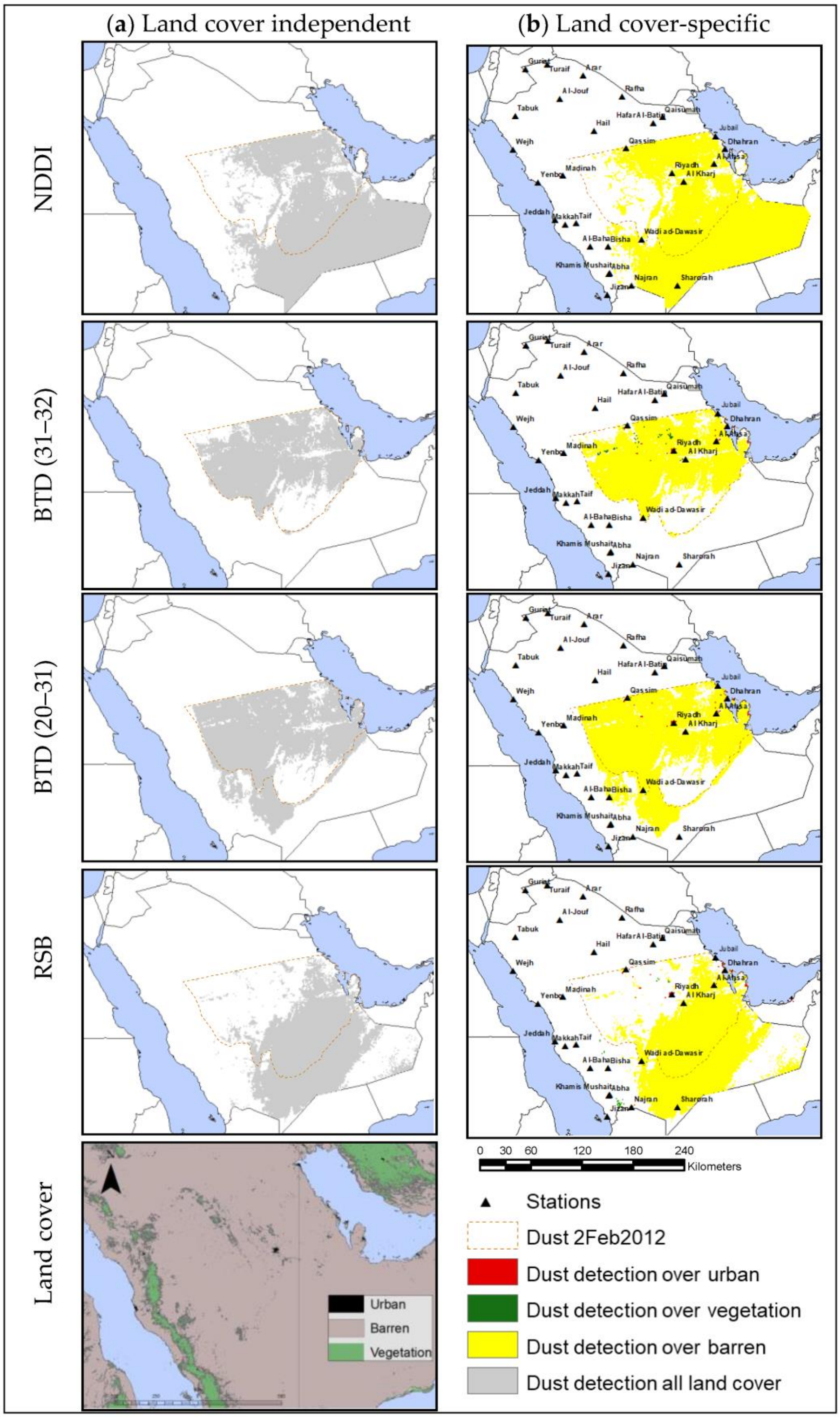


Figure 10 Validation results within subpanels (a) the detected dust-storm area irrespective of land cover types, and in subpanels (b) the detected dust-storm area using different threshold values for each land cover type (the dashed polygon indicates the extent.

4.5.2. Land cover independent analysis

When considering all the land uses together, the results show that the NDDI values under dust and dust-free conditions are significantly different (Wilcoxon P value = 0.000, Table 6), suggesting that NDDI is a useful index for dust-detection. Nevertheless, Figure 5 shows a clear increasing trend in mean NDDI values over time under non-dust circumstances, as indicated by significant slope parameter values ($P<0.01$, Table 6) representing yearly index increases of 0.0109 ± 0.0035 yr-1 under non-dust conditions (Table 7).

Figure 5 shows that the trend lines fitted through the dust and non-dust situations for the BTD indices are close to each other in the early years (2000-2004), in which the 95% uncertainty bounds overlap. However, the Wilcoxon signed-rank test indicates a significant result with P values of 0.002 for BTD (31-32) and for BTD (20-31). Furthermore, the associated linear regression slope parameter for the BTD (31-32) index has been found to be significant only at the 90% but not at the 95% level of confidence for the dust value (i.e., -0.0174 ± 0.0100 yr-1, Table 6), whereas, under dust-free conditions, this was found not to be significant. However, the threshold value to detect dust in the atmosphere for the BTD (31-32) and BTD (20-31) varies over time (between 2000 and 2016) from below ca. 0.45 K to 0.7 K and above ca. -8 K to -9 K, respectively (Figure 5). Our results show that differences in MEDI values between dust and non-dust values are not significant when considering all land uses (i.e., a Wilcoxon signed-rank test with a P value 0.758; Table 2). In addition, the analysis did not show a significant linear regression slope parameter (Table 6) underlining the absence of a temporal trend in MEDI value as shown in Figure 11. The Wilcoxon test showed that the RSB index provides significantly different values for dust versus non-dust values detected (P =0.005; Table 4). The trend line in the RSB index demonstrates clear discrimination between the dust and non-dust data-series (see Figure 11).

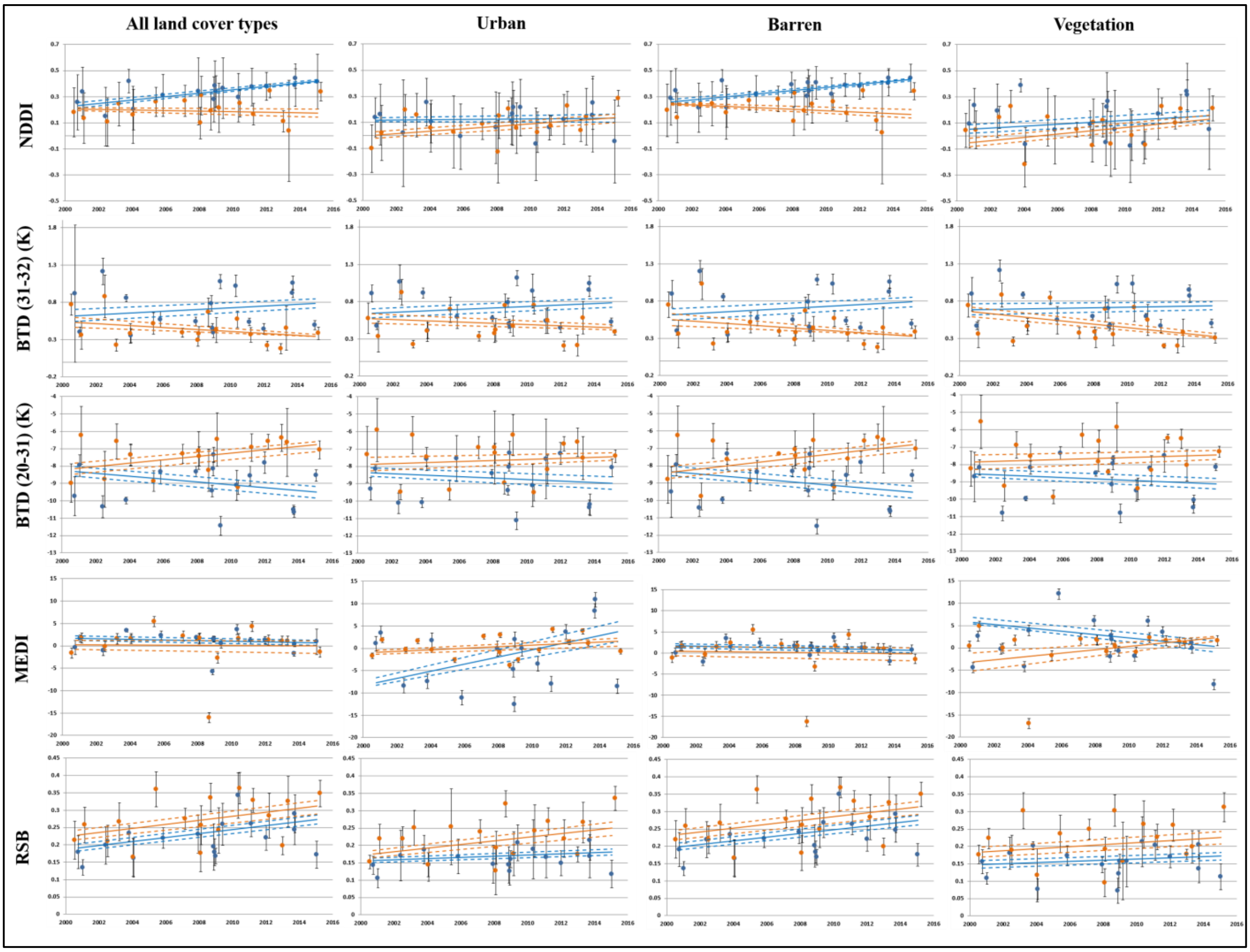


Figure 11 Dust indices generalized for all land-cover types and land cover-specific analysis (Urban, Barren and Vegetation).The scatter plots showing for all indices the temporal trends fitted through the mean index value per event as a result of a linear regression, with associated model error bounds (at 95% confidence interval) considering all pixels. The error bars represent the standard deviation for each individual observation. The orange dot represents the dust data and the blue non-dust. The units for all indices are dimensionless, except for BTD where this is in Kelvin.

Table 6 Wilcoxon Signed Ranks Test P Values for Each Index Considering All Pixels and Land Cover.

	NDDI	**BTD(31-32)**	**BTD(20-31)**	**MEDI**	**RSB(2-18)**
All land cover	0.000 **	0.002 **	.002 **	.758	.005 **
Urban	0.381	0.005 **	.015 *	.210	.002 **
Barren	0.000 **	.002 **	.003 **	.868	.000 **
Vegetation	0.049 *	.006 **	.007 **	.943	.001 **

* p *<0.05 (95% confidence),* ** p *<0.01 (99% confidence).*

Table 7 Slope Coefficient Values of the Temporal Linear Regression Analysis with Associated Uncertainty Value (and Level of Confidence).

Slope coeff ± SE (yr^{-1})	**NDDI**		**BTD(31-32)**		**BTD(20-31)**		**MEDI**		**RSB(2-18)**	
	Non-Dust	**Dust**	**Non-Dust**	**Dust**	**Non-Dust**	**Dust**	**Non-Dust**	**Dust**	**Non-Dust**	**Dust**
All land cover	0.0109± 0.0035**	-0.0042± 0.0050	0.0008 ± 0.0164	-0.0174 ± 0.0100°	-0.0261 ± 0.0708	0.0733 ± 0.0548	-0.0473 ± 0.1252	-0.0536 ± 0.2658	0.0054 ± 0.0026*	0.0062 ± 0.0033°
Urban	-0.0019 ± 0.0056	0.0097 ± 0.0058°	0.0023± 0.01452	-0.0083 ± 0.01181	-0.0055± 0.0719	0.0072± 0.0679	0.2668 ± 0.3839	0.1041 ± 0.1326	0.0015 ± 0.0016	0.0051± 0.0030 °
Barren	0.0101 ± 0.0031**	-0.0035± 0.0050	0.0001 ± 0.0164	-0.0198 ± 0.01120°	-0.0310 ± 0.0713	0.0842 ± 0.0591	-0.0276 ± 0.0891	-0.0777 ± 0.2704	0.0050 ± 0.0027°	0.0060 ± 0.0033°
Vegetation	0.0057± 0.0086	0.0063 ± 0.0070	-0.0050 ± 0.0142	-0.0210 ± 0.0116°	-0.0075 ± 0.0671	0.0183 ± 0.0730	-0.0980 ± 0.2719	0.1960 ± 0.2625	0.0011 ± 0.0024	0.0031 ± 0.0035

° 0.05< p *<0.1 (90% confidence),* * p *<0.05 (95% confidence),* ** p *<0.01 (99% confidence).*

4.5.3. Land Cover-specific Analysis

We investigated the inter-annual variability of dust and dust-free values over different land cover (Figure 11). This approach was chosen to evaluate which of the dust indices is the most useful test for detecting airborne dust over the different major land-cover types present in Saudi Arabia (i.e., urban, barren and vegetation), building on the findings of previous studies that found differences in dust-detection results depending on the land-cover settings (Samadi et al., 2014).

Considering the NDDI index for urban areas, the trend line and the data overlap in recent years. This convergence of the lines seems to be the consequence of remarkably different slope parameter values of the linear regressions, which has been found to be significant at P <0.1 (but not at P < 0.05) under dust conditions (i.e., 0.0097 ± 0.0058 yr-1, Table 7), but not significant under non-dust conditions (i.e., -0.0019 ±

0.0056 yr-1, Table 7). In addition, the Wilcoxon signed-rank test shows that the result is not significant at $P \leq 0.05$ in NDDI values under dust versus non-dust circumstances (P value = 0.381; Table 6).

The results of the BTD (31-32) and BTD (20-31) are significantly different under dust versus dust free conditions (i.e., P value = 0.005 and 0.015, respectively; Table 4). We note from Table 6 that BTD (31-32) and BTD (20-31) have no significant linear regression slope parameters for both dust and non-dust values. Therefore, we suggest a dust-detection threshold value for the BTD (31-32) of below 0.5 K and above -8 K for the BTD (20-31).

As shown in Figure 5, the high inter-annual variability in the index values in MEDI does not allow the determination of a clear threshold value for dust detection. Additionally, the P value is 0.210, which means it is not significant at $P \leq 0.05$ for dust and non-dust values (Table 6).

Finally, the RSB index result shows a significant difference under dust versus non-dust conditions. with a P value = 0.002), especially in recent years, as the difference between dust and non-dust image increases considerably over time in particular between 2012 and 2015. Moreover, the threshold value remains approximately constant at 0.175 (Figure 5). Also, our analysis shows a significant difference in the linear regression slope parameter only over dust conditions at $P < 0.1$ (but not $P < 0.05$) (i.e., 0.0051± 0.0030 yr-1) (Table 7).

In addition, significant difference between dust and non-dust index values over the barren area have been identified for NDDI, BTD (31-32), BTD (20-31) and RSB (Figure 11), characterised by P values of 0.000, 0.002, 0.003 and 0.000 respectively (Table 6).

Figure 5 also presents the indices for vegetated areas. The associated differences in the NDDI index values under dust and the non-dust condition is significant (P value = 0.049; Table 6). In addition, the associated linear regression slope parameter values for this index are found to be not significant under dust free and dust conditions (i.e. 0.0057 ± 0.0086 yr-1 and 0.0063 ± 0.0070 yr-1, respectively) (Table 7). The BTD (31-32) analysis confirms a significant difference between dust versus non-dust conditions (i.e., P value = 0.006; Table 6). Our analysis shows that the threshold value is ca. 0.6 K (Figure, 11).

Our results suggest that the RSB index is effective at detecting dust when considering vegetated areas (with significantly different index values under dust versus non-dust conditions at a P value = 0.001; see Table 6). Moreover, the associated linear regression slope parameter has been found to be non-significant (see Table 7, with a threshold value of ca. 0.16-0.18) (Figure, 11).

4.6. Discussion

4.6.1. Validation

From the validation results, as shown in Table 1, we can see that the NDDI index has limitations in distinguishing airborne dust from the desert areas. The BTD method reveals an ability to detect dust and distinguish dust from different lands, however, the

BTD (31-32) did not detect dust over two locations (Table 5). Furthermore, the BTD index failed to detect dust because the barren area was falsely detected as a dust storm (Park et al., 2014). In addition, there is some false detection over the urban areas (Figure 4). Moreover, the RSB method highlighted false detection over the vegetation area; however, it did detect 8% of the dust storm area (Table 5). Also, it is interesting to note that the BTD (20-31) and RSB detect dust in the urban area (Bisha) which is not in the extent of the dust storm as shown in figure 4. Our results show that each dust detection method has some limitations in detecting dust over different land covers.

4.6.2. Land cover independent

4.6.2.1. NDDI

The threshold value to detect dust in the atmosphere (defined in this case as the lower 95% confidence interval line of the model error bound of the trend line fitted through the non-dust observations) increases over time from below ca. 0.25 in 2000 to 0.4 in 2015 (Figure 5). Hence, the strong significant temporal trend in NDDI values illustrates that the NDDI can only be considered as a successful method to detect dust storms when a dust-free image from a period in time nearby (preferentially < 1 year apart) is available. In addition, the dust in the NDDI index will be detected whenever the index value exceeds the identified threshold.

4.6.2.2. BTD

The results from the commonly used BTD indices (i.e., BTD [31-32] and BTD [20-31]), were in line with previous studies (Ackerman, 1997; Hansell et al., 2007) as we found that the indices are useful for detecting dust storms across the Arabian Peninsula, especially in recent years. However, these indices seem less suitable in early years (ca. 2000 – 2003) as, here; the 95% confidence intervals tend to overlap. Moreover, the BTD indices will detect dust whenever the index value is above the threshold.

4.6.2.3. MEDI

As few studies have been published using the MEDI test (e.g., Karimi et al., 2012; Moridnejad et al., 2015), in our analysis, we found that band 29 has an error which might have affected the results in some of these cases. However, the results clearly indicate that the use of the MEDI is not advisable for dust detection in Saudi Arabia due to the lack of a clear distinction between dust and not-dust values as indicated in Figure 11. It is worthwhile noting that this poor performance of this index was not expected because it is specifically designed to detect airborne dust in arid areas.

4.6.2.4. RSB

For this test, our results reveal a significant linear increase in index values under dust conditions ($P < 0.1$, $0.0062 \pm 0.0033\ yr^{-1}$) and a significant increase in non-dust values (i.e., $P < 0.05$, $0.0054 \pm 0.0026\ yr^{-1}$), which highlights the need for a contemporaneous dust-free image in order to be able to detect the presence of airborne dust. Therefore, the threshold value also increased over time from ca. 0.21 to 0.29 between 2000 and 2016 (Figure 11). Our analysis indicates that the RSB index can detect dust whenever the index value is over the fixed threshold.

