SPATIO-TEMPORAL VARIABILITY OF AEROSOL OPTICAL DEPTH IN THE UAE USING MODIS DATA

by

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DEDICATION

This is dedicated to my family, friends, and everyone in my life who encourage me through love and patience.

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I would like to thank my committee chair, Dr. John Qu, for his passion, support, encourage, and helpful feedback. My committee member, Dr. Dogluang Sun, and Dr. Ron Resmini, for their support. My Dr. Abdelgahder Abulghsim for his continuous support and assist.

Special thanks to my family for their trust and love, to my friends who always keep in touch with me even abroad.

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LIST OF ABBREVIATIONS AND SYMBOLS

Aerosol Columnar Size Distributions .... CSDs
Aerosol Optical Depth .... AOD
Arabian Peninsula .... AP
Inverse Distance Weighting .... IDW
Micrometer .... μm
Moderate Resolution Imaging Spectroradiometer .... MODIS
National Center of Meteorological and Seismology .... NCMS
National Oceanic and Atmospheric Administration .... NOAA
Particulate Matter .... PM
Relative Humidity .... RH
United Arab Emirates .... UAE

ABSTRACT

SPATIO-TEMPORAL VARIABILITY OF AEROSOL OPTICAL DEPTH IN THE UAE USING MODIS DATA

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Natural and anthropogenic aerosols over the Arabian Peninsula play a major role in regional and global climate change, influencing radiation budget, and affecting regional hydrological cycle. The interactions between atmospheric aerosols and solar radiation via the scattering and absorption processes significantly affect the Earth's radiative budget and introduce great uncertainties in global climate models ((Ackerman, et al., 2000); (Haywood, Roberts, Slingo, & Edwards, 1997). Moreover, high concentrations of aerosols at local scale due to natural or anthropogenic activities have adverse effects on human health including cancers, pulmonary inflammation and cardiopulmonary mortality (Atkinson, et al., 2001); (Pope, et al., 2002). Monitoring the high temporal and spatial variability of aerosol concentrations require regular measurements of their optical properties such as aerosol optical depth (AOD). AOD is defined as the extinction coefficient of solar light in the atmosphere due to aerosols.This research uses the Moderate

Resolution Imaging Spectro-radiometer (MODIS) AOD product at 1km resolution, for investigating the factors affecting its spatiotemporal variability of over the UAE. This study attempts to investigate the primary reasons that governs AOD variability over the UAE from a meteorological variables perspective. The significant findings are AOD strength over the coastal areas, and southwest direction from the UAE, natural dust storms with the meteorological variables increase the level of AOD (positive linear correlation in both temperature and wind speed). Finally, the summer and spring seasons contribute to the most extent of AOD over the region.

CHAPTER 1 INTRODUCTION

Aerosol optical depth is the degree to which aerosols prevent the transmission of light" in the atmosphere. It is a dimensionless quantity with extremely lower values referring to clear skies with maximum visibility and higher values indicating the presence of significant amounts of aerosols in the atmosphere that can significantly affect visibility. The presence of aerosols in the atmosphere have a huge impact on the earth radiation budget, climate and local weather. Depending upon their size, type, and location, aerosols can either cool the surface, or warm it. They can help clouds to form, or they can inhibit cloud formation.

Studying the formation, and spatio-temporal distribution of aerosols in the atmosphere is a fundamental part of atmospheric science. There are many applications where aerosol optical depth (AOD) data is important, such as air quality, health and environment, atmospheric correction of satellite data, earth radiation budget and climate change. Air quality monitoring is among the important applications of AOD data. Analysis of AOD data can help provide quantitative measures of particulate matter PM_{10} and $PM_{2.5}$ for assessing health risk factors. This particularly important in the UAE as air pollution is among the rising health hazards in the UAE in the past decade. It has been observed in the UAE that short-term exposures to common air contaminants such as fine particulate matter are linked with increased hospital admissions due to cardio-respiratory conditions, increased emergency room visits and work/school absenteeism, increased respiratory symptoms and decreased lung function. The sources of air pollutants can be both natural and anthropogenic in the UAE, furthermore, transboundary transport pollutants add an additional source.

Air pollution has been always achieved with networks of ground monitoring stations and the use of models that evaluate emissions and predict changes in air quality (Holben, et al., 2001). The ground monitors have obvious advantages. The measurement techniques can be standardized and applied across all locations. They can measure pollution 24 hr/day and provide hourly, daily, monthly, or any type of time average. They can measure pollution regardless of clouds because these are filter-based measurements that are usually fixed at the surface. However, they also have certain disadvantages. The obvious one is that they are point measurements and are not representative of pollution over large spatial areas and therefore cannot capture the gradients in pollution. These ground monitors often miss pollution that is not within the sampling area of the measurement and are unable of capturing pollution for a large area. Moreover, these ground monitors are expensive and require regular maintenance. Also, the lack of a large scale picture makes it difficult to assess where the pollution is coming from and where it is heading.

Satellite remote sensing is the only viable method for monitoring air pollution over a large spatial extent on continuous basis. Advancement in satellite remote-sensing techniques has opened new corridors for the monitoring and mapping of air pollution over large regions. Currently, there are several satellites in orbit that have instruments suited for air quality measurements. Polar orbiting satellites make reliable and repeated measurements over the globe with high spatial resolution when compared with surface instruments, which are limited because they are point observations. The processing of satellite-calibrated spectral radiance data provides estimates of the columnar contents of various atmospheric constituents on regular and continuous basis. However, in order to derive satellite-based concentrations of pollutants ($PM_{2.5}$) at ground level, it is necessary to integrate satellite data with ground-based measurements (e.g., meteorology, height information from space/ground-based lidars) and/or modelling simulations) ((Grguric, et al., 2014)

Moderate Resolution Imaging Spectroradiometer (MODIS) sensors provide systemic retrieve of aerosol properties over land and ocean with daily basis (Kaufman, et al., 1997). For instance, MODIS data that come from the Terra satellite offer daily data from the late-morning view of aerosol and cloud distributions over the world (Alsaadi, et al., 2005). In Figure1, will see five different daily aerosols predict products created by near real-time since MODIS try to provide quick information related to spatial resolution, daily coverage and detect aerosol in the troposphere with high accuracy (Alsaadi, et al., 2005). The Effective coordination among different agencies and organizations captured both space and surface observations of aerosol and delivered compact visualizations to assist forecasters MODIS near-real-time AOD and COT data were obtained from the NOAA/National Environmental Satellite, Data and Information Services (NESDIS) "bent pipe" link at SSEC/CIMSS (Alsaadi, et al., 2005).