The findings of the four dust detection indices (BTD methods, NDDI and RSB) confirm the temporal trends in the observed values. We suggest that these may indicate changes in prevailing atmospheric conditions and/or changing land use, although more research is required to identify the drivers behind these temporal trends. In addition, our analysis emphasises that all indices require a cloud mask to avoid misclassification between the dust and clouds. Our analyses suggest that all MODIS indices except MEDI are useful in determining dust detection thresholds when considering all land cover types. However, during the period 2000-2003, the NDDI and BTD tests require a contemporaneous dust-free image to identify the optimal threshold. This is also the case for the RSB index after 2014 (Figure 11).

4.6.3. Land cover specific analysis

4.6.3.1. Urban

Our results demonstrate that the NDDI is not useful index in detecting dust over urban areas (Figure 11). On the contrary, the results seem to indicate that the BTD (31-32) and BTD (20-31) are efficient indices for detecting dust over urban areas, with significantly different index values under dust versus non-dust conditions. However, it is important to note that, in early years (2000 – 2003), this index seems less suitable as the curve's 95% confidence intervals are overlapping. Furthermore, the results illustrate that the RSB index is effective at detecting dust over the urban area. Importantly, our findings suggest that no comparison with a dust-free image from a comparable period of time is required in order to detect dust.

4.6.3.2. Barren

The results of the barren area are similar to the results obtained when considering the overall land cover results because the majority of the Arabian Peninsula is barren (Figures 11). Hence, the same conclusions can be made as presented in the previous section which considered the land cover independent analysis. Temporal trends in the NDDI index values under dust and non-dust storm conditions, as well as an associated threshold values, have been identified for the indices. The NDDI result shows that the associated linear regression slope parameter has been found to be significant for the non-dust images (i.e., 0.0101±0.0031 yr^{-1}); therefore, the threshold value does not remain constant but varies from ca. 0.25 to 0.4 (Figure 5). Our findings agree with previous studies indicating that NDDI can be used to detect dust over barren areas (e.g., Li & Song, 2009; Qu et al., 2006). Our results reveal the existence of a temporal trend in this particular index value, which makes the NDDI only suitable when a non-dust image from a nearby moment in time is available between (2000 - 2003). However, in more recent MODIS images, there is no need to compare a dust-storm image with a non-dust image when attempting to detect airborne dust over the Arabian Peninsula using the NDDI.

When considering the BTD (31-32) output, our findings are in line with Samadi et al. (2014), showing a detection threshold increasing over time from ca. 0.6 K to 0.7 K (Figure 11). However, the associated linear regression slope parameter has been found to be significant for the dust values ($P < 0.1$, -0.0198 ± 0.01120 yr^{-1}) (Table 7). In addition, for the BTD (20-31) index, the associated slope parameter value for dust and dust-free circumstance has been found to be non-significant (Table 6), but the threshold values tend to decline over time from ca. -8 K to -9 K.

As mentioned in the section above, the MEDI index is unable to make a distinction between dust and non-dust circumstances for barren areas, as indicated by the Wilcoxon signed-rank test P values of 0.868 (Table 6). Hence, this analysis confirms the unsuitability of this index under this specific land cover. For the RSB index, the Wilcoxon test reveals significant different values between dust and non-dust values ($P = 0.000$; Table 6) However, the associated slope parameter values have been found to be significant ($0.05 < P < 0.1$) under both dust circumstances (i.e., 0.0060 ± 0.0033 yr^{-1}) and non-dust circumstances (0.0050 ± 0.0027) , resulting in an increasing threshold value over time from ca. 0.2 to 0.3 (Figure 11), underlining the need for a non-dust image from a nearby moment in time in order to make this index suitable for dust detection over barren areas.

4.6.3.3. Vegetation

Our result shows that the NDDI values representing dust and non-dust conditions almost overlap in more recent years (especially from 2008 to 2015) (Figure 11). Hence, the converging character of these curves indicates that the suitability of this index is restricted to the early years only (2000-2008). On the contrary, the BTD (20-31) and MEDI methods have failed to distinguish dust values from non-dust values over the vegetated areas. Despite the significantly different index values under dust versus non-dust conditions (i.e., P value = 0.007; Table 6), the pattern of inter-annual variability in the index values indicates that the determination of a clear threshold value for dust detection is impossible. This is demonstrated by the fact that the uncertainty bounds are overlapping. However, our findings confirm previous studies (e.g., Samadi et al., 2014) which demonstrate that RSB index can detect airborne dust over dark surfaces such as vegetation.

Unexpectedly, our results clearly show temporal trends for dust and non-dust values. Moreover, as can be seen in Figure 11, the RSB trends are mostly consistent across the different land cover in dust and dust-free values. In contrast, the other indices show that there is a difference in the trends observed for dust and non-dust conditions. Previous studies have noted that MODIS sensor degradation can introduce temporal artefacts into time series of MODIS C5 observations (Levy el al., 2010; Wang el al., 2012), we suggest this is unlikely in our study as we are using C6 data, which includes an improved calibration to take this into account (Sayer el al., 2015; Casey el al., 2017). However, the observed temporal trends may indicate long-term changes in atmospheric conditions such as the increased temperature and the decrease in the precipitation over the Arabian Peninsula, which may alter the reflectance properties of the surface over time (AlSarmi and Washington, 2011; Almazroui el al., 2012; Donat el al., 2014). This is supported by studies which have sown increased desertification in the study area (Abahussain el al., 2002; Amin, 2004; Sen, 2013). It is also possible that land use changes in the region have changed the surface reflectance properties, such as the expansion of the urban areas in Saudi Arabia (Alqurashi and Kumar 2014; Rahman, 2016). In addition, the various trends of the dust storm values may reflect variations in atmospheric conditions (i.e. temperature, wind speed, and precipitation), the human activities of urbanization and the changes in the feature of the land cover. (Kaskaoutis el al., 2011; Aili el al., 2016). While we note that these suggested temporal trends are very interesting and warrant further investigation, an in-depth analysis of them is beyond the scope of this study.

4.7. Conclusions

We have evaluated the suitability of multiple MODIS dust-detection indices across the entire Arabian Peninsula. The main finding of this study is that the BTD (31-32) test and the RSB test are the most useful MODIS indices to detect airborne dust over different land cover settings. Furthermore, the NDDI is a suitable method to distinguish dust from non-dust circumstances over barren areas. Our results show unambiguously that the detection of airborne dust above urban areas is not possible when using the NDDI index. Also, the BTD (20-31) is a useful method except for the vegetation areas.

Our findings suggest that the determination of a suitable dust-detection threshold, to be used with these indices, requires the use of dust-free ‘reference images’ from the same period. Further, the dust-validation analysis reveals that the BTD (31-32) method is a successful index for detecting dust storms over different land cover. However, more work is needed to improve the accuracy of detection thresholds as a function of time. Finally, we identified a clear need for further research to investigate the possible drivers of the temporal trends we observe in our results.

5. Spatial and temporal variations in the incidence of dust storms in Saudi Arabia revealed from in-situ observations[2]

5.1. Abstract

Monthly meteorological data from 27 observation stations provided by the Presidency of Meteorology and Environment (PME) of Saudi Arabia were used to analyze the spatial and temporal distribution of atmospheric dust in Saudi Arabia between 2000 and 2016. These data were used to analyze the effects of environmental forcing on the occurrence of dust storms across Saudi Arabia by considering the relationships between dust storm frequency and temperature, precipitation, and wind variables. We reveal a clear seasonality in the reported incidence of dust storms, with the highest frequency of events during the spring. Our results show significant positive relationships ($p < 0.005$) between dust storm occurrence and wind speed, wind direction, and precipitation. However, we did not detect a significant relationship with temperature. Our results reveal important spatial patterns, as well as seasonal and inter-annual variations, in the occurrence of dust storms in Saudi Arabia. For instance, the eastern part of the study area experienced an increase in dust storm events over time, especially in the region near Al-Ahsa. Similarly, an increasing trend in dust storms was also observed in the west of the study area near Jeddah. However, the occurrence of dust storm events is decreasing over time in the north, in areas such as Hail and Qaisumah. Overall, the eastern part of Saudi Arabia experiences the highest number of dust storms per year (i.e., 10 to 60 events), followed by the northern region, with the south

[2] This chapter has been published as a peer-reviewed journal article, as: Albugami, S., Palmer, S., Cinnamon, J., Meersmans, J. 2019. Spatial and temporal variations in the incidence of dust storms in Saudi Arabia revealed from in-situ observations. Geosciences, 9, 162

and the west having fewer dust storm events (i.e., five to 15 events per year). In addition, our results showed that the wind speeds during a dust storm are 15–20 m/s and above, while, on a non-dust day, the wind speeds are approximately 10–15 m/s or lower. Findings of this study provide insight into the relationship between environmental conditions and dust storm occurrence across Saudi Arabia, and a basis for future research into the drivers behind these observed spatio-temporal trends.

5.2. Introduction

Dust storms are natural phenomena which usually occur in desert areas (Goudie and Middleton, 2001; Yang et al., 2008; Rezazadeh et al., 2013). These events happen as a result of strong winds which raise dust and sand from deserts and surrounding areas and carry it over large distances. The African and Asian deserts are the major sources of dust worldwide (Knippertz et al., 2007; Miller et al., 2008; Pye, 2015). Besides the African Sahara region, the Middle East is the world region most affected by dust storms (Furman, 2003; Washington et al., 2003; Barnum el al., 2004; Rezazadeh; et al., 2013) and within the Middle-East it is well known that the Arabian Peninsula is one of the largest source areas of dust storms (Prospero et al., 2002; Luo et al., 2004). The vast dunes and deserts on the Arabian Peninsula and surrounding topographically-complex terrain characterized by very low amounts of precipitation and sparse vegetation cover are the essential ingredients to rouse dust into the air (Al-Sanad et al.,1993; Edgell, 2006; Al-Bassam et. al., 2014; Shepherd et. al., 2016). Furthermore, the dominant northwesterly winds contribute to the extensive mobilization of dust across the peninsula (e.g. the Al Shamaal winds) (Glennie & Singhvi, 2002; Rao et al., 2003; Bartlett, 2004; Babikir, 2004).

Anthropogenic activities such as the construction of dams are likely to be associated with increasing dust storm incidence (Goudie and Middleton, 1992; Goudie, 2009). For instance, research has shown that the construction of the Ilisu Dam in Turkey has reduced the downstream discharge of the Tigris and Euphrates River which resulted in more periods of extensive drought, triggering dust storms in the wider region (Bastan and Shokoufi, 2013; Pirsaheb et. al., 2014; Cao et. al., 2015; Notaro et. al., 2015). Moreover, overgrazing by cattle and off-road driving, which can lead to serious soil degradation, have been considered as important additional contributing factors in mobilizing sand and dust (Mohammad, 1989; Zhang et al., 2003; Goudie and Middleton, 2001; Akbary, and Farahbakhshi, 2015).

Finally, recent and ongoing conflicts in the Middle East region (e.g. Syrian civil war) and associated failures in land management, such as the abandonment of cultivated land, should also be considered as important factors contributing to the occurrence of dust storms in the region. Although dust storms can occur throughout the entire year in Saudi Arabia (Prospero et al., 2002; Notaro et al., 2013; Yu et al., 2013; Notaro et. al., 2015; Albugami et al. 2018), on the local scale these phenomena are known to be variable in space and time. Previous studies have shown that the peak in dust storm activity occurs at different times of year in different regions; for instance, in the Southern region near the Red Sea coast, dust storms mostly occur during the middle of the winter season (December - January - February); whereas in the Northern region around the An Nafud desert it peaks in the spring season (March - April - May) (Yu et al., 2015). However, there is limited systematic understanding of how variations in environmental drivers lead to spatial and temporal variations in the occurrence of dust storms across the entire Arabian Peninsula. Hence, this study aims to improve our understanding of how climate variables – specifically temperature, precipitation, wind speed, and wind direction – influence the incidence of dust storms in Saudi Arabia. This study also seeks to provide a comprehensive characterization of the seasonal variation in the frequency and the distribution of dust storms over different regions in the study area.

5.3. Materials and Methods

5.3.1. Study Area

Saudi Arabia is located in the southwest of the Asian continent. Most of its territory is covered by vast arid deserts, with the exception of the south-western part of the country (Zahran, 1983). The largest desert is the Empty Quarter (or Rub' al Khali), which dominates the southern part of the Arabian Peninsula and covers more than 650,000 km^2. Other important deserts are found in the north, including the An Nafud desert with an area of 57,000 km^2, and in the east of Saudi Arabia, including the Ad Dahna desert, with an area of 1,450 km^2. (Edgell, 2006; Alaamer, 2012; Puthan et al., 2013) (see Figure 12).

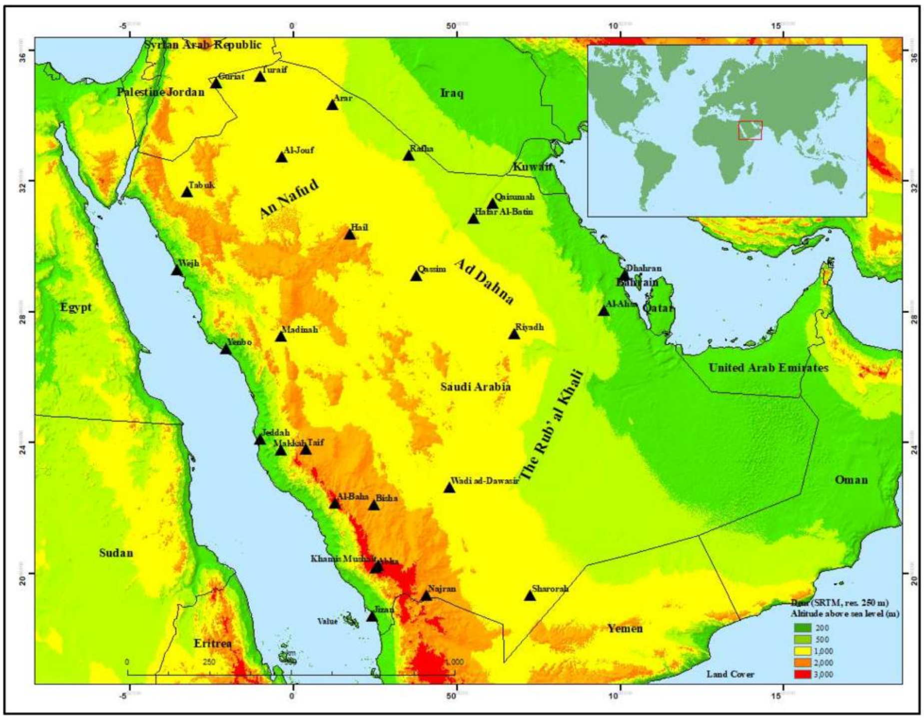


Figure 12 Elevation map of the Arabian Peninsula with annotation of major cities and deserts as well as the location of the in-situ dust storm measurement stations. The triangles represent the observation stations.

Climatologically, Saudi Arabia is known to be one of the driest places in the world, with an average annual precipitation of less than 100 mm per year (De Pauw, 2002). The temperatures excess about 50°C in the summer season. Whereas, in the winter season the average maximum temperature drops to 8 - 17°C (Kamel et al., 2006), at which time most of the annual rainfall occurs, especially in the western and southern regions. Central regions are relatively cold and dry in the winter.

5.4. Dust Storm and Climate Variable Data

5.4.1. Monthly Dust Storm Observations

Monthly dust storm data for 27 in-situ stations were obtained from the Presidency of Meteorology and Environment (PME) of Saudi Arabia, which is the official governmental climate agency in Saudi Arabia (Goyal and Harmsen, 2013) for the period 2000–2016 (Figure 12). Incomplete observational records were available for two years in this period (2002 and 2009) so these records were omitted from the analysis. This dataset was used to analyze the spatio-temporal distribution of dust storm events across Saudi Arabia, including seasonal and inter-annual variations. The raw data for each station were analyzed in Microsoft Excel, including temporal linear trend fitting and 5-pass filtering. The stations are situated across all of the 13 regions of Saudi Arabia (i.e. Riyadh, Makkah, Madinah, Al-Qassim, Eastern Province, Asir, Tabuk, Hail, Northern Borders, Jizan, Najran, Baha and Al-Jouf). Moreover, the Pandas package for Python (WinPython-64bit-3.5.2.3) (McKinney, 2011) was used to analyze the seasonal variation in the frequency of dust storms as well as meteorological conditions (precipitation, temperature and wind).

Vector dust storm data from all 27 stations were spatially interpolated by using the “Spline with barrier” tool in ArcGIS 10.5.1, producing continuous raster layers representing the spatio-temporal variability of dust storms across the entire study area. The Spline with barrier interpolation method estimates values using a mathematical algorithm which minimizes the surface curvature with a barrier of a chosen area, producing a smooth surface based on the input points (Samanta et al., 2012). The interpolation was applied to provide the rate of the change of the frequency of dust storms over the study period.

5.4.2. Climate Variable Data

I also used monthly averaged climate data provided by PME for 27 in-situ meteorological stations, covering the period 2000 – 2016, in order to determine the correlation between specific climate variables and the occurrence frequency of dust storms. These climate variables were average temperature (°C) and average numbers of rain events, per station. To investigate the wind speed and direction at each in-situ station we used daily data from the METAR/TAF aviation routine weather report for the validation exercise issued at hourly or half-hourly intervals. This data contains observations of the meteorological elements such as surface wind, visibility and present weather (e.g. dust storm, haze, mist and thunderstorm), clouds of operational significance, air temperature, dew-point temperature, and atmospheric pressure. These reports are based on the coding of the present weather, which is observed and forecasted by the World Meteorological Organization (WMO, 1995; Mahringer, 2008; Papadopoulos and Katsafados, 2009).

In order to understand the relationship between the wind velocity and the occurrence of the dust storms at each of the 5 monitoring stations, we compared wind patterns under dust free weather conditions versus dust storm conditions for the period 2005 - 2017. To do so, we created wind rose diagrams to compare the prevailing wind directions and wind speed under these 2 conditions across 5 different regions within Saudi Arabia (i.e. Riyadh - Jeddah - Al- Ahsa - Arar - Jizan) as an example of the impact of the wind velocity on the occurrence of dust storms.