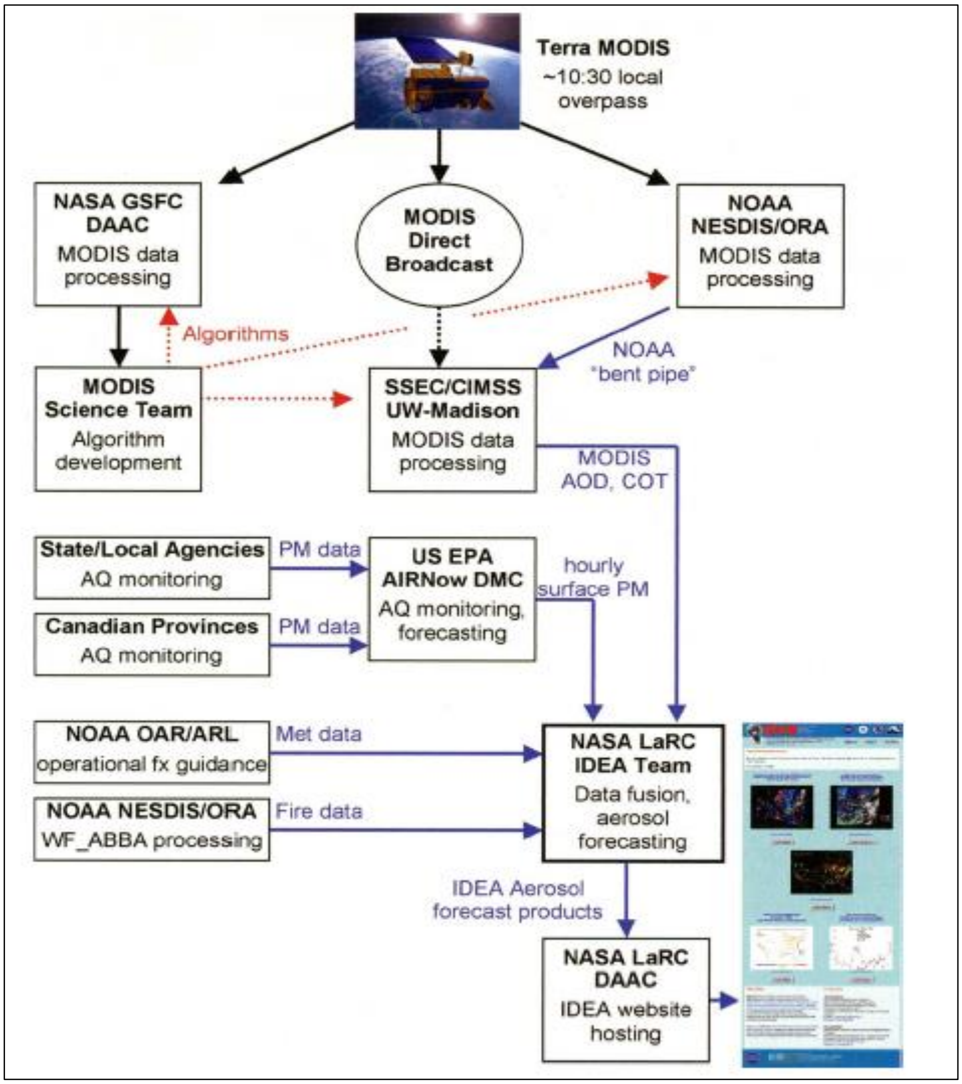

Figure 1 Data sources and flow for development of forecast products.

Satellite derived products of AOD show that the occurrence and intensity of AOD varies substantially at seasonal, annual and decadal timescales over the UAE. The primary factors that governs such variability are not quite understood. Some studies in other parts of the world suggest that such variability is mostly influenced by meteorological and weather variables while other studies such the variability is mostly influenced by changes in the local land cover and/or land use. The primary objective of this study is to investigate the role of meteorological variables of factors in influencing the spatiotemporal variability of AOD over the UAE. The key research questions that this research will attempt to address focuses on:

1. What is the role of meteorological variables in influencing the spatiotemporal variability of AOD over the UAE?
2. What are the primary sources of AOD whether natural or anthropogenic?
3. Identify seasonal periods of high and low levels of AOD and why?
4. Identify locations within UAE characterized by high/low AOD levels and why?

Major Hypothesis

Spatiotemporal variability of AOD is mostly influenced by meteorological variables.

CHAPTER 2 LITERTURE REVIEW

In atmospheric science, the term aerosols can be defined as collection or mixture of solid and suspension liquid in the air, and that could be both the particles and the suspending gas (Boucher, 2015). Aerosols generate naturally in the environment such as sea spray, volcanoes eruptions and dust from aired and semi-aired lands. Whereas, most aerosols emitting from industrial and commercial areas caused by a human (Dayou, Chang, & Sentian, 2014). Aerosols concentration always find in the atmosphere, but the amounts are changeable from place to others. Strength depends on the sources and Spatial-temporal in the atmosphere (hours/weeks) of the aerosols (Boucher, 2015). The Aerosol Optical Depth (AOD) measurement can shortly explain as the parameter of aerosol thickness in large-scale that represent the greatness of depletion of aerosol effects on human health and climate (Dayou, Chang, & Sentian, 2014).

In addition to that, Dayou et al. (2014), point the vital role of AODs in the aerosol columnar size distributions (CSDs) that offers an estimation of the aerosols type. AOD detecting has enormous uses, especially in environmental researches that utilize the retrieval with satellite data to obtain the measurement (Dayou, Chang, & Sentian, 2014). Moreover, the AOD significant in studying interaction aerosols with clouds and satellite aerosol data (Khoshsima, Ahmadi-Givi, Bidokhti, & Sabetghadam, 2013). Despite the aerosols are very tiny in size, and it is not accessible to visible to the human eyes due to microscope size, but it has a massive effect on the atmosphere (Boucher, 2015). For example, the haze which reduces the visibility occurs when the concentration of aerosols reach an enormous amount in the air, and this case aerosols interact with the solar radiations (Boucher, 2015).

According to Alföldy et al. (2007), Aerosol optical depth (AOD) symbolizes the total of scattering and absorption influence of particles which comes directly from sunlight or scattering. Monitoring particulate matter (PM) and other organic combination are critical. Remote sensing from space obtains very high spatial coverage that helps to study the atmosphere pollution from the optical properties of aerosols (Alföldy, Osán , Tóth, Török, & Harbusch , 2007). Moreover, the concentration of aerosol particles in the atmosphere mostly generated from the surface (Alföldy, Osán , Tóth, Török, & Harbusch , 2007). On the other hand, aerosol effects could be direct and indirect regarding radiative forcing from the climate system (Boucher, 2015). Changing in energy flux of solar radiation in the atmosphere, and change in the atmospheric composition and earth surface because the aerosols are high reflecting the radiation to cause cooling in the surface (Boucher, 2015). Similarly, Forster et al. (2007), argued that aerosols influence the atmosphere mainly in cooling the surrounding air; hence, the radiation properties of clouds will change indirectly. Therefore, aerosols reflection of the visible light back makes the atmosphere shiny from space (Dayou, Chang, & Sentian, 2014).

A valuable way in measuring aerosols optical depth (AOD) is the columnar aerosol burden that can evaluate by spectroscopic measurement of the AOD. The measurement can immediately by sun photometer from the ground or indirectly by satellite sensors which receive the reflected radiations from Earth's surface ((Alföldy, Osán , Tóth, Török, & Harbusch , 2007). According to Dyou et al. (2014), there are two ground-based AOD retrieval methods LIDAR and sunphotometry. Sunphotometry is a passive optical system to measure the extinction from direct beam radiation in individual wavelength. While LIDAR defines as an active optical system where transmit lights and then collect the backscatter of the light beams from retrieving the aerosol reduction in the total columnar atmosphere (Dayou, Chang, & Sentian, 2014). In-ground sunphotometry the down-welling of solar radiation is used to retrieve the total columnar of aerosols optical depth (AOD) in the known area (Dayou, Chang, & Sentian, 2014). Moreover, Dayou et al. (2014), mentioned in their paper that with the cloudless event, the extinction value of solar transmission resembles to top aerosol loading. In Figure 2 will have a glance at how the AOD increasing from 0 to 1 with stable air mass.