5.5. Statistical Analysis

To gain a stronger understanding of the variability in the observed occurrence of dust storm, we analyzed the possible existence of temporal trends across several Saudi Arabia stations between 2000 and 2016 by conducting regression analyses (Rao, 1973). The associated coefficients of determination (R^2) and model uncertainty have been considered to evaluate the goodness of these fits. Moreover, a Pearson correlation coefficient (r) analysis was used to investigate the potential existence of significant relations between the weather variables and the frequency of dust storm occurrence (Figure 13)

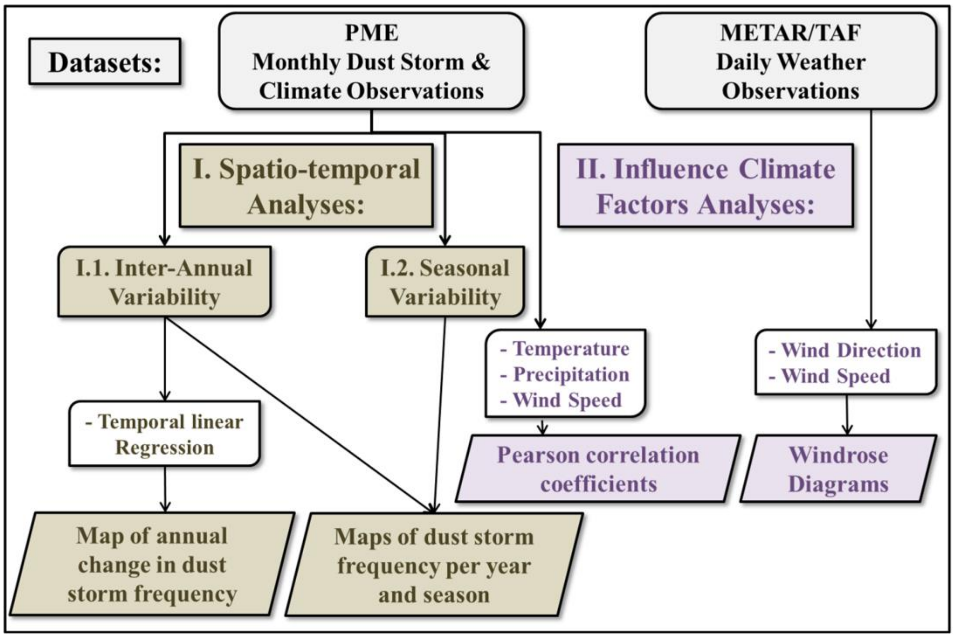


Figure 13 Methodological flowchart of spatio-temporal variability in dust storms over Saudi Arabia.

5.6. Results

5.6.1. Inter-annual variation of dust storms

Figure 14 presents a moving average (5-pass) filter applied to the total number of dust storms recorded across all in-situ stations within the study area between the years 2000 and 2016. This figure highlights the temporal trend of the annual number of dust events as recorded over all the in-situ stations across entire Saudi Arabia by using the linear regression line with associated model error bounds (at 95% confidence interval) method. Figure 15 shows the linear regression analysis with associated model error bounds (at 95% confidence interval) which was applied to the dataset of the total dust events per PME station between the years 2000 and 2016, including the 5 pass filter. This figure illustrates the temporal trend in the frequency of dust events in each station. Furthermore, Table 8 shows the slope coefficient values of the temporal linear regression analysis (annual change in the number of dust storms) with associated standard error value (and level of confidence) for each station over the study area. Figure 16 shows the results of the spatial interpolation analysis, highlighting inter-annual variability in dust storms and their spatial distribution between the years 2000 and 2016.

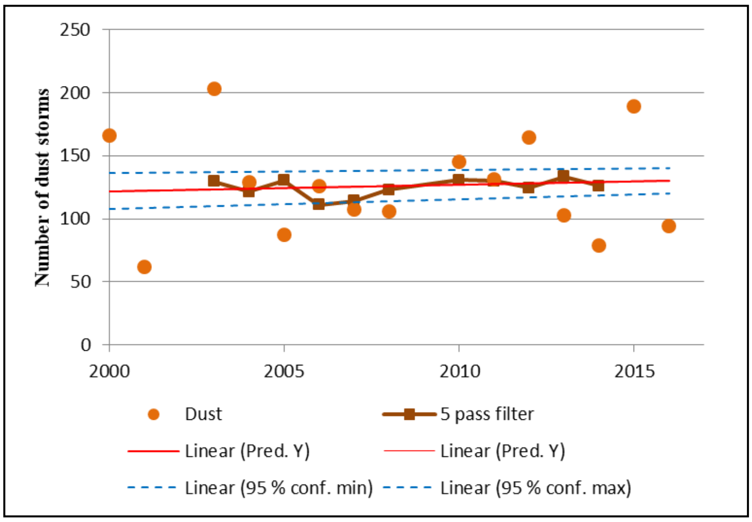


Figure 14 Temporal trend analysis of the total annual number of dust storm events as recorded over all the in-situ stations across entire Saudi Arabia between the years 2000 and 2016, including a 5-pass filter and linear regression line with associated model error bounds (at 95% confidence interval).

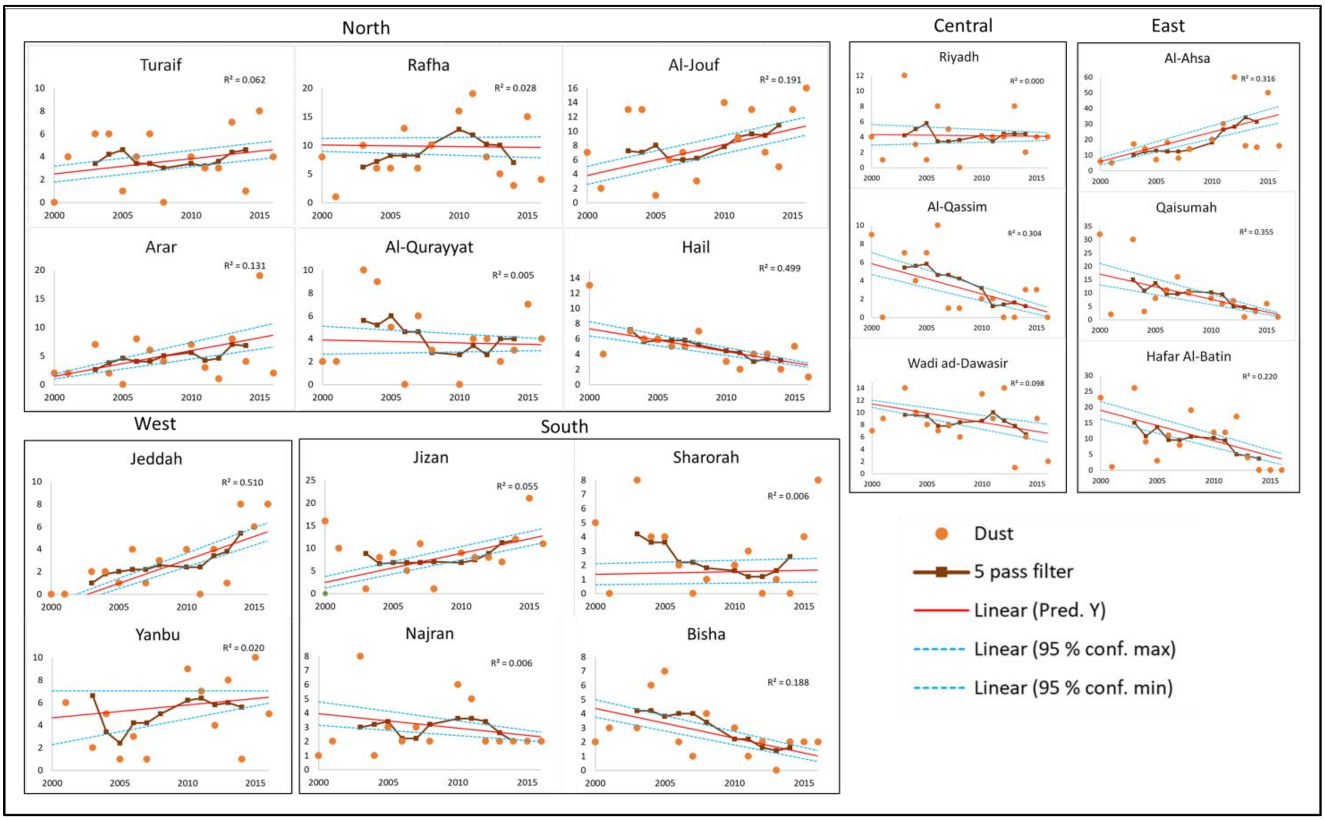


Figure 15 Scatter plots showing the total annual number of dust storm events per PME station between the years 2000 and 2016, including a 5-pass filter and linear regression line with associated model error bounds (at 95% confidence interval). The y-axis represents the total dust storm events per year.

Table 8 Slope coefficient values of the temporal linear regression analysis (annual change in number of dust storms) with associated standard error value (and level of confidence).

Station	**parameter value**	**uncertainty**	**Sig. Level Code**
Turaif	0.1083	0.1323	
Arar	0.3249	0.2358	
Al-Qurayyat	0.055	0.1579	
Al Jouf	0.3763	0.2368	
Rafha	0.1696	0.274	
Hail	-0.3944	0.1094	***
Qaisumah	-1.1019	0.419	***
Hafar Al-Batin	-0.8023	0.407	**
Al-Ahsa	1.7066	0.7068	**
Riyadh	0.0225	0.1675	
Al Qassim	-0.3583	0.1551	**
Wadi ad-Dawasir	-0.2355	0.1924	
Jeddah	0.3745	0.1031	***
Yanbu	0.0237	0.2589	
Jizan	0.2364	0.2665	
Sharorah	0.0823	0.1455	
Najran	-0.0252	0.1055	
Bisha	-0.1525	0.0898	*

Color Code		level of significance P<0.1	P<0.05	P<0.01
increase over time	POS	*	**	***
Decrease over time	NEG	*	**	***

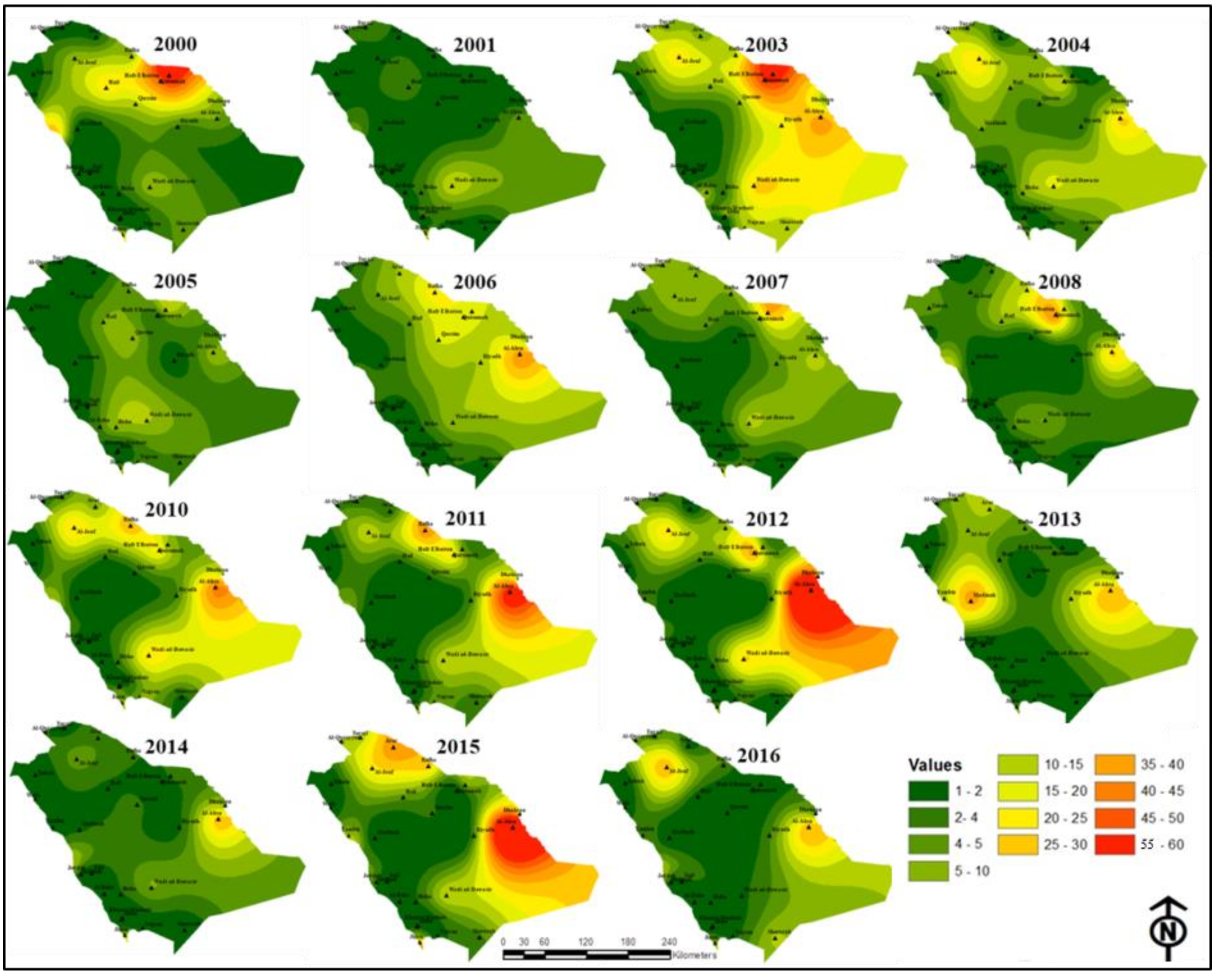


Figure 16 Spatially interpolated dust storm frequency per year over Saudi Arabia for the period 2000-2016. Note that the highest frequency of total dust event occurrences varies from year to year with a concentration mostly in the east region.

5.6.2. Spatio-temporal variability analysis of dust storm is Saudi Arabia

Figure 17 presents the inter-annual trend in dust storm event occurrence over entire Saudi Arabia after interpolating the associated slope parameter value from each station.

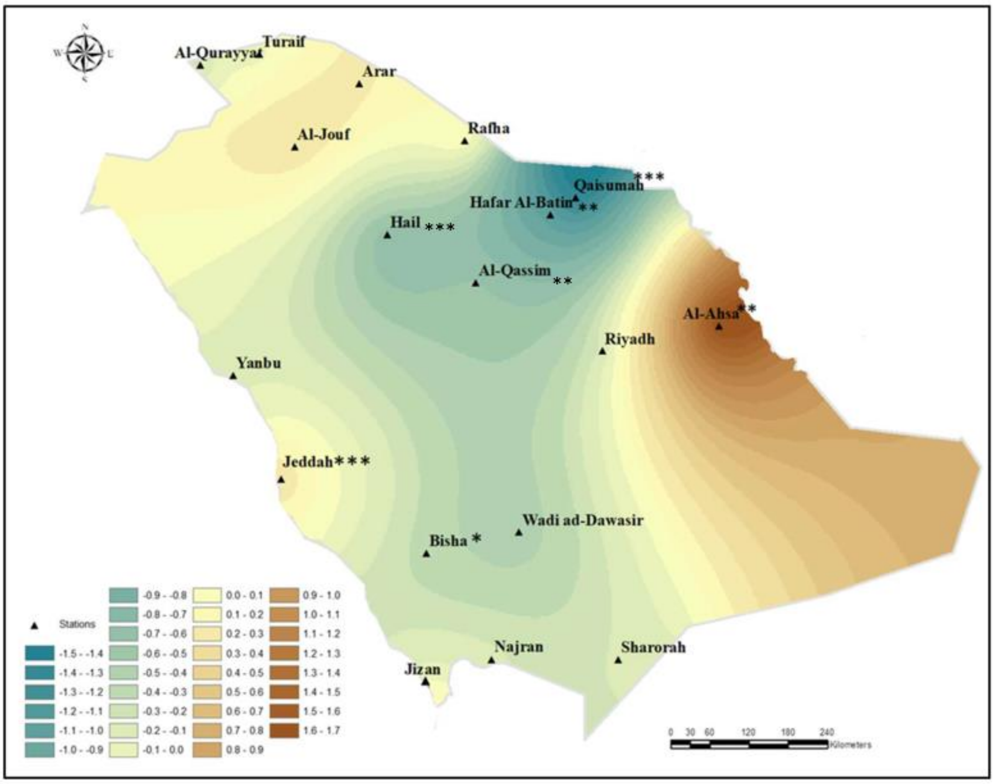


Figure 17 Annual change in dust storm frequency (number of events/year) over Saudi Arabia. Increasing trends are shown in brown, while decreasing trends are shown in blue (Table 8)

5.6.3. Regional differences in seasonality of dust storms

Figure 18 indicates the spatial distribution of the total number of dust storms per season as being recorded over the entire period 2000 - 2016.

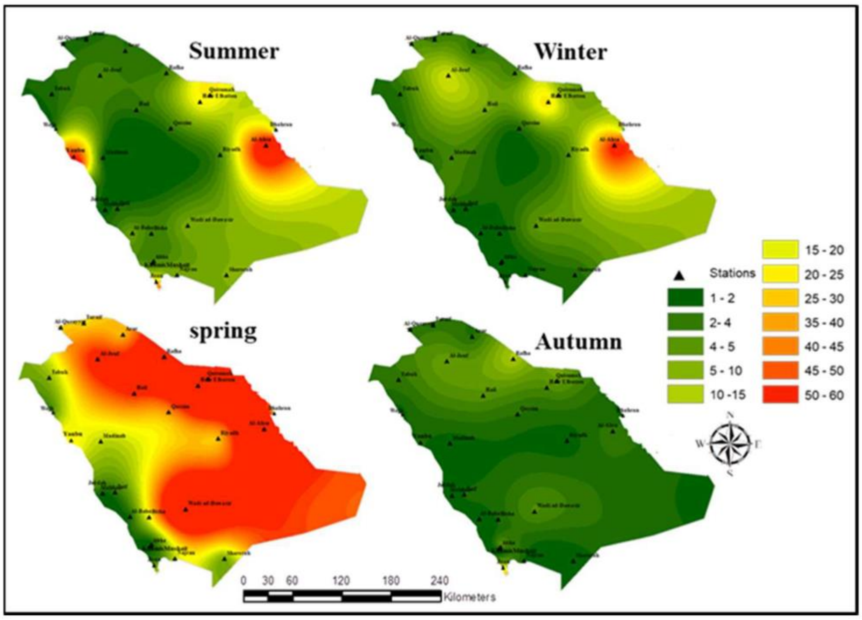


Figure 18 Map of the total amount of dust storms per season recorded over the period 2000-2016.