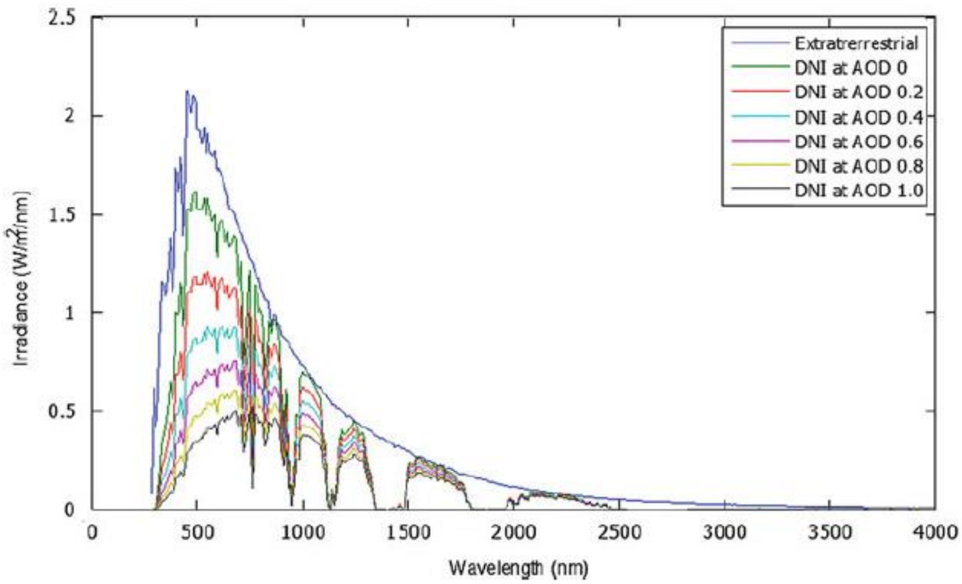

Figure 2 AOD increasing from 0 to 1 with stable air mass (Dayou et.al, 2014)

From above Figure2, the solar spectrum in direct normal irradiance (DNI) gradually decline while the aerosol optical depth (AOD) increase, that reason from both scattering and absorbing in atmospheric aerosol in each wavelength (Dayou, Chang, & Sentian, 2014). Majority of aerosol measurements used visible range wavelengths for spectral AOD retrieval since the mid-visible range in the spectrum (visible range 400-700nm) has much higher diminution (Dayou, Chang, & Sentian, 2014). However, there is no spatial distribution information provider of the AOD when using direct measurement. The indirect approach deal with satellite images delivers AOD only correlated to the reference image, that offers information about AOD spatial distributions ((Alföldy, Osán , Tóth, Török, & Harbusch , 2007).

On the other hand, Khoshsima et al. (2014), in their paper, discussed that climate conditions and aerosols composition have a significant role in the mean diurnal variation. Moreover, influences the aerosol optical depth (AOD) variability to be less during spring and winter and more in fall and summer. In addition to that, AOD raise at afternoon when events of high wind speed, air temperature and lower relative humidity (RH) happen, but decline before this time (morning to noon) in diurnal scale ((Khoshsima, Ahmadi-Givi, Bidokhti, & Sabetghadam, 2013). whereas, the AOD increasing a lengthy day time even reach the peak at afternoon in the most urban area ((Smirnov, Holben, Eck, Slutsker, & Dubovik, 2003).

Furthermore, Khoshsima et al. (2014), argued in their study that vertical mixing of the aerosol is less intense in winter than summer. This result helps us to realize that difference of correlation associated with the degree of local mixing and effect the vertical distributions of aerosols. In the atmosphere, NO2 is highly variable atmospheric constituent which has a significant function in complex ozone cycle, presenting naturally in the stratosphere and high concentration in the troposphere due to pollution ((Khoshsima, Ahmadi-Givi, Bidokhti, & Sabetghadam, 2013). Regarding Khoshsima et al. (2014), all gassy toxins associate with local sources such as the industrial pollutions, exhaust emissions, and internal heat. Therefore, the dust particles covered by different types of chimerical in the atmosphere (nitrate, black, and organic carbon, sulfate) that might be a reason of the difference in correlation of aerosol optical indices in both summer and winter (Khoshsima, Ahmadi-Givi, Bidokhti, & Sabetghadam, 2013).

Meteorological parameter and conditions are critical to study aerosol optical depth (AOD) in any part of the world. To understand the correlation between the AOD and particles matter (PM) observe, the influence of meteorological satiations are necessary (Khoshsima, Ahmadi-Givi, Bidokhti, & Sabetghadam, 2013). Maghrabi et al. (2011), in their study, used multiple meteorological parameters in dust storm situation such as temperature, atmospheric pressure, relative humidity, and wind speed and direction. Dust storm influences the meteorological parameters by following; wind speed increase, air pressure decline to the minimum value, and the temperature continue decreasing over the time (Maghrabi, Alharbi, & Tapper, 2011). However, the relationship between the aerosol optical depth (AOD) and the particles matter (PM) rely on the meteorological variability, locations (spatial distributions) and seasons (time) ((Khoshsima, Ahmadi-Givi, Bidokhti, & Sabetghadam, 2013). Moreover, the dissimilarities in meteorological conditions from region to another and aerosols chemical compositions request to determine the correlation regionally (Khoshsima, Ahmadi-Givi, Bidokhti, & Sabetghadam, 2013).

CHAPTER 3 STUDY AREA

Section 3.1 Location

United Arab Emirates (UAE) is a federation of seven emirates in the Middle East Region located in the Asia continent and part of the Arabian Peninsula. UAE is lying between 22° 30' and 26° 10' north latitude and between 51° and 56° 25' east longitude which Equivalent approximately 54.366 in longitude and 24.466 in latitude (Where Is The United Arab Emirates?, 2019). The capital of the United Arab Emirates is Abu Dhabi. The land area of the United Arab Emirates contributed around 83,600 km^2 (32,278 mi^2) (Geography, 2019). It shares a common border with Saudi Arabia on the west, south, and southeast and with Oman on the southeast and northeast. It also shares a border with Qatar in the northwest. In figure 3 illustrates the United Arab Emirates (UAE) location in the yellow box from the Global satellite image.

Figure 3 United Arab Emirate location from satellite image (Google Earth, 2019)

Most land of the United Arab Emirates (UAE) is desert and cover with yellow sand dunes since the Arabian Peninsula is known with desert and contains one of the most significant desert areas, which called Rub' al Khali (Arabian Desert) (Crystal & Peterson, 2019). The United Arab Emirates has part of the Rub' al Khali in the Capital Abu Dhabi, east of Liwa Oasis, near from Saudi Arabia border. The United Arab Emirates surround by water bodies such as the Arabian Sea and the Persian Gulf (Geography, 2019). The coastline is around 1318 Kilometers which includes economic zone, continental shelf, and the continental margin (Geography, 2019). Figure 4 below shows the United Arab Emirates borders with Saudi Arabia, Oman, and Qatar. There is a type of topography in the northern portion of the United Arab Emirates called the Hajar Mountains that have a border with

Oman (Crystal & Peterson, 2019). The elevation of these mountains reaches about 2000 meters (6500feet) at the highest point (Crystal & Peterson, 2019).

Figure 4 UAE Image with Saudi Arabia and Oman borders, (WorldAtlas, 2019)

Section 3.2 Climate

The United Arab Emirates located in the desert region that classified under the arid and semi-arid areas. Desert covered around 80% of the United Arab Emirates, which cause several dust storms per year (Omari, Abuelgasim, & Alhebsi, 2019). This exposing of dust in the desert support particulate matter (PM), aerosols and air pollutants to move through the country. Thus, there is Hugh influence of storms in air quality and airborne particles, which contribute to overall aerosol optical depth (AOD) over the United Arab Emirates (Omari, Abuelgasim, & Alhebsi, 2019). The climate in the United Arab Emirates is hot and humid in the coastal areas, while warm and dry in the interior areas (Crystal & Peterson, 2019). The precipitation average is about 4 to 6 inches per year. The distinct seasons that easy to notice in the United Arab Emirates are summer and winter.