5.6.4. Seasonal variations across all stations

The graphs below show the seasonal variation in the frequency of dust storms, temperature, frequency of precipitation and wind speed for all PME stations and for each station (Figure 19 and 20).

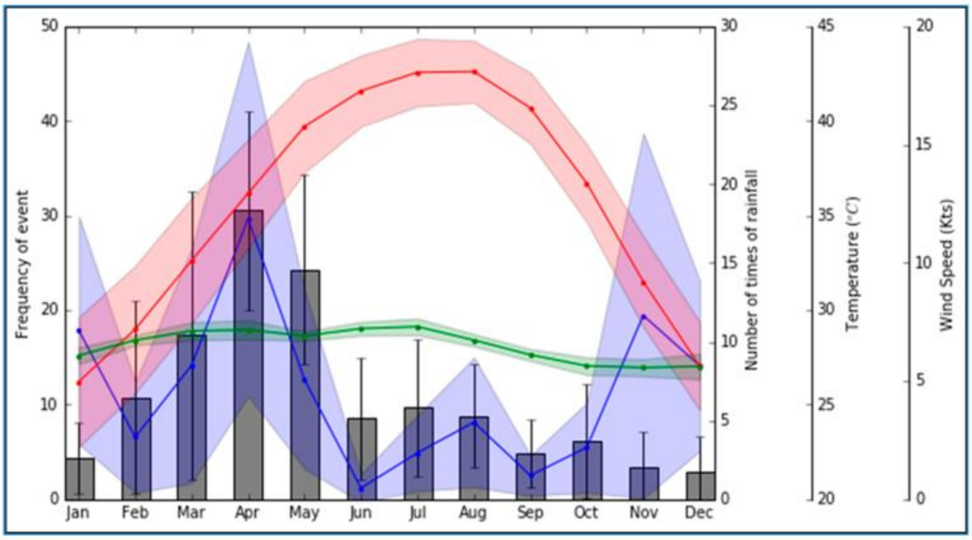


Figure 19 Seasonal variation in (i) the frequency of dust storms in grey, (ii) temperature in red, (iii) frequency of precipitation in blue and (iv) wind speed in green for all PME stations. The values in the graph represent the average and the associated standard deviation (by error bars / shaded surface) for the period 2000 – 2016.

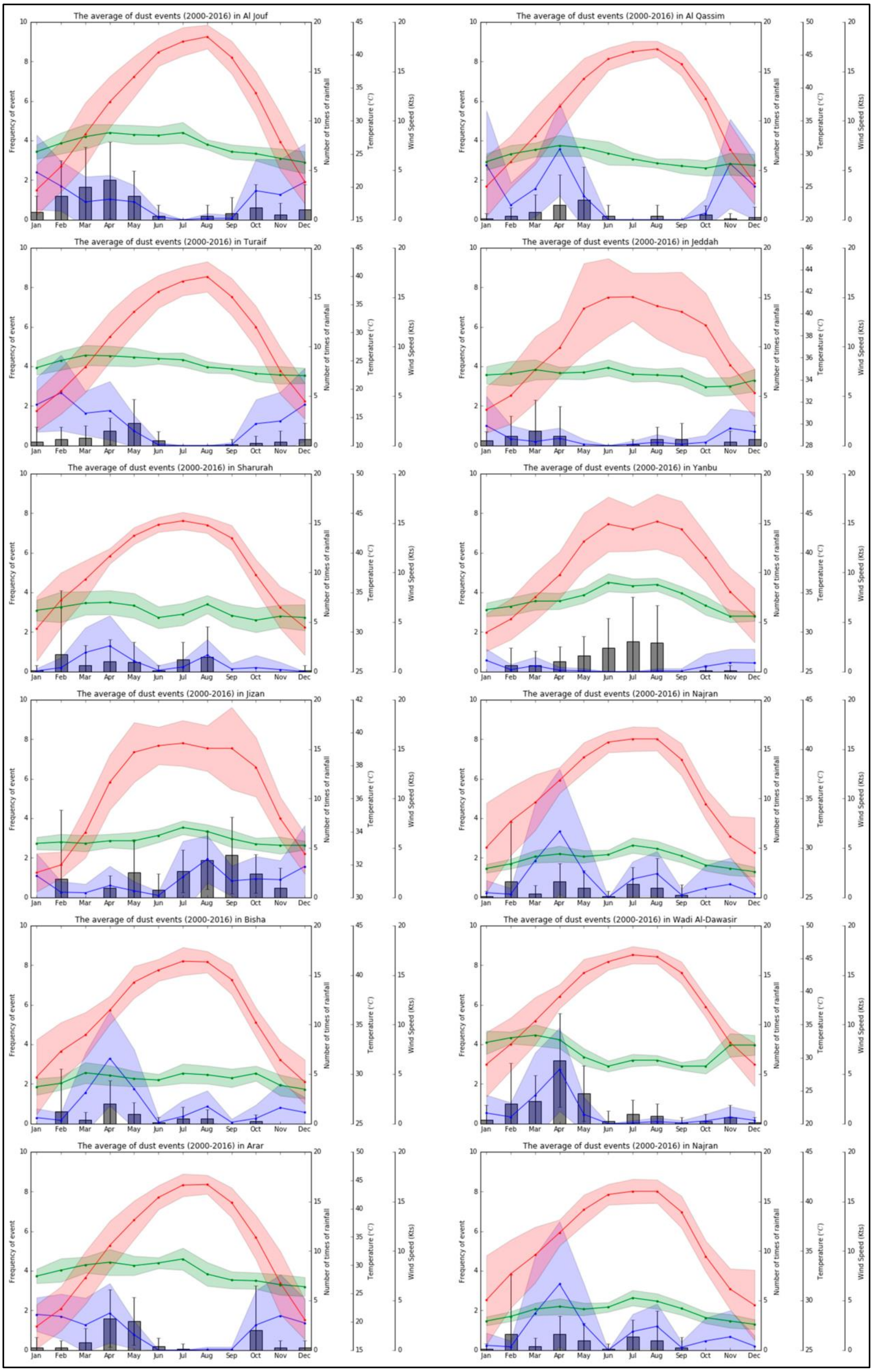


Figure 20 Scatter plots showing the total annual number of dust storm events per PME station between the years 2000 and 2016, including a 5-pass filter and linear regression line with associated model error bounds (at 95% confidence interval).

5.6.5. Spatio-temporal variations in Wind speed and direction

Figure 21 illustrates the wind speed and direction for two dust presence conditions, dust free and dust storms for the period 2005 - 2017. To make this comparison across entire Saudi Arabia, we chose the following 5 main cities, Riyadh representing the central region, Al-Ahsa representing the eastern region, Jeddah representing the western region, Arar representing the northern region, and Jizan representing the northern region.

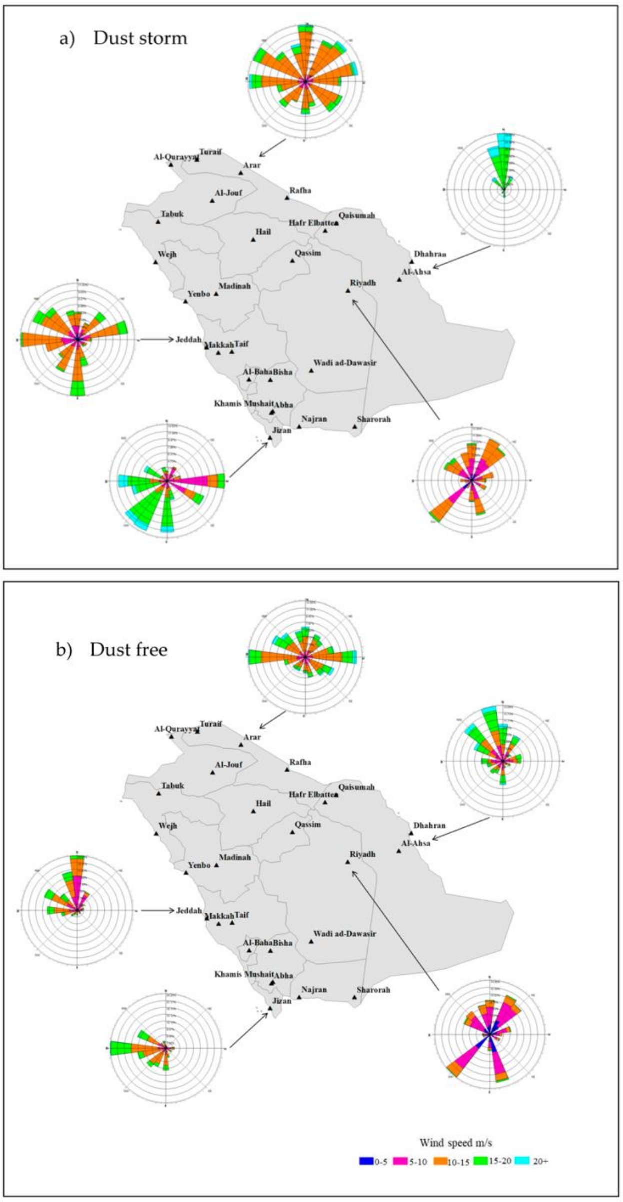


Figure 21 Wind roses representing wind direction and wind speed covering the period 2005 –2017 under dust free conditions (top) and dust storm conditions (bottom).

5.7. Discussion

5.7.1. Inter-Annual Variation of Dust Storms

Figure 14 shows that when considering all the dust storms recorded in the 27 in-situ stations across Saudi Arabia, 2013 has the highest 5-pass filter value. However, when looking at the unfiltered data, the highest annual total number of dust storm events was recorded in 2003 with 203 events (Fig.14). From the temporal analysis of each station (i.e. graphs in Figure 15), both the frequency of occurrence of dust storms as well as the long-term trends varies to a large extent depending on the location. A gradual increase in dust events with an associated significant linear regression slope is noted in Al-Ahsa (1.71 ± 0.71 y^{-1}) and Jeddah (0.37 ± 0.10 y^{-1}). Furthermore, our analysis reveals a considerable increase in the frequency in dust storm in Arar (0.32 ± 0.24 y^{-1}), Turaif (0.11 ± 0.13 y^{-1}), Al-Jouf (0.38 ± 0.24 y-1) Rafha (0.17 ± 0.27 y^{-1}) and Jizan (0.24 ± 0.27 y^{-1}), however, the analysis did not show a significant linear regression slope parameter in these cases (Table 8). Moreover Figure 14 suggests a decrease in the number of dust storms over more recent years with fewer dust storms in 2013, 2015 and 2016, resulting in a long-term decreasing trend of dust storm occurrences across multiple stations as indicated by significant negative regression slope parameters in Hail (-0.39 ± 0.11 y^{-1}), Qaisumah (-1.10 ± 0.42 y^{-1}), Hafar Al-Batin (-0.80 ± 0.41 y^{-1}), Al Qassim (-0.36 ± 0.16 y^{-1}) and Bisha (-0.15 ± 0.09 y^{-1}) (Table 8).

From Figure 16 it is evident that the highest annual frequency of dust events varies in space and, depending on the year, may occur either in the east (i.e. near Qaisumah, Hafar Al-Batin and Al-Ahsa) north (i.e. near Turaif, Arar, Al-Qurayyat, Al-Jouf and Rafha) and the center (i.e. near Wadi ad-Dawasir, Riyadh and Al-Qassim).

The highest frequency of dust storms in Saudi Arabia occurred in 2003, which accounted for 10.74% of the total events recorded between 2000 and 2016. Notably, in 2003 dust storms were concentrated in the Eastern region with 30, 26 and 17 events recorded in Qaisumah, Hafar Al-Batin and Al-Ahsa, respectively. The second highest frequency was recorded in 2015 which accounted for 9.99% of the total dust storm events during the study period, which were particularly concentrated in the region around Al-Ahsa. Figure 16 also highlights that the lowest number of dust storm events were recorded in the years 2005, 2014 and 2016, which is in line with the observations made for Figures 14 and 15.

5.7.2. Spatio-Temporal Variability Analysis of Dust Storms in Saudi Arabia

In general, our results show that despite the rather high inter-annual variability of dust events across entire Saudi Arabia, there exists some remarkable long-term trends in total annual number of dust storm, i.e. (i) an increasing trend in the east towards southeastern and (ii) a decreasing trend in the northeast towards central and southern parts of the country, as illustrated in Figure 6. More precisely, Al-Ahsa in the east and Jeddah in the west were marked by a significant increases ($p<0.05$) in dust storm over the past 16 years and that probably because of the impact of the Saharan Desert dust storm on western Saudi Arabia (Notaro et al., 2013), whereas for the same period of time significant decreases in dust storm occurrence were recorded in Hail, Qaisumah, Hafar Al-Batin and Al-Qassim in the northeast – centre ($p<0.05$) and Bisha in the south ($p<0.1$).

5.7.3. Regional Differences in Seasonality of Dust Storms

Findings of this study demonstrate a strong spatial variability in dust storm occurrence in Saudi Arabia, with the highest frequency of dust storm events in the Eastern region, especially in Hafr Al-Batin, Qaisumah and Al-Ahsa, which is in line with other findings in the literature (e.g. Notaro et. al., 2013; Alharbi et. al., 2013; Nabavi et. al., 2016). Besides the Eastern region, also the north part of the study area is characterized by a high frequency of dust storm events, in particular, Al-Jouf and Rafha. Furthermore, it can be seen that the dust storm frequency reduces from the center to the southwest and increases slightly to the west (e.g. Yanbu) (Figure 16). However, Figure 12 reveals some remarkable seasonal differences. In general, when considering the entire country, our results emphasize that the highest frequency of dust occurs during the spring and summer (i.e. March - August), whereas the lowest number of dust storms events took place in the autumn and winter (i.e. September - November). More precisely, Figure 12 highlights that in most regions, except the west, the dust storm frequency reaches its maximum during the spring (i.e. March - May). However, during the summer the very high frequency of dust storm occurrence is restricted to the areas around Al-Ahsa in the east and Yanbu in the west (Mashat, 2011). Furthermore, we also identified a high-frequency of dust events during the winter season in the eastern and northern part of the study area (i.e. near Al-Ahsa, Hafar Al-Batin and Al-Jouf, respectively) as well as two regions characterized by a slightly higher frequency of dust storms over the autumn, of which one is located in the north of the Arabian Peninsula (i.e. near Rafha) and the other is located in the southern region (i.e. near Jizan) (Figure 12).

5.7.4. Seasonal Variations across All Stations

According to our analysis of the seasonality of dust storms for the entire study site, dust storm events across Saudi Arabia occur throughout the entire year, but similar to observations at the regional scale, there is a clear seasonal variability, with a maximum peak in dust storm occurrence (30 ± 11) in April (Figure 13). The monthly incidence of dust storms remains high (25 ± 10) during May, then drops significantly to less than 10 per month for the remainder of the calendar year. The period with the fewest dust storms is November to January (~4 ± 3). Between January and April, there is a steady increase in dust storm frequency risng to the peak in April.

Considering the bar graphs for the individual stations in Figure 14, the most noticeable feature is that the mean dust storm frequency reaches its maximum peak in April in most of the regions (e.g. Riyadh, Jeddah, Hail, Al-Jouf, Bisha, Hafr Al-Batin, Arar, Rafha and Al-Ahsa). Moreover, it is evident that in Al-Ahsa there is a longer period of high frequency dust storm occurrence, i.e. between the months of February and June, after which the frequency of dust storms dramatically declines to less than 2 per month in (August- October). Furthermore, the plots for Yanbu and Jizan, both located on the west coast, do not follow the general intra-annual distribution of dust storms, but have the highest frequency in dust storms around September for Jizan and for the period July - August for Yanbu. However, their frequency in dust-storms is low overall (Figure 14).

5.7.5. The relationship between dust storms and temperature

There is a clear and robust seasonal variation in air temperature across the Peninsula, with a peak of 42 ± 2 °C in August, decreasing steadily to a minimum around 26 ± 4 °C in December (Figure 13). Pearson correlation coefficient analysis (Table 8), was used to investigate the relationship between air temperature and dust storm occurrence. Our results (Table 8) indicate that although there is a positive correlation (i.e. value of 0.24) between the two variables, it was not statistically significant. However, Figure 13 show that the seasonal maximum temperature occurs in a period (July to September) characterized by a relatively small amount of dust storms.

A very similar intra-annual trend in temperature can be observed across all of the individual station (Figure 14). Hence, the relationship between dust storms and temperature was not significant in most of the regions, except for the 3 stations located along the western coast of Saudi Arabia. However, across these locations no consistent pattern could be identified, because Jeddah is characterized by a significant negative correlation (i.e. R = -0.55), whereas Yanbu and Jizan by significant positive correlation (i.e. R = 0.69 in both cases) (Table 8).

Table 9: The Pearson correlation coefficient (R) of the frequency of dust storms versus temperature, precipitation and wind speed considering each PME stations from 2000 until 2016.

Stations	Precipitation	Temperature	Wind Speed
Overall	0.490	0.236	0.686 **
Riyadh	0.529 **	0.195	0.490
Jeddah	0.195	-0.548 **	0.262
Hail	0.511 **	0.066	0.751 **
Al-Qassem	0.298	0.128	0.748 **
Jizan	0.236	0.693 **	0.546 **
Yanbu	-0.696 **	0.686 **	0.842 **
Al-Jouf	0.257	-0.280	0.408
Bisha	0.740 **	0.189	0.338
Turaif	0.276	-0.125	0.499 **
Hafr Al-Batin	0.104	0.018	0.799 **
Arar	0.314	0.094	0.322
Rafha	0.223	0.109	0.756 **
Najran	0.805 **	0.140	0.173
Al Qurrayat	0.277	-0.110	-0.023
Sharurah	0.506 **	0.317	0.705 **
Al-Ahsa	0.300	0.003	0.772 **
Wadi Al-Dawasir	0.894 **	0.096	0.461
Al-Qaysumah	-0.038	0.284	0.697 **

** $p < 0.005$

5.7.6. The relationship between dust storms and precipitation

In general, the rainy season in Saudi Arabia runs from November to April and the dry season is primarily during the months of June to September (Hasanean and Almazroui, 2015). The overall highest frequency of precipitation events occurs in April (i.e. an average monthly number of rain cases occurred 20 times) which coincides with the highest dust-storm frequency. Moreover, our results illustrate that the peak in dust storms are clearly related to a peak in frequency of precipitation events in the period March – May. There is notably less precipitation in the period June – October, with in average 5 rainfall occurrence per month, as well as a lower frequency in dust storm events as compared to the antecedent wetter period. A second peak in rainfall is situated in November, with an average frequency of 10 rainfall events per month, which does not coincide with a higher frequency in dust storm events; however, it is important to note that the average frequency of precipitation events for this particular month has a greater frequency of variability.

Previous research has highlighted a negative correlation between precipitation and dust storms (Littmann, 1991; McTainsh et. al., 1998; Qian et. al., 2002). Furthermore, it has been demonstrated that dust events tend to suppress rainfall (Maley, 1982; Goudie, 1983). Also, Middleton (1986) claims that the correlation between annual numbers of dust events and the total annual amount of precipitation is weak. Nevertheless, our results showed a positive correlation between dust storms and precipitation, because the occurrence of dust storms is mostly followed by rainfall (Giuggio, 2012; Vukovic et. al., 2013). Moreover, Zender and Kwon (2005) suggest that there is a significant positive correlation between precipitation and the increase of dust emissions in the same month, especially in Saudi Arabia, Oman and the Thar Desert (in India) (Namdari et. al., 2018). Yang et al. (2008) also found that the relationship of dust storm event occurrence with precipitation is stronger than with temperature. Moreover, it is known that in Central Asia the seasonality of precipitation is strongly linked to intra-annual variability in the frequency of dust storms (UNESCAP, 2018).

Furthermore, the associated correlation coefficient between dust storm frequency and average frequency of precipitation events is found to be positive and statistically significant at $p<0.005$ in Riyadh, Hail, Bisha, Najran, Sharurah and Wadi Al-Dawasir (i.e. R-value = 0.53, 0.51, 0.74, 0.81, 0.51 and 0.89 respectively) (Table 6). In addition, in many stations a second peak can be observed in November with a figure approximately above 10 rainfall events per month (e.g. Riyadh, Hail, Al-Qassem, Arar, Rafha, Jeddah, Rafha and Hafr Al-Batin). Although, the correlation between dust occurrence and precipitation is negative and statistically significant at $p<0.005$ in Yanbu located along the Western coast of Saudi Arabia with a R-value of -0.696. Hence, this result shows that there is an inverse relationship between annual dust storms and the frequency of precipitation events in Yanbu, which is a clear difference as compared to other regions. However, it should be noted that this station is characterized by remarkably low precipitation throughout the year with typically less than 5 events per month (Figure 14).

5.7.7. The relationship between dust storms and wind speed

As highlighted in Figure 13 the average wind speed remained fairly constant below 10 m/s across all months with slightly higher values in the period March – July and slightly lower values in the period October - December. However, despite this limited variation in wind speed, Table 7 illustrates that there is a significant positive correlation ($p<0.005$) between the frequency of dust events and wind speed (i.e. R = 0.69), which is in accordance with other studies (e.g. Rezazadeh et al., 2013, Aili et al., 2016).

Moreover, it can be seen that the months with the highest frequency in dust storms, i.e. March - May accounted for more than 50% of the total annual number of dust storm, and are characterized by both high wind speeds and high precipitation amounts (Middleton, 1986; Yu et al., 2015). In contrast, the lower frequency of dust storm events in the period November – January coincides with lower wind speeds (Notaro et al., 2013). The average wind speed remained fairly steady between 6 and 8 knots across all months in Riyadh, Jeddah, Hail, Al-Qassem, Jizan and Al-Qaysumah, with slightly higher values between the period March – July and slightly lower values between the period October- December. Whereas in some other regions the variability in average wind speed is larger with monthly average values between 6 and 12 knots (e.g. Al Qurrayat and Al-Ahsa) (Figure 9). We found a significant positive correlation ($p<0.005$) in Hail, Al-Qassem, Jizan, Yanbu, Turaif, Hafr Al-Batin, Rafha, Sharurah, Al-Ahsa and Al-Qaysumah (R-Value = 0.751, 0.748, 0.546, 0.842, 0.499, 0.799, 0.7051, 0.772 and 0.697, respectively) (Table 8).

Overall, the two meteorological variables of precipitation and wind speed are positively correlated with the occurrence of dust storms. Moreover, we found no correlation between temperature and dust events. However, the most surprising positive correlation is with the precipitation, few studies have been published on the relationship between dust events and precipitation and they found that dust storms are negatively correlated with precipitation, which means dust storms are reduced due to precipitation (Goudie, 1983; Littmann, 1991; McTainsh et. al., 1998; Qian et. al., 2002). A possible explanation for this result is that our analysis is based on the frequency of rainfall events, while other studies consider the amount of the precipitation. A further explanation is that rainfall might be caused or followed by the dust storms.

5.7.8. Spatio-temporal variations in Wind speed and direction

In order to understand the spatial changes in dust storm frequency, we investigated wind speed and direction at each in-situ station for dust free conditions and during dust storms (Figure 15). To make this comparison across entire Saudi Arabia, we chose the following 5 main cities, Riyadh representing the central region, Al-Ahsa representing the eastern region, Jeddah representing the western region, Arar representing the northern region, and Jizan representing the northern region. It can be seen that while the prevailing wind direction in Riyadh is from the southwest regardless of the conditions, the mean windspeed is between 5-10 m/s during dust free days and 10-15 m/s during dust storm events (Figure 15). In the Eastern part of Saudi Arabia (i.e. Al-Ahsa), the prevailing winds are from the north and the northwest with a mean speed of 10-15 m/s under dust-free conditions, whereas during dust storms the wind directions are the same with a mean speed above 20 m/s. Hence, the dust storms in this region are often linked to the Al Shamal wind, which has a predominately north to northwest wind-direction, transporting dust from the Tigris and Euphrates plain over Syria and Iraq towards the northern and eastern part of the Arabian Peninsula (Membery, 1983; Middleton, 1986; Shao, 2001; Bartlett, 2004; Goudie and Middleton, 2006). However, Al Senafi and Anis (2015) concluded that dust storm events in the east of Saudi Arabia are not always associated with the Al Shamal wind, but might also be a result of local unsettled weather systems. This may explain the high frequency of dust storm incidents in the eastern part of Saudi Arabia (Figure 10).

In addition, Figure 15 shows that in Arar the prevailing winds are from all directions with a mean speed of 10-15 m/s and during both dust free and dust storm conditions.

This station is located on the border with the Syrian Desert which is one of the dust storm source areas in the north (Yu et al., 2015). Finally, the wind rose (Figure 15) reveals that the prevailing wind in Jeddah, located in the west, is from the North with a mean wind speed of 15-20 m/s during dust storm conditions and 10-15 m/s during dust free conditions. The Sahara Desert can be considered as an important source area for the dust storms in the Western and Northwestern part of Saudi Arabia. This also may apply to Jizan which is located along the south-western coast of the Red Sea and the prevailing wind is from the west during the dust storms with a mean speed above 20 m/s and for the dust free days the mean wind speed is between 10-15 m/s. In addition, as Doronzo et al. (2015) concluded that buildings are having a significant impact on dust storms with velocities between 10-20 m/s, an interesting future research avenue could be to investigate the potential of residential areas to function as dust storm corridors across Saudi Arabia.

The observed temporal trends might be a result of large scale land use change dynamics within Saudi Arabia (e.g. urbanization and variability in vegetation coverage) (Alqurashi et al., 2014; Rahman, 2016), as well as in neighboring military conflict areas, such as Syria and Iraq, where a widespread abandonment of fields resulted in an enhanced dust erodibility of the soil (Solomos et al., 2017). As these regions are located on the most important dust trajectories reaching the northeastern part of the Arabian Peninsula (Al-Dousari et al., 2017), it is likely to result in a locally increased dust supply. Furthermore, climate change might also have an impact on the frequency of dust storms as drier and hotter conditions may reduce the overall vegetation coverage, and therefore intensify the desertification process (Du et al., 2009; Yu et al., 2015). This underlines the urgent need for future research investigating the spatio-temporal trends of dust storms across the Arabian Peninsula taking into account large scale influencing factors such land use change and climate change.

5.8. Conclusion

Our analysis shows that dust storms in Saudi Arabia occur most frequently in the eastern and northern regions of the country. These two regions are located near two major deserts in the study area, Ad-Dahna desert in the east and An Nafud in the north. The analysis illustrated that the dust storm frequency reaches its maximum during the spring, whereas the lowest number of dust storms events took place in autumn. As dust storms are positively correlated with precipitation and wind speed $p<0.005$, these two meteorological factors have an impact on the frequency of dust storms, although there is a negative correlation between dust events and temperature. The most notable result is that dust storms for the period 2000 - 2016 are increasing in the eastern part of the country, especially in the area around Al-Ahsa by 13.87%. Moreover, there is also a constant increase in the frequency of dust storms over time in Jeddah by 2.81% which is located on the west coast. In contrast dust storm frequency is decreasing over time in Hail, Qaisumah, Hafar Al-Batin, Al-Qassim and Bisha. Also, our results show a shift in dust storms from the northeast, which are possibly caused by the wind between high pressure over the Mediterranean Sea and the low pressure in Saudi Arabia (Rousta, 2017), to the southeast. The prevailing wind–direction during dust free and dust storm days varies across different parts of the country. The mean wind speeds during a dust storm are between 15 and 20 m/s while during non-dust days this is around 10-15 m/s. Future research should seek to identify the drivers behind the observed spatio-temporal trends in dust-storm event occurrence across Saudi Arabia and aim to further explain the significant correlations with climatological factors such as the frequency of precipitation events.

6. Impact of dust events on daily emergency admissions for respiratory infections in children in Riyadh city, Saudi Arabia[3]

6.1. Abstract

This study analysed the impact of dust storms on the health of children in Riyadh, Saudi Arabia for the period February 2015–January 2016, drawing on data on hospital emergency department admissions for respiratory tract infections from King Fahad Medical City (KFMC), interviews with hospital personnel and dust data from the World Meteorological Organization (WMO). The findings demonstrate that there is a statistically significant difference between URTI and LRTI across the three weather conditions examined, which are widespread dust, blowing dust and dust-free (i.e., r =0.3090, 0.4545 and 0.3068, respectively). The results show that the number of emergency admissions for lower respiratory tract infections (LRTI) was higher during 'widespread dust' events than during periods of 'blowing dust activity', with the average number of visits to hospital admissions being 11.62 per day, compared to 10.36 for upper respiratory tract infections (URTI). We found clear seasonal variability, with a peak in the number of emergency admissions during the months of February to April. Furthermore, qualitative evidence suggests that there is a significant impact on hospital operations due to the increase in patients and pressure on staffing and hospital consumables. Clearly, further research will be needed to understand the dust storm impacts on the respiratory system.

[3] This chapter has been drafted to be submitted as a peer-reviewed journal article, as: Albugami, S., Cinnamon, J., Meersmans, J., Palmer, S. 2019. Impact of dust storms on daily emergency admissions for respiratory infections in children in Riyadh city, Saudi Arabia, International Journal of Environmental Research and Public Health, In Prep

6.2. Introduction

Dust storms have significant impacts on society, health, the economy and the environment. Dust storms occur when strong surface winds pass over dry sandy areas and when airborne dust decreases atmospheric visibility to 1 km or less (McTainsh & Pitblado, 1987; Miller et al., 2008). Dust events are an annual meteorological phenomenon in Saudi Arabia (Albugami et al., 2018), and are known to cause negative impacts on society. For example, the severe dust storm of 10 March 2009 affected many cities in Saudi Arabia, in particular those in the north, east and central regions. During this dust event, vehicle accidents were reported, and there was an increase in hospital admissions due to respiratory problems. In addition, King Khalid International airport in Riyadh was shut down, leading to large economic impacts (Maghrabi et al., 2011; Alharbi et al., 2013). Another huge dust storm swept over the Arabian Peninsula on 18 March 2012. Due to that dust event, schools were closed and hundreds with respiratory illness were sent to the hospitals (Yu el al., 2013). At that same event it was reported by the Saudi Press Agency (SPA) that 830 people visited Riyadh hospitals with asthma, allergies and breathing problems. While there is clear evidence that dust storms lead to a range of negative impacts on society, there is a lack of understanding of how different types of dust storms lead to differing societal impacts. Drawing on the findings of our previous work, this paper aims to examine the impacts of different types of dust storms (widespread dust versus blowing dust) on hospital admissions and operations in Riyadh using statistical and qualitative evidence.

6.2.1. Previous Work

Recently, researchers have shown an increased interest in the impact of dust storms on society, especially in the USA, Australia and China (Brazel & Nickling, 1986; Tam et al., 2012; Merrifield et al., 2013). Decreased visibility is a serious issue caused by dust storms. It increases the risk of road-traffic accidents and affects aircraft operations, leading to delayed departures and sometimes to closures of airports (Kutiel & Furman, 2003; Goudie & Middleton, 2006; De Villiers & Heerden, 2007; Goudie, 2014). Dust events interrupt communications and also affect infrastructure, such as livestock watering points (Huszar & Piper, 1986; Goudie & Middleton, 2006).

Dust storms also have a negative effect on agriculture (Sivakumar, 2005), damaging soil fertility and crops (Goudie & Middleton, 2006) which in turn decreases biological and economic productivity, affecting the communities that depend upon it (i.e. the Al-Ahsa Oasis) (Almuhanna, 2015). Furthermore, the high frequency of dust storms is responsible for the distribution of pollutants via the air over the Arabian Peninsula, which further affects agriculture and threatens human health (Farahat, 2016), because the dust storms are usually contaminated with heavy metals and airborne pathogenic microbes that cause air pollution (Molloy & Mihaltcheva, 2013).

6.2.2. Dust and respiratory diseases

When inhaled, larger dust particles (<10 μm) can cause tracheobronchial irritation (Taylor, 2002; Adar et al., 2014). In addition, smaller dust particles (≤ 2.5 μm) are able to affect the respiratory system by inhalation, which immediately impacts the epithelium of the airways (Wei & Meng, 2006; Watanabe et al., 2011). An increase in dust particles due to dust storms may lead to acute respiratory disease, as shown by Rutherford et al. (1999), who found that the occurrence of dust storms contributed to increasing the number of patients admitted to hospitals with severe asthma in Brisbane, Australia. Moreover, Kanatani et al. (2010) have shown that there was a significant increase in the prevalence of asthma in children due to the Asian dust storms, which led to an increase in hospitalization in Japan. Chien et al. (2012) found that there was a significant association between dust storms and children with respiratory illness in Taiwan. The former can severely affect the pulmonary system, particularly in individuals with pre-existing respiratory diseases (e.g. allergies, asthma and chronic obstructive pulmonary disease) (e.g. Waness et al., 2011; Samarkandi et al., 2017).

In Saudi Arabia, dust storms are one of the main factors associated with the development of respiratory disease (Samarkandi et al., 2017). Some preliminary work carried out in the 1990s (Korenyi-Both et al., 1992) found a relationship between dust storms and several diseases, including pneumonitis and Al Eskan disease, which affect the lungs when people inhale contaminated dust. According to Kwaasi (1998) dust storms in Riyadh contain a variety of allergens and antigens, and thus produce allergy and respiratory diseases that affect human health. As Al-Ghazawy (2013) has mentioned, 24% of people are affected by asthma in Saudi Arabia, and dust storms are one of the reasons of that disease. Infections of the respiratory tract are also very common, especially in children, because they have weaker immunity than adults (Inglis, 2005; Mucia et al., 2015; Sprenger et al., 2018). Different parts of the respiratory tract can be affected by inhaled dust. For example, it may cause inflammation in pulmonary in the lower respiratory tract (Sprenger et al., 2018) and bronchitis and chronic obstructive pulmonary disease (COPD) in the upper respiratory tract (Gross et al., 2018). Dust storm activity has been previously associated with the occurrence of upper respiratory tract infections (URTIs) including asthma, bronchitis, and COPD (Gross et al., 2018) and lower respiratory tract infections (LRTIs) such as pneumonia (Tregoning & Schwarze, 2010; Kang et al., 2012). In addition, Xu et al. (2016), in their study of urban areas in Beijing (China) in 2013, concluded that the $PM_{2.5}$ (particulate matter) affects LRTIs more than URTIs. Moreover, Gross et al. (2018) mentioned that fine dust particles have a negative impact on lower respiratory tract infections (LRTIs).

Only a few studies have been published on the impacts of dust storms on upper respiratory tract infection and lower respiratory tract infection. Watanabe el al., (2011) findings showed that 30% of adults with asthma had worsened the upper and or lower respiratory during Asian dust storms (ADS) (Watanabe el al., 2012). A recent study by (Al-Hemoud el al., 2018) found that there is a strong association between dust particles and upper and lower respiratory diseases. This paper therefore draws on the findings of our previous research, which identified the incidence and spatiotemporal patterns of dust storms in Saudi Arabia (Albugami et al 2018; 2019), but here we aim to analyse the statistical relationship between the elevated atmospheric dust presence and patient admissions to the emergency department of King Fahad Medical City (KFMC) hospital. Specifically, we examine the effects of dust storms on child hospital admissions for upper and lower respiratory tract infections (URTI, LRTI). The findings of the study provide important insight into the health impacts of dust storms in Saudi Arabia, creating knowledge that could be used to develop policy initiatives and a basis for further research.

6.3. Study area

Saudi Arabia is situated on the Arabian Peninsula (see Fig 6, Chapter 5), a large desert plateau covering approximately 2,590,000 km^2 that encompasses various dry valleys (De Pauw, 2002; Maghrabi et al., 2011). The widespread areas of sand dunes in deserts and the sparse vegetation coverage are the main factors affecting the amount of dust in the air (Ta et al., 2004). This paper will focus on Riyadh, the capital and largest city in Saudi Arabia, which has a population of 7 million people and is located in the central region of the country (Abdul Salam, 2013). It is one of the major cities, and attract families, workers and students from different regions in the country because of work opportunities, universities and the high quality of healthcare (Alameri, et al., 2009).

6.4. Materials and Methods

6.4.1. Data

The medical data examined here were obtained from King Fahad Medical City (KFMC) in Riyadh, a centre that provides medical and surgical treatments and critical care, and is a leader in health education, research and specialised medical training programs (KFMC, 2015), The data obtained were daily paediatric emergency admissions numbers for conditions of the respiratory system, categorised as upper respiratory tract infections (URTI) and lower respiratory tract infections (LRTI), for the study period, 1 February 2015–31 January 2016.