The temperature generally in minimum during winter months from December to February with the temperature around 64 F (18C), while in summer from June to August the temperature raise to peak to be about 115 F (46 C) or even more in the desert area far away from the water body (Crystal & Peterson, 2019). Worth mentioning that even in winter days, the rainfall is rarely or could not happen (Geography, 2019). The predominate of arid climate in both mountain and coastal lead to variety of environments such as desert and Gulf islands, then variances of relative humidity (RH) which lead to difference of aerosol optical properties (Omari, Abuelgasim, & Alhebsi, 2019).

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CHAPTER 4 DATA SOURCES AND MEHTODS

Section 4.1 MODIS Data

Moderate Resolution Imaging Spectroradiometer (MODIS) is one of a reputable data source to study the Global and environmental aspects. It contains two significant instruments aboard the Aqua, which known as EOS PM-1 Satellite and Terra as EOS AM-1 Satellite. In the Terra Satellite, the orbit around the Earth starts in the morning from north to south and across the equator. While Aqua satellite orbits from the opposite direction (south to north) in the afternoon time (MODIS, 2019). The entire Earth is viewing with both MODIS Aqua and Terra within one day or two days, obtaining data in 36 spectral bands, or it is in groups of wavelengths (MODIS, 2019). These data play a vital role in improving our understanding of the Earth dynamics and process since it is focused on the lower atmosphere, lands, and oceans (MODIS, 2019).

Since MODIS data consider as a significant data source to study the Earth Atmosphere and other phenomena related to the Atmosphere, I chose to use MODIS atmospheric products to study aerosols optical depth (AOD). The data used in this research is combined with MODIS Aqua and Terra of land aerosol optical depth (AOD) daily (MCD19A2) from 2003 to 2015 in the United Arab Emirates (UAE). The shortcut (MCD19A2) related to "the Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm-based Level-2 gridded (L2G) aerosol optical thickness over land surfaces product." (MCD19A2, 2019). The resolution of the data is 1 km pixel, which helps to generate enormous atmospheric and geometric properties. In this data package, several science datasets divided into two main groups Grid500m and Grid5km (MCD19A2, 2019). Both of the two groups have parameters such as AOD Model, AOD Uncertainty, and other Cosine of View Zenith Angle (MCD19A2, 2019). In this research, Aerosol Optical Depth (AOD) at 055-micron layer is used to produce the average map for each year in the United Arab Emirates.

Section 4.2 National Center of Meteorology and Seismological

It is an Institution in the United Arab Emirates (UAE) established in 2007. The National Center of Meteorology aims to provide the sources of meteorological information within the United Arab Emirates. This information comes from monitor the changes in the atmosphere and the Earth's crust to end with meteorological services. The Center has the vision to achieve excellence and contribute to the development of science through the promotion of the sustainable development of the UAE (National Center of Meteorology, 2019). Moreover, there are services the center offers it such as Weather prediction, forecasting for temperature, relative humidity, surface winds, clouds jet stream details, climate reports, and others (National Center of Meteorology, 2019).

In this research of the UAE, three parameters used to see the relationship between the meteorological variables and aerosol optical depth (AOD). These parameters are mean of temperature, winds speed, and pressures over the UAE. The data provided by the National Center of Meteorology from 2003 to 2015. Table 1 below show sample of the data which used in the research.

Table 1 Meteorological parameters temperature, wind speed and pressure in 2003

Year	Month	Air Pressure [hPa]	Temp.Dry[°C]	Wind.Speed.[Km/h]
		Mean	Mean	Mean
2003	1	1018	18.9	6
2003	2	1014	21.7	8
2003	3	1013	24.8	9
2003	4	1010	28.4	9
2003	5	1006	32.4	8
2003	6	998	35.1	8
2003	7	996	36.1	11
2003	8	999	36.0	10
2003	9	1004	33.6	8
2003	10	1011	29.5	7
2003	11	1015	25.2	8
2003	12	1018	21.0	6

Section 4.3 Geography Information System (GIS)

GIS is a framework used for managing, analyzing, and gathering data. It is the science of geography, which assists in integrating enormous types of data (What is GIS?, 2019). Furthermore, analyzing the spatial data and organize layers information by using 3D senses and maps (What is GIS?, 2019). Then, it counts as significant for decision making. ArcGIS is software where applies the GIS for analyzing and integrating the data. In this research, ArcMap was used to mosaic the Aerosol optical depth (AOD) data to generate one image for each day of the year. This process comes because the datasets used in the research from MODIS are daily. Thus, a model builder in ArcMap aids to merge, clip, and mosaic the data. In addition to producing maps that show the AOD for each year in the UAE. Figure 5 shows the model designed to run the MODIS data.