Daily dust presence readings from weather stations in Riyadh were obtained from the World Meteorological Organization (WMO). These data include observations of elements in climatology such as surface wind, temperature, atmospheric pressure, visibility and present weather (e.g. dust storm, haze, mist and thunderstorm). These data are based on the coding of the present weather, which is observed and forecasted by the World Meteorological Organization (WMO, 1995; Mahringer, 2008; Papadopoulos and Katsafados, 2009). The WMO classifies the presence of dust by the level of visibility (Shao, 2006): (a) Widespread dust; (b) Blowing dust; (c) Slight or moderate dust storm or sandstorm; and (d) Severe dust storm or sandstorm. In this study, we focused on two categories of dust presence (e.g. widespread dust and blowing dust) and dust-free days due to the nature of our data. These two weather events were dominant in the period from February 2015 to January 2016.

It is difficult to distinguish between the two different dust events by considering the level of visibility. However, several researchers have attempted to define them, as follows: the ‘widespread dust’ is dust in suspension in the air with a visibility of less than 1 km (Middleton, 1986) or not greater than 10 km (Shao, 2006; Rezazadeh et al., 2013). This airborne suspended particulate matter is described as fine dust of PM2.5 (WMO, 1995; OFCM, 1995; Todhunter & Cihacek, 1999). ‘Blowing dust’, on the other hand, is defined as dust or sand raised by the wind at the time of observation and when visibility is less than 11 km (Hinds et al., 1975) but not below 1 km (Middleton, 1986; WMO, 1995; Todhunter & Cihacek, 1999; Shao, 2006; Rezazadeh et al., 2013). In Ozer’s (2002) definition, blowing dust reduces the visibility to less than 5 km.

Widespread dust is commonly constituted of fine airborne particles of 2.5 microns in diameter or less ($PM_{2.5}$), which are very dangerous for human health because they are easily inhaled through the mouth and nose, and can be transported deep into the respiratory system and into the bloodstream, then spreading into other organs (De Longueville et al., 2014; Schulze et al., 2017; WMO, 2019). Moreover, these fine particles tend to stay airborne for longer than when a ‘blowing dust’ storm occurs (Andreae & Crutzen, 1997; Autrup, 2010). However, the PM_{10} particles are typically inhaled through the mouth and nose and can be drawn into the lungs (Soderholm, 1989; Lippmann, 1995). They can cause respiratory symptoms such as cough (Gupta et al., 2012). The effect of $PM_{2.5}$ on long-term exposure has a stronger risk for health and possibly a greater effect on mortality than the coarse part of PM_{10} (WMO, 2013).

To provide further contextual information on the wider impacts of dust, semi-structured interviews were conducted with participants from the medical administrative staff of different hospitals in the study area (i.e. Riyadh, Al-Ahsa and Al-Khobar) to seek the opinions of participating emergency physicians on the impacts of dust storms on population health and hospital operations. Emergency physician participants were interviewed by phone at times convenient for them. The interviews were recorded, then transcribed. Ethics approval was granted by King Fahad Medical City (KFMC) hospital and the University of Exeter prior to the beginning of the study.

6.4.2. Statistical analysis

A Pearson correlation coefficient analysis was performed to investigate the potential existence of relationships between URTI and LRTI during the three weather conditions (widespread dust, blowing dust and non-dust days) by using RStudio (The R Foundation for Statistical Computing) (Table 8). Furthermore, to quantify the hospital admission for the two respiratory symptoms (upper and lower respiratory tract infections) during widespread dust, blowing dust and non-dust, we used a cumulative graphing technique that calculates the number of patients at hospital admissions. I also investigated the delayed effect of the dust event on hospital admission by selecting multiple dust events and the day after, which might reveal a consistent pattern of either increase or decrease in the number of attendees at hospital admissions.

6.5. Results

6.5.1. Descriptive Statistics

There were 7,976 patients admitted to KFMC with respiratory problems (URTI and LRTI combined) from 1 February 2015 to 31 Jan 2016. The total admissions were 3,645 and 4,331 patients for URTI and LRTI, respectively. For URTI, 2,176 patients were admitted to emergency on widespread dust days, 427 patients on blowing dust days and 1,033 patients during clear days. For LRTI, 2,452 patients were admitted to emergency on widespread dust days, 585 patients on blowing dust days and 1,275 on non-dust days (Figure 16).

The daily median number of admissions for URTI and LRTI in dust-free conditions was 21 and 23, respectively. Figure 17 presents the total number of hospital admissions over the period (February 2015–January 2016), including the five-pass filter. Figures 18 and 19 illustrate the difference between the hospital admissions for the two respiratory symptoms (upper and lower respiratory tract infections) during widespread dust, blowing dust and non-dust, using a cumulative graphing technique. Fig. 20 gives an example of the time delay between the dust event and attendance at the emergency department.

Table 10: the Pearson correlation coefficient R-value of the (URTI and LRTI) versus the 3 weather conditions.

	R-value	P-value
Widespread dust	0.3090	0.00001
Blowing dust	0.4545	0.00090
Dust free	0.3068	0.00190

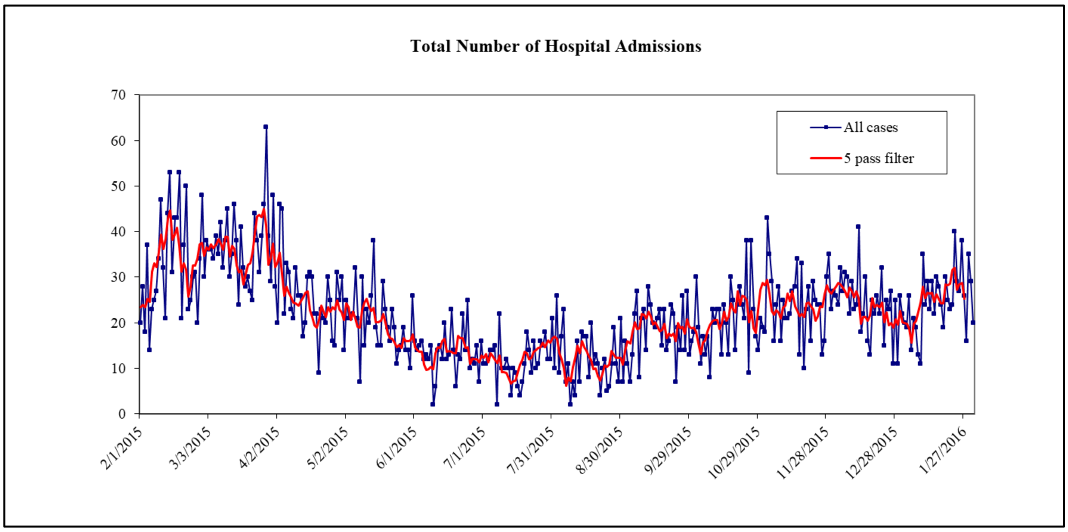


Figure 22 the total number of daily hospital admissions of respiratory patients (URTI and LRTI combined) in blue for the period (Feb-2015 - Jan- 2016) including the five-pass filter in red. The y-axis represents the total daily hospital admissions of respiratory patients.

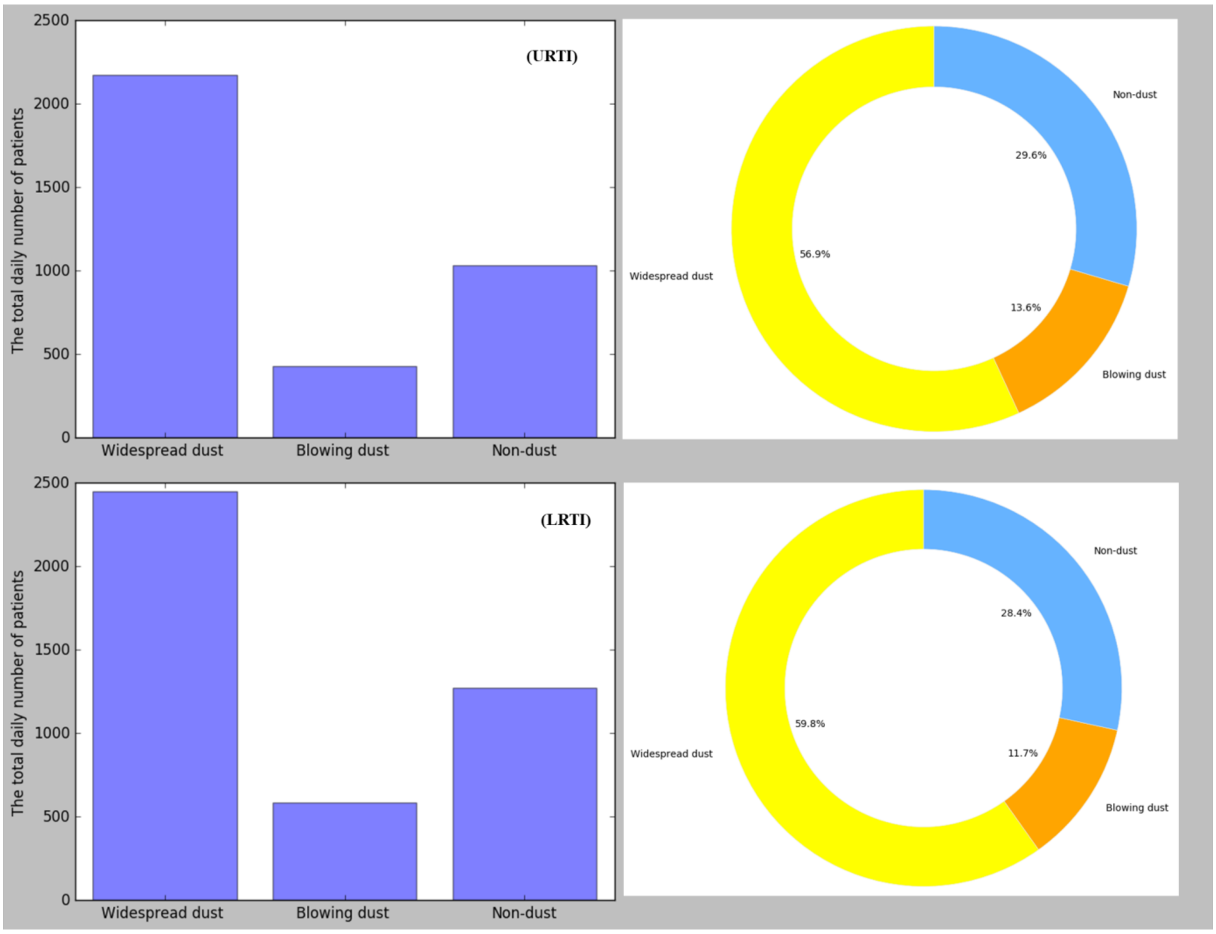


Figure 23 the total number of cases in widespread dust days, blowing dust days and dust free days for both respiratory tract infections (URTI and LRTI) with the total ratio of (URTI and LRTI) patients for the 3 categories, widespread dust in yellow, blowing dust in orange, non-dust days in blue (Feb 2015 - Jan 2016).

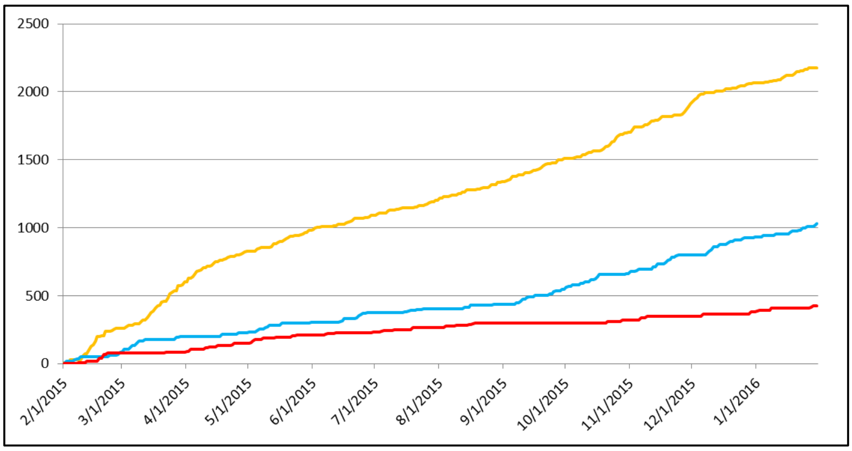


Figure 24 A cumulative number of upper respiratory tract infections and admissions to hospital because of the 3 weather conditions, widespread dust in orange color, blowing dust in red color and non-dust days in blue color.

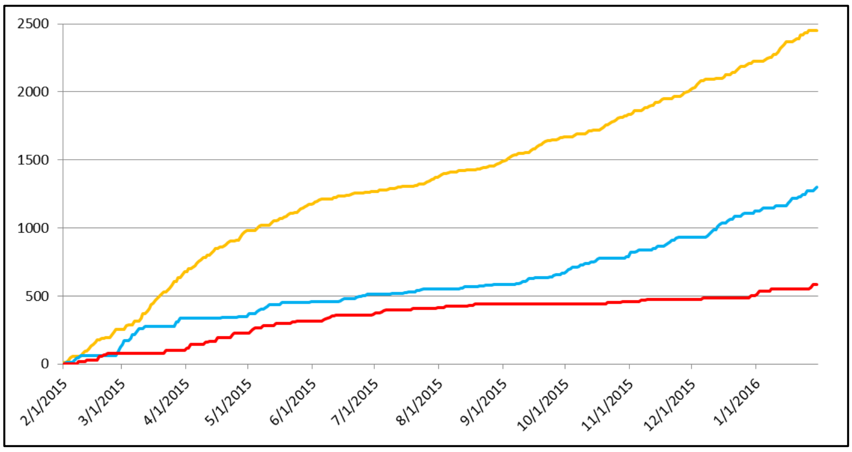


Figure 25 A cumulative number of lower respiratory tract infections and admissions to hospital because of the 3 weather conditions, widespread dust in orange color, blowing dust in red color and non-dust days in blue color.

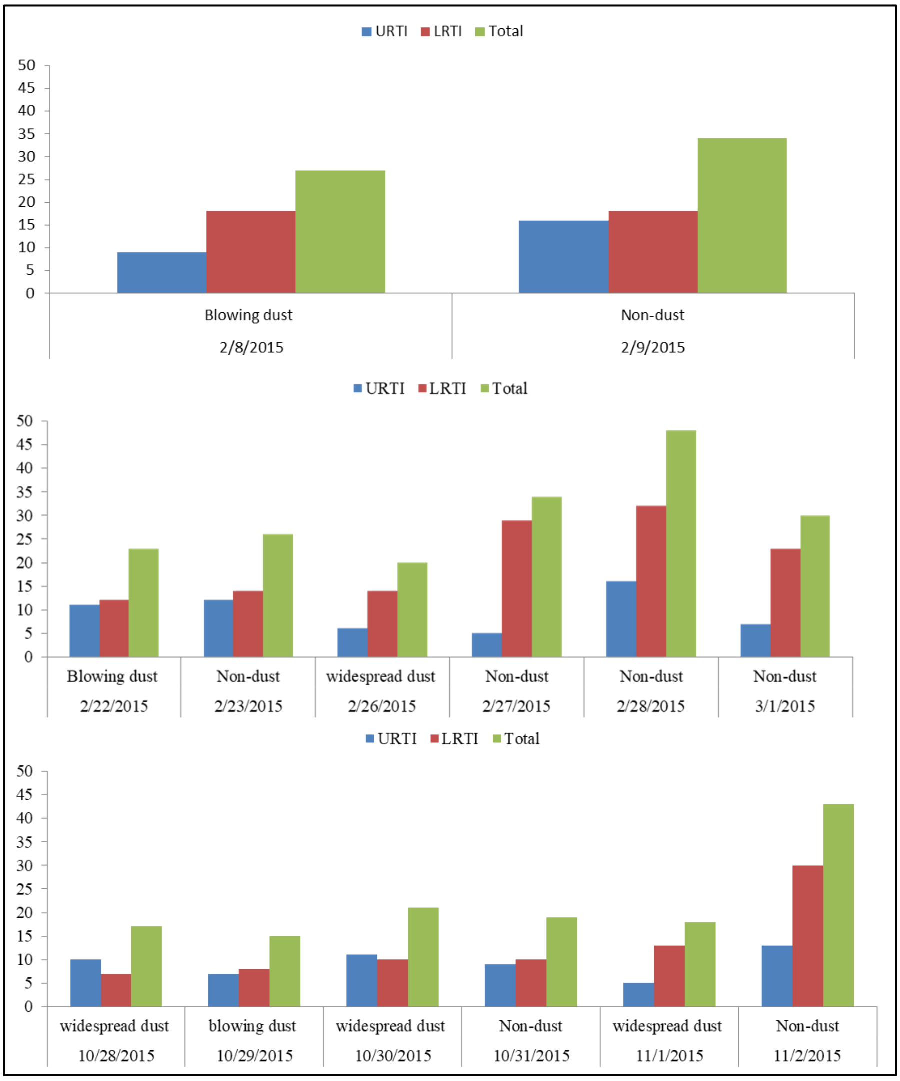


Figure 26 the total number of daily hospital admissions of respiratory patients with an illness in the URTI and LRTI one day or more after a blowing dust and widespred dust event. The y-axis represents the total number of daily hospital admissions of respiratory patients.

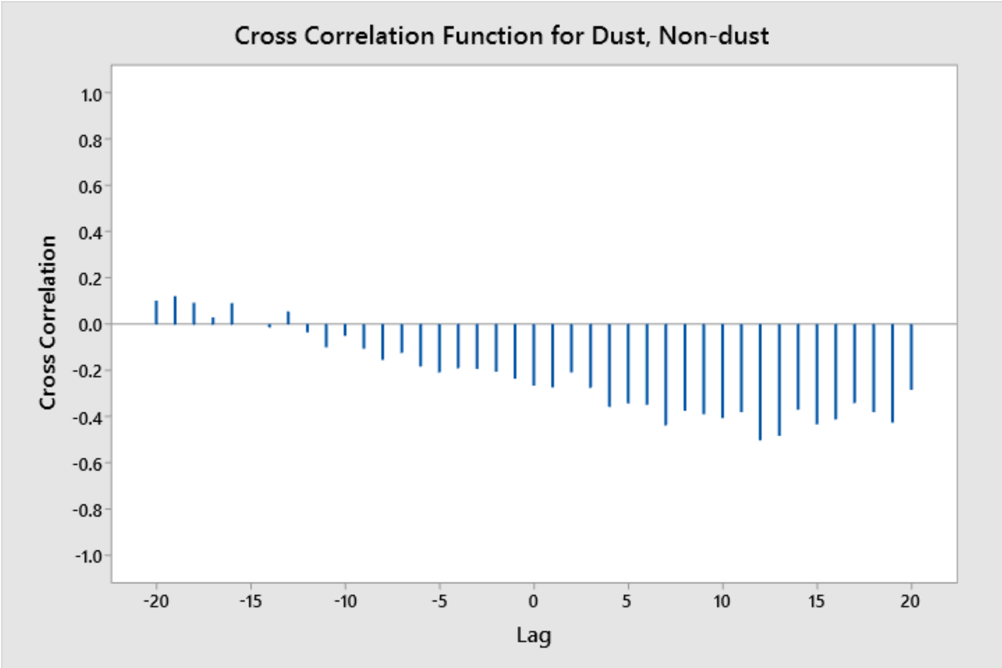


Figure 27 Cross-correlation (95% confidence intervals) of the total numbers of emergency medical pediatric admissions during dust events and dust-free (2015 - 2016).

6.6. Discussion

6.6.1. Statistical findings

The results of the Pearson correlation coefficient show that URTI and LRTI are statistically significant correlated ($p < 0.05$) for all of the 3 weather conditions (i.e. widespread dust, blowing dust and non-dust days) during the study period (i.e. 0.309, 0.4545 and 0.3068, respectively). According to the Pearson correlation coefficient analysis, there is a strong correlation between the meteorological variables (e.g. widespread dust, blowing dust and non-dust days) with both upper and lower respiratory tracts hospital admissions.

6.6.2. Seasonality of Dust Presence and Hospital Admissions for Respiratory Conditions

The results shown in Fig. 22, which plots the total number of daily hospital admissions of respiratory patients (URTI and LRTI combined) across all weather conditions during the study period, show that the majority of the patients visited the emergency department in March to April. This period corresponds with the well-known seasonal maximum peak in dust storm activity in the region (e.g. Notaro et al., 2013; Yu et al., 2015; Albugami et al., 2019). The analysis demonstrates that the number of paediatric emergency department visits for both URTI and LRTI substantially decreased during the months from June to August. Further, the period from October to January saw a fluctuation in the number of cases. This period had several substantial peaks, with a higher average number of admissions than in the June-to-August period, but lower than that in the February-to-April period.

6.6.3. Impacts on admissions for upper respiratory tract infections

As shown in the upper panel of Fig. 23, the bar chart gives information about the number of total admissions to the hospital for URTIs during the three weather conditions indicated. The rate of visits to the emergency department during widespread dust events is 56.9%, in contrast to that in blowing dust, at 13.6%, and dust free days, at 29.6%. It is worth mentioning that in this part of the study period, the number of widespread dust days was 210, blowing dust days was 50 and clear weather days was 105 days. An interviewee from King Faisal Specialist Hospital and Research Centre in Riyadh noted that severe allergic rhinitis, a disease of the upper respiratory tract, is related to direct dust exposure. Al Anazy et al. (1997) claimed that a high concentration of dust particles in the air is one of the factors for the rising number of patients with the condition. Furthermore, most of the interviewees explained that the most common respiratory health conditions in the emergency department during a dust event is chronic obstructive pulmonary disease (COPD), a disease exacerbated by URTIs (Blanc el al., 2009; Sethi, 2010; Khan el al., 2014; AAl el al., 2016; Samarkandi el al., 2017).

It has been found that the cumulative number of upper respiratory tract infections produces the highest hospital attendance over time, leading to average numbers of daily hospital admissions of 10.36 on widespread dust and 9.71 on non-dust days. Furthermore, the number of URTI patients who came to hospital admissions during the widespread dust mostly remained stable, especially between the months July and November. However, as can be seen from Figs. 24 there was an increase of 10.16% over the total annual number during the month of April. The average number of patients during blowing dust events was 8.54 per day. Further, the cumulative number of URTI admissions under the blowing dust condition shows a constant pattern over time, as noted in Fig. 24.

6.6.4. Impacts on admissions for lower respiratory tract infections

The lower panel of Fig. 23 indicates the total number of hospital admissions for LRTI symptoms during the three weather conditions. The percentage of the total attendance at admissions during the widespread dust days was 59.9%, whereas for the blowing dust and non-dust days it was11.7% and 28.4%, respectively. From this figure, it can be seen that there were 12.68% more visits for LRTIs during widespread dust events than for URTIs. This aligns with the perceptions of an interviewee from King Fahd Medical City, who described how dust storms are associated with serious conditions such as pneumonia and other diseases of the lower respiratory tract. That assessment supports previous findings in the literature (Korenyi-Both et al., 1992) which demonstrated that the dust storms in Saudi Arabia contribute to a considerable number of pneumonitis infections. Several previous studies have also illustrated the relationship between dust storms and pneumonia around the world. For example, Meng and Lu (2007) reported that pneumonia prevalence is associated with proximity to desert regions, where people are more exposed to dust storms. In Asia, Cheng et al. (2008) found a significant positive correlation between dust events and daily pneumonia admissions in Taipei, Taiwan. Gudavali et al. (2009) showed that dust storms also have an association with increased admissions for pneumonia in Korea. Other respiratory tract infections have also been associated with dust storms; for instance, Uduma and Jimoh (2013) have described how Saharan dust storms are associated with the diseases of asthma, bronchitis and pneumonia in Nigeria. In the present case, the cumulative number of lower respiratory tract infections generated the most visits over time, leading to an average of 11.62 daily hospital admissions under widespread dust conditions (Fig. 25). These admissions also showed an increase compared to URTIs in April, rising by 31.67 during the same month. Fig. 25 illustrates a slight increase in the number of admissions for LRTI through the month of April, and subsequently shows a stable pattern over time.

The finding of both admissions (lower and upper respiratory) aligns with the perceptions of interviewees, who described how patient admissions for respiratory conditions increase both during and after dust storms. For instance, one mentioned an increase of 3.4% above the normal monthly average during dust events in Sanad Hospital in Riyadh. Moreover, an interviewee in Dammam mentioned that there the emergency admissions increased by 20% due to a dust storm.

6.6.5. Impact of delay in admission during a dust event

Figure 26 gives examples of delayed visits to hospital admissions during a dust event. From this figure, it can be seen that the number of patients increased by 26% on 9 of Feb 2015 and 13% on 23rd February 2015 as compared to the previous days, which were both dust-free days following a blowing dust day. Mostly, the data shows that blowing dust days are followed by widespread dust. Figure 26 also illustrates that the number of visits to hospital admissions increased by 70% over the total admission the day after the widespread dust on 27 Feb 2015. Moreover, on the second day after the widespread dust, there was an increase of 42% in the total admissions, as we see from the example of 2 November 2015 (see Figure 26). However, these examples suggest there may be a relationship between the type of dust presence for the days after a blowing dust event and the number of admissions. To gain a better understanding, I applied the cross-correlation to investigate if there is a delay in admission during a dust event. Figure 27 displays the cross-correlation as a negative lag. The strongest negative correlation values (r= -0.5) are reached between 10 and 15 days. This result suggests that there is no lag between a dust event and the number of hospital admissions on dust-free days. Nevertheless, further research on a larger number of events is needed.

6.7. Further health, operational and financial impacts of dust storms on hospitals

This study also identified an association between dust presence and hospital admissions for respiratory conditions; however, there are potentially much more widespread health effects, including impacts on mental health (Yahya & Seker, 2018). For instance, several of the interviewees mentioned that dust storms might increase the rates of depression, mood swings, anxiety, headaches, psychological disturbances and sleep disturbances. These psychological issues are due to shortness of breath during a dust event (Saint-Armand et al., 1986).

It is worth also briefly considering the financial and logistical impact of dust storms on hospital operations. The majority of the interviewees commented that hospitals in Riyadh have an emergency management plan (EMP) in place to ensure the availability of resources for the continuation of patient care during a dust event. Moreover, this EMP also assures readiness inside the hospital for varying severities and numbers of casualties. Interviewees noted that dust events often cause wards and emergency departments runs above their base bed capacity by approximately 20 to 30% (Tam et al., 2012).

Dust events also have a financial impact due to the increased strain on hospital resources, including daily consumables, respiratory equipment, medication, supplies of oxygen and personal protective equipment such as masks, as well as ambulance transfers. For example, one interviewee estimated that daily operating costs increase by 30 to 50%, beginning from the first day of the dust storm and typically continuing until the third. Another interviewee explained how elevated levels of dust require the use of additional cleaning services in the hospital, which can cost as much as 30,000 SAR ($8,000) per event.

6.8. Limitation, contributions and wider implications

This study also has some limitations that could be addressed in future research. Limited access to data restricted our study to just one year of data in one city in the country. While the data acquired from the King Fahad Medical City is likely to be representative of typical hospital admissions for respiratory conditions in areas subject to dust storms, acquiring data from other hospitals was not possible in this study. Analysing multiple years of data from locations across the country would strengthen the findings further, and should be the focus of further research in order to develop a stronger understanding of how dust presence contributes to the risk of respiratory conditions in children.

The overall aim of this study was to analyse the effects of different types of dust conditions (widespread dust, blowing dust and dust-free) on emergency department admissions for respiratory symptoms, in particular for URTIs and LRTIs. The research was intended as a step towards addressing a gap in work on this topic in Saudi Arabia. As far as we are aware, there is no other study about the impact of dust on the upper and lower respiratory tract due to different weather conditions. This study therefore makes a key contribution, beginning to address the knowledge gap in respiratory studies and the dust impact on the upper and lower respiratory tract, which may be of value to other researchers in this field. Moreover, the findings might have implications for policy decisions at hospitals, enabling administrators to understand the hazardous effect of the exposure to widespread dust on the lower respiratory tract. In terms of seasonality, our findings highlighting an increase in admissions in the early months of the year are likely to align with existing knowledge about the annual pattern of dust storms; however, the specific increases that the study reveals could be valuable for effectively distributing funds and staffing in hospitals at critical times of the year. Furthermore, the findings suggest that this approach could also be useful for the authorities in hospitals. By asking to receive an update on the weather conditions, for example, they could help the medical staff to prepare for the arrival of patients with respiratory problems.

6.9. Conclusions

From the outcome of this study, it is possible to conclude that there is a statistically significant correlation between URTIs and LRTIs across the three weather conditions noted, which are widespread dust, blowing dust, and dust free (i.e., r =0.3090, 0.4545 and 0.3068, respectively). This research has clearly shown that during widespread dust events, LRTIs prompt more visits to hospital admissions with an average related attendance of 11.62 patients per day. In contrast, the average number of hospital admissions for URTIs under the same conditions was 10.36 per day. The finding has shown a clear seasonal variability, with a peak in the number of emergency admissions during the months of February to April. Furthermore, the results show an increase of 31.67 in total cases LRTI cases in April compared to URTI ones. These findings suggest the need for further analysis of the health and economic impacts of dust in order to develop policies and countermeasures to mitigate harmful societal impacts.

7. Conclusion and Synthesis

7.2. Introduction

This thesis presents an evaluation of the suitability and efficiency of existing satellite dust detection methods over the Arabian Peninsula, as well as describing the spatial-temporal distribution patterns of atmospheric dust in Saudi Arabia between 2000 and 2016. In addition, it assesses the associations between two types of dust events (widespread dust and blowing dust) and emergency hospital admissions due to lower and upper respiratory tract infectious disease in Riyadh. The study objectives included: evaluating the suitability of five different MODIS-based methods or detecting airborne dust over the Arabian Peninsula; understanding the spatial and temporal relationship between dust storms and environmental conditions in Saudi Arabia; and understanding the relationship between dust presence and hospital admissions.

7.3. Main findings and Contributions

7.3.1. Dust storm detection indices:

This part of the study focused on the evaluation of the MODIS dust detection indices over the Arabian Peninsula. Chapter 4 presents the five methods (i.e. NDDI, BTD [31–32], BTD [20–31], MEDI and RSB) which were computed by Top of Atmosphere (TOA) reflectance calibration from MODIS images (White, 2007). In this study, I tested the differences in the indices between dust and non-dust settings for two moments close in time. Accordingly, I had to consider these as dependent samples. Therefore, I used the Wilcoxon signed rank test for paired samples. When I considered all the land cover for testing the indices, I found that values differed significantly under the dust and dust-free conditions for the NDDI index, with a

Wilcoxon p-value = 0.000 for the BTD (31–32), a p-value of 0.002 for the BTD (20–31) and a p-value = 0.005 for the RSB index. The MEDI values between dust and non-dust values are not significant when considering all land uses (i.e., a Wilcoxon signed-rank test with a p-value 0.758). Another of the main findings is that the overlapping of dust and non-dust distributions over time has implications for the suitability of the different indices for detecting dust over the Arabian Peninsula between 2000 and 2016, which means the index is only suitable when a non-dust image from a nearby moment in time is available (e.g. NDDI and RSB).

The NDDI is a useful index for dust-detection over the land in general. Nevertheless, there is one significant limitation to this method, which was that it was not useful in detecting airborne dust over urban areas. It is interesting to mention that a recent study by Butt and Mashat (2018) concluded that NDDI is an effective method for distinguishing dust storms from clouds over Saudi Arabia. The Brightness Temperature Difference (BTD) is a method that can detect dust by the subtraction between the brightness temperatures of different infrared wavelengths (Ackerman, 1997; Baddock et al., 2009; Legrand et al., 2001). This method, BTD (31-32) was successful in detecting dust storms over different land-cover types across the Arabian Peninsula.

However, BTD (20-31) methods have limitations in identifying dust over multiple land-cover types, such as the vegetation areas. The results of this study demonstrated that the RSB method is also a useful index to distinguish dust from non-dust over different land cover settings. Even though the MEDI method was proposed for detecting dust over the Middle East (Karimi et al., 2012; Komeilian et al., 2014; Moridnejad et al., 2015), the results have shown that this method is unsuitable for detecting dust in the study area across all land-cover types. The results of the validation of the index performance over different land cover showed that the NDDI index has limitations in distinguishing airborne dust from the desert areas. The BTD (20–31) and RSB had shown false detection in urban areas. All the dust indices have limitations and uncertainties, as was stated by Miller (2016), due to the possibility of false detection. However, the dust-validation analysis revealed that the BTD (31-32) method is a suitable index for detecting airborne dust over different land cover.

The novelty of this study was that I used the dust detection methods over different land cover types in Saudi Arabia and bordering states located on the Arabian Peninsula, whereas most of the previous studies only used the dust detection methods to distinguish between dust and bright land cover (Barren), dark land cover (vegetation) or water. For example, Zhao et al. (2010) applied the BTD dust detection index over land and ocean, and found it to be successful in both cases. Furthermore, Samadi et al. (2014) employed the dust indices (BTD, NDDI, RSB) to differentiate dust from bright surfaces, dark land cover and water. Moreover, Xie et al. (2017) used MODIS solar (RSB) and thermal bands (TEB) for observing and monitoring dust airborne over bright (barren) and dark (vegetation) surfaces.

Here, I derive detection thresholds for each index by comparing observed values for 'dust-present' versus 'dust-free' conditions, taking into account various land cover settings and analysing associated temporal trends by applying regression analyses and the model uncertainty, as well as the uncertainty on the slope parameter of the linear regression model for dust and non-dust values. The findings presented are the threshold values for each dust detection method. These thresholds were defined by the upper or the lower 95% confidence interval line of the model error bound of the trend line fitted through the non-dust observations, and whichever was closest to the trend line fitted through the dust storm observations.

In this study, I examined the temporal trends for dust and non-dust values. With the RSB index, the trends in dust and dust-free values are mostly consistent across the different land covers. In contrast, the other indices have shown that there was a contradiction between dust and non-dust trends. It is difficult to explain such results; however, the observed temporal trends may indicate long-term changes in atmospheric conditions, such as the increased temperature and the decrease in the precipitation over the Arabian Peninsula (AlSarmi & Washington, 2011; Almazroui et al., 2012; Donat el al., 2014). It is also possible that land-use changes in the region, such as urban expansion in the study area (Alqurashi & Kumar 2014; Rahman, 2016), have changed the surface reflectivity properties (see Chapter 4).

This work is the first step in the field of dust storm detection in Saudi Arabia and the surrounding area. Most of the existing studies have focused on the Middle East (Karimi et al., 2012; Jafari & Malekian, 2015; Moridnejad et al., 2015; Shahraiyni et al., 2015). Other studies have addressed the Asian dust storms over China (Gu et al., 2003; Roskovensky & Liou, 2005; Qu et al., 2006; Huang et al., 2006; Zhao, 2012; Han et al., 2013) or those in Iran (Samadi et al., 2014; Jafari & Malekian, 2015; Khamooshi et al., 2016). The dust detection test has also applied over Australia (Bullard et al., 2008; Baddock et al., 2009). In addition, there was a recent study by Butt and Mashat (2018) in which they used MODIS images for the period 2002–2011 to evaluate and monitor dust storms in Saudi Arabia by applying the NDDI index.

Little research has considered the linear regression in the dust detection field; however, the use of the regression analysis is different from the approaches of this study. Others, such as Di et al. (2016) employed linear regression to investigate the association between the Enhanced Dust Index (EDI) and visibility, which demonstrated a significant negative relationship. However, the regression analysis revealed significant relationship between the brightness temperature adjusted dust index (BADI), which is a method to detect dust storms by using MODIS images, and MODIS Deep Blue AOD values (Yue et al., 2017). Nonetheless, no study has considered investigating the temporal trends between dust and non-dust values by conducting a regression analysis.

7.3.2. The Spatio-temporal distribution of dust storms:

Prior to this research, there have been no studies on the spatial and temporal variations in the occurrence of dust storms in relation to influencing factors, such as climate variables, specifically temperature, precipitation, wind speed and wind direction, across Saudi Arabia (Chapter 5). The temporal trend analysis of the total number of dust storms has shown that the highest annual total amount of dust storm events was recorded in 2003, which had 203 such events. The findings showed that long-term trends varied to a large extent depending on the location of each station. The results indicated there was a significant positive relationship ($p<0.005$) between dust storm occurrence and wind speed, wind direction and precipitation. That finding is consistent with what has been found in a previous study by Chin et al. (2014), which concluded that dust events are associated with regional wind speeds in the Middle East. However, we did not find a significant relationship with temperature. This finding is similar to that of a previous study by Amanollahi et al. (2015), who found no effect of high and low temperatures on the occurrence of dust storms.