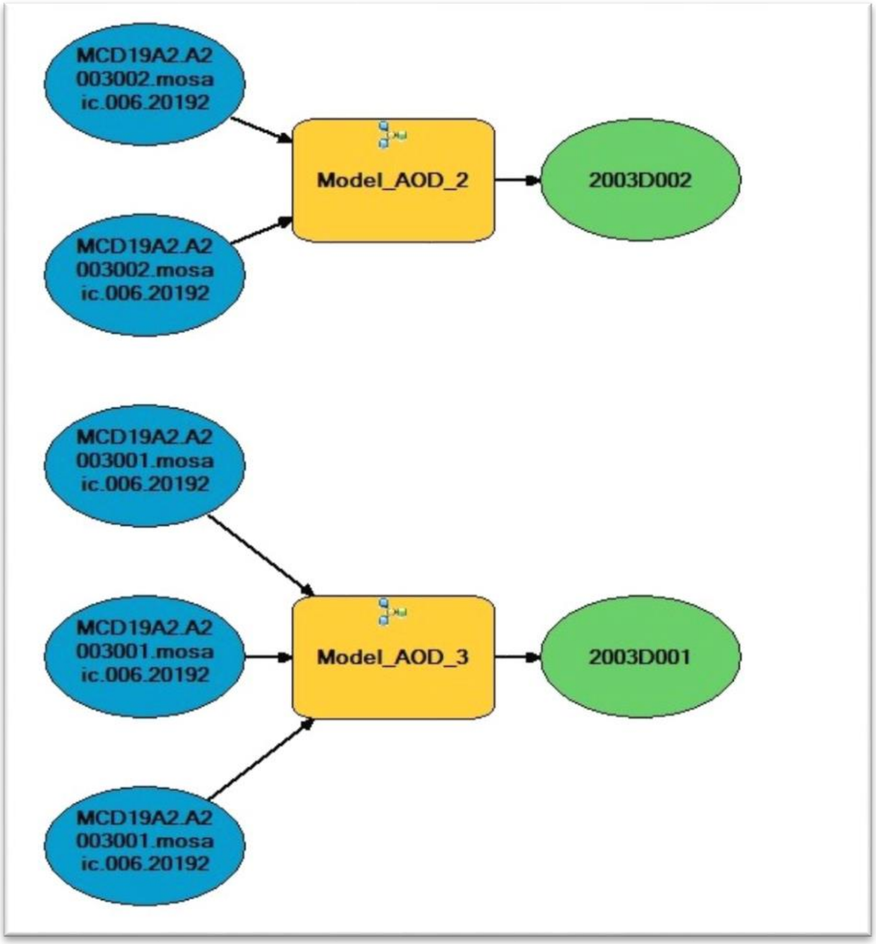

Figure 5 Model Builder designed to run the AOD data to the final map

Section 4.4 Interpolation Method

It is a process that use multi points with values to predict values of other location or points that unknown. Interpolation use in any unknown geographic value such as elevation and precipitation. There are many types of interpolation, but most are using inverse Distance Weighting (IDW) and kriging (Types of Interpolation Methods, 2019). In

IDW interpolation, the primary method is to measure the distance from the point to estimate the unknown location (Types of Interpolation Methods, 2019).

Kriging method utilized in the research to assess the unknown values across the UAE areas to predict how the meteorological parameters are looks by year. Kriging define as a geostatistical interpolation technique, estimating