The analysis found evidence for important spatial patterns as well as seasonal and inter-annual variations in the occurrence of dust storms in Saudi Arabia. For instance, there has been a gradual increase in dust storms over Al-Ahsa, which is located in the eastern part of Saudi Arabia (1.71 ± 0.71 y-1) and Jeddah, which is in the west (0.37 ± 0.10 y-1). It can be noted that there were several increases in the frequency of the dust storms over Riyadh (see Chapter 5). However, the findings showed that the dust storm events were marked by a decrease over time in locations in the north, such as Hail and Qaisumah.

Dust storm events across Saudi Arabia occur throughout the entire year (Prospero et al., 2002; Notaro et al., 2013; Yu et al., 2013; Notaro et. al., 2015), but similar to observations at the regional scale, there was a clear seasonal variability. The analysis illustrated that the dust storm frequency reaches its maximum during the spring, whereas the lowest number of dust storm events took place in autumn. A similar conclusion was reached by Wang (2015), who contended that the dust activities peak during the spring-summer in the Middle East. The present study's findings also demonstrated that there was a shift in dust storms from the northeast, which is possibly caused by the wind between high-pressure currents over the Mediterranean Sea and low-pressure ones in Saudi Arabia (Rousta, 2017), to the southeast. Moreover, the prevailing wind direction during dust-free and dust storm days varies across different parts of the country.

This chapter provided fresh insight into the influence of climate variables on the incidence of dust storms in Saudi Arabia. This type of analysis was widely used because of the considerable impact of dust storms have revealed a clear seasonality in dust events, with the highest frequency of storms occurring during the spring and summer, which aligns with the findings of previous studies (Ackerman & Cox, 1989; Washington et al., 2003; Notaro et al., 2013; Yu et al., 2013). The findings contribute to the existing knowledge of the spatial and temporal variations of dust events in Saudi Arabia. They also illuminate the effects of environmental forces on the occurrence of dust storms across Saudi Arabia by considering the relationships between dust storm frequency and temperature, precipitation, and wind variables, as recorded by the observation stations in 13 regions of Saudi Arabia (i.e., Riyadh, Makkah, Madinah, Al-Qassim, Eastern Province, Asir, Tabuk, Hail, Northern Borders, Jizan, Najran, Baha and Al-Jouf).

This part of this study provides useful information that may be of interest to researchers and specialists in the field of physical geography with an emphasis on weather and climate conditions such as dust events. The present study might be useful to local, regional and international policy-makers seeking to understand the variation of dust storm events over the Arabian Peninsula, which can help them to develop better monitoring systems or warning systems. The current research also observes temporal trends in dust events and offers several possible causes, such as example climate change and land-use changes (i.e. urbanisation and vegetation coverage) in Saudi Arabia, as discussed in detail in Chapter 5.

7.3.3. Impact of dust storms on human health:

The aim of the work presented in Chapter 4 was to explore the dust's impact on health and hospital admissions. Data used for the analysis were the counts of daily paediatric patient admissions for respiratory tract infections to the emergency department at King Fahad Medical City (KFMC), Riyadh, for the one-year period from February 2015 to January 2016. Moreover, we conducted semi-structured interviews with participants from the medical administrative staff in different hospitals in the study area (i.e. Riyadh, Al-Ahsa and Al-Khobar), and analysed daily dust presence readings from World Meteorological Organization (WMO) weather stations in Riyadh. Based on the WMO protocol, dust presence is classified by the level of visibility. In this study, I focused on three categories of dust presence. The first category is 'widespread dust', dust in suspension in the air with a visibility of less than 1000 m (Middleton, 1986). This airborne suspended particulate matter is described as fine dust of $PM_{2.5}$ (WMO, 1995; OFCM, 1995). The second category is 'blowing dust', which is defined as dust or sand raised by the wind at the time of observation and which reduces visibility, but not to below 1000 m (Middleton, 1986; WMO, 1995; Shao &Dong, 2006).

In Chapter 4, the findings illustrated that URTI and LRTU are significantly correlated ($p < 0.05$) in the three weather conditions (widespread dust, blowing dust and non-dust days) considered during the study period (i.e. 0.309, 0.4545 and 0.3068, respectively). The findings demonstrated that there is more of an increase in LRTI cases more than in URTI ones during dust events. This confirms previous findings in the literature. For example, Watanabe et al. (2012) found that across the Asian deserts, dust storm occurrence has a significant impact on LRTIs. Moreover, I found an increase of paediatric patients in emergency admission during dust storms compared to dust-free days, especially in URTI cases. This finding aligns with the perceptions of interviewees, who described how patient admissions for respiratory conditions increase both during and after dust storms.

It is interesting that I found a clear seasonality trend of dust presence and hospital admissions for respiratory conditions. The results show that the majority of the patients visited emergency departments in March and April, which corresponds with the intra-annual max peak in dust storms in the region (Notaro et al., 2013; Yu et al., 2015; Albugami et al., 2019). Our findings have shown that widespread dust is the more dominant dust condition overall, especially in the early months of the year. The analysis has demonstrated that the number of paediatric emergency department visits for both URTIs and LRTIs substantially decreased from June to August. Furthermore, the period from October to January saw a fluctuation in the number of cases. Dust events have a considerable impact on hospital admissions because of the incidence and frequently time-consuming visits for the patients, especially those who have a chronic respiratory disease. The latter will contribute to increasing the costs for patients, staff, beds, and effort for staff to manage the patients.

My results expanded on these by demonstrating that most of the visits to emergency admissions were patients with lower respiratory symptoms during a dust event; this finding is consistent with what has been found in a previous study by Watanabe el al. (2011). To my knowledge, this is the first research to examine the association between the daily hospital admissions visits and dust events in Riyadh, Saudi Arabia, especially for the upper and lower respiratory illness, with a consideration of the effects of three weather conditions (widespread dust, blowing dust and non-dust days). In addition, this chapter highlighted the time lag between the dust event and patient attendance at the emergency department. A study by Tam et al. (2012) reported that there is a 5% increase in hospital admissions after two days of a dust storm. The results for three examples can be found in (Fig. 26), and confirm that there is indeed a time lag of up to one day or even two days between a dust event (widespread dust and blowing dust) and hospital visits.

7.4. Synthesis

The present research provides detailed insight into methods for remotely identifying dust patterns, spatiotemporal variation in dust storms and their relation to environmental conditions, as well as for assessing associated implications for people living in dust-prone areas. Moreover, dust storms are becoming more of a global phenomenon due to climate change, such as in Asia (e.g. China, Iran, Afghanistan and

Pakistan) [Middleton, 1986; Prakash et al., 2015; Zhang et al., 2016] and Europe, (e.g. Spain and Italy [Middleton, 1986, Zhang et al., 2016]). North America and Australia are also affected by dust storms (Middleton, 1986; Yang et al., 2015). There have been numerous studies to investigate different aspects of dust storms, and with different methods and tools. However, I focus on three aspects of this research: the suitability of dust detection methods by remote-sensing and MODIS images over the Arabian Peninsula; the spatial and temporal variations of dust storms over Saudi Arabia; and dust's impact on health.

7.4.1. Data integration

Remote sensing, satellite images and in situ observations are playing an important role in dust detection. The more traditional dust detection methods have their strengths and limitations, because the in-situ measurements might have missing records due to the fact that measurements stations were under construction or repair. Hence, the combination of satellite images and the in-situ measurements can provide us with full insight into the dust event dynamics across larger geographical entities. In this case, satellite imagery allowed us to detect the development of the dust storms over a certain area and differentiate dust from non-dust and clouds, even over different land covers such as urban areas, barren and vegetation. The ground dataset helped us identify the month, season or the annual trends over the study area. Furthermore, the link between the seasonality of dust events and respiratory disease, as recorded in hospital admissions provided us with the impact of dust storms on human health. The analysis of the MODIS was used to detect dust storm over the Arabian Peninsula, and the methods of this analysis were validated by the in-situ observations. Hence, these ground data were helpful in identifying the spatial, seasonal and inter-annual patterns of dust storms over Saudi Arabia and assessing the correlation with hospital admissions and weather conditions.

7.4.2. Spatially and temporally varying dust storms:

The eastern part of the study area experienced the highest frequency of dust storms and an increase in dust storm events over time, especially in Al-Ahsa. This was demonstrated in dust detection and the spatial-temporal analysis. As can be seen from Figs. 2 and 11 (Chapter 4 and Chapter 5, respectively), most of the MODIS images which were used the dust detection analysis recorded dust events that occurred in the east part of the study area and were shown in the in situ observation data. Moreover, the highest frequency of dust events was during the spring. Similarly, a spring trend in increased hospital admissions for respiratory symptoms for children in Riyadh, the centre of Saudi Arabia, was identified. I concluded that dust events were associated with the hospital admission, especially widespread dust (fine dust), which mostly affects the lower respiratory tract infections (LRTIs).

7.4.3. Temporal trends

Surprisingly, the analysis of this present research has shown temporal trends from both observations the MODIS data and in situ data. These temporal trends might be a result of large-scale land-use change dynamics over the study area, such as urbanisation and variability in vegetation coverage (Alqurashi & Kumar, 2014; Rahman, 2016). An early study by Behairy et al. (1985) demonstrated that human activities and expansion of urban and industrial development lead to an increase in local dust in the construction phases. In addition, the observed temporal trends may indicate long-term changes in atmospheric conditions such as the increased temperature and the decrease in the precipitation over the Arabian Peninsula, which may alter the reflectance properties of the surface over time for the dust and non-dust MODIS values (AlSarmi & Washington, 2011; Donat et al., 2014). Moreover, climate changes might have a role in the frequency of dust events (Du et al., 2009). Climate change is also associated with human health problems such as cardiopulmonary and respiratory disease, as it enhances harmful and extreme weather including hurricanes, droughts or heavy rainfall events, resulting in floods and dust storms (Rice et al., 2014). PSR (2019) emphasised that climate change contributes to the frequency of dust storms, which contribute to chronic pneumonia and other deleterious effects of human health. A possible explanation for these temporal trends is the widespread abandonment of areas in Syria and Iraq due to military conflict in these regions, inducing desertification and thus forming the main source areas of dust for the north-eastern part of the Arabian Peninsula (Al-Dousari et al., 2017). This is particularly the case for the Iraqi deserts, Al-Hajarah and Al-Dibdibah (Notaro et al., 2013).

7.5. Wider implications:

The findings of the present thesis may have useful implications for the evaluation of the existing dust detection methods. This may be helpful in early detection and investigation of the occurrence of dust storms over Saudi Arabia and the Gulf countries. Another advantage of these dust detection approaches is that they allow researchers to select and apply a given threshold value in order to test the effectiveness of the dust detection index over the same study area. Helpful elements of the findings in Chapter 4 are the approaches and the statistical analyses which were applied in this study, and which shed light on different perspectives and interpretations in evaluating dust detection methods. Furthermore, the current research provides valuable information for researchers seeking to understand the suitability of the dust detection indices across different land cover types. It has an important implication for authorities in the field of meteorology, and may help them to realise the importance of the use the dust detection techniques and MODIS imagery in identifying dust storms over the Arabian Peninsula. Overall, these findings have potential implications for practice in the field of developing these dust detections (NDDI, BTD, MEDI and RSB) over the Arabian Peninsula. In addition, these results are useful for further research in monitoring and detecting dust storms in general.

Dust storm spatial and temporal variations have been identified in this research (see Chapter 5). The findings of this study provide an insight into the spatial and temporal variations of dust storms and the relationship between environmental conditions and dust storm occurrence across Saudi Arabia. The current research explores the different impacts of the weather variables (i.e. temperature, precipitation, wind speed and wind direction) on the dust events, and the findings would be useful in understanding the role of each climate variable and identifying the explanatory factors. A core implication of this present study is that it draws attention to the spatial and temporal variability in dust storms over Saudi Arabia and the significant correlations of that variability with climatological factors, which would help in generating useful information for the policy-makers as well as researchers in this field. In essence, this study requires awareness of government when constructing policies to reduce dust storm event impacts in the region, especially in the most frequently affected areas, such as the eastern region.

This research also helps in understanding dust storm dynamics and their impact on upper and lower respiratory tract infections in children in Riyadh, Saudi Arabia. The two dust types (widespread dust and blowing dust) which were used in the analysis for this part of the study had different impacts on upper and lower respiratory tract infections. For instance, in widespread dust events the average number of visits to the hospital admissions department for LRTIs was 11.62 per day, while it was 10.36 per day for URTIs (See Chapter 4).

These findings might have implications for future respiratory research, and could contribute to a more efficient decision-making process at hospitals, which might illuminate the hazardous effects on the lower respiratory tract stemming from the exposure to widespread dust events. These findings might be also be beneficial regionally and internationally, helping policy-makers in hospitals to understand the dust types and their impact on the respiratory system. This requires preparing resources such as respiratory equipment, medication and arranging more spaces for the patients arriving at the emergency department during a dust event. Furthermore, this study suggests establishing communication or a direct link between the hospital in region and other governmental authorities such as the ministry of health (MOH) for regular feedback about the census and another direct contact with any national entity for the weather forecast. The results of the study may be useful for raising awareness in families in order to avoid them carrying out outside activities during dust events and exposing their children to respiratory disease.

More importantly, this thesis suggests that there exists a need for authorities and policy-makers to enhance and update the dataset in order to provide complete data, which will help researchers in their assessment of the health impacts of dust storms. I would also like to highlight the importance of the cooperation in providing data or reports to support studies and scientific research, because the latter will have an important role in further expanding knowledge and delivering key contributions to the decision-making process.

7.6. Limitations and further work

This research is subject to several limitations in the data. First, I found MODIS sensor degradation in band (B29). This band was used for the MEDI index. When I downloaded it, it appeared degraded which might be the reason the MEDI method was unsuccessful. Further, there were limitations in dust detection methods. For example, the NDDI and BTD (20–31) methods have limitations in identifying dust over multiple land-cover types. Second, in my opinion, a daily dataset provides the number of dust storms might provide more information than the monthly data which was used in this study for the spatial and temporal dust variability analysis. Third, the missing records in the monthly data (i.e. 2002 and 2009) of the in-situ stations might influence the statistical analyses. Fourth, there was restricted access to daily hospital data for all regions in Saudi Arabia. We even struggled to obtain the required data for just the hospitals in Riyadh, because there were missing records, which limited our analysis to records involving children and only covering a one-year period. Fifth, we attempted to study the economic impact of dust storms; unfortunately, it was very difficult to have data regarding that matter – data related to aviation or agriculture, for example. On the other hand, timing was also one of the limitations. Submitting the papers required us to much more time for revision and answering the reviewers.

The thesis presents an overview of and a fundamental base for future work in the field of dust events, especially in dust detection, spatial and temporal analysis of dust storms and determinations of their impact on health. The main suggestions for future work are as follows. As shown in Chapter 4, the evaluations of the MODIS dust detection indices over the Arabian Peninsula revealed that the most successful methods are BTD (31–32) test and the RSB test. It would be useful to improve the accuracy of detection thresholds as a function of time over the Arabian Peninsula or across the entire Middle East, perhaps by using different MODIS bands. In this thesis, I focused on the land for detecting dust events; however, the water is also an important area of study, especially over the Red Sea, as it is well known that dust events contribute towards coral reef degradation. For example, research has provided evidence that there is a decrease in coral reefs in the Caribbean because of dust storms originating from Sahara Desert (Griffin & Kellogg, 2004). As dust storms often contain metal (especially iron) and microbial diseases, they have significant impacts on multiple fragile ecosystems, including coral reefs (Hayes et al., 2001).

Future research is needed to delimit the possible drivers of the identified long-term temporal trends in MODIS-derived indices under both dust and non-dust conditions. Future studies could fruitfully explore this issue further by applying the dust detection indices over water near the Arabian Peninsula (e.g. the Red Sea). Future research on the spatial and temporal variations in the incidence of dust storms in Saudi Arabia might extend the analysis concerning the driving factors behind the observed trends across Saudi Arabia. Explaining the significant correlations between the occurrence of dust storms and precipitation events might be another important future research avenue. This might help to understand and predict the occurrence of dust storms and precipitation. Furthermore, there are many aspects of spatial and temporal dust events that could be considered for future work, such as the role of the land cover changes on the occurrence of dust events over Saudi Arabia. A study by Qiu et al. (2003) suggested that land-use types might play a role in the intensity of a dust storm over the Tarim Basin in northwest China. Land-cover changes are found to be responsible for 25% of airborne dust. In particular, anthropogenic activities such as urbanisation, construction of dams and unsustainable farming practices are important (Goudie and Middleton, 1992; Goudie, 2009; Mahowald et al., 2010).

This thesis highlighted the impact of dust events on daily emergency admissions for respiratory infections in children in Riyadh. Despite the limitations of data, this section provides a good starting point for discussion and further studies. For example, future research should investigate how dust presence contributes to the risk of respiratory conditions. These studies could investigate the association between different dust types and health issues such as asthma and allergy.

The health effects of dust storms are a serious problem which was pointed out by the Ministry of Health of Saudi Arabia. It reported that there is an increase in patients visiting the hospitals with respiratory illnesses, especially asthma symptoms, as a result (MOH, 2019). Therefore, future research is needed for to analyse the sampling of dust storms, which might make for more effective assessments of the size of the dust. For example, the fine $PM_{2.5}$ dust particles easily penetrate deep into the respiratory system, which causes major health problems (Zhang et al., 2013; Liu & Coulthard, 2017). A recent study used the samples of $PM_{2.5}$ and PM_{10} from seven sites over Jeddah and concluded that the particles were associated with dust storms concentrated with carcinogenic metals and polycyclic aromatic hydrocarbons (PAH). Exposure to $PM_{2.5}$ particles, therefore, might lead to cancer risks (Harrison et al., 2017). Future work could also consider more detailed investigations into the wider effects of dust storm events on society, such as dust's impact on socio-economic development and environmental quality in Saudi Arabia.

Appendix

1. Abbreviations

Abbreviation	Meaning
MODIS	Moderate Resolution Imaging Spectroradiometer
NDDI	Normalized Difference Dust Index
BTD	Brightness Temperature Difference
MEDI	The Middle East Dust Index
RSB	The Reflective Solar Band-derived index
TOA	Top of Atmosphere
MISR	Multi-angle Imaging SpectroRadiometer
METAR	METARMETeorological Aerodrome Report
SYNOP	Surface synoptic observations
PME	Presidency of Meteorology and Environment
WMO	World Meteorological Organization
SDEs	Sand and dust storm events
URTI	Upper respiratory tract infection
LRTI	Lower respiratory tract infection
COPD	Chronic Obstructive Pulmonary Disease
PM	Particulate matter

Reference

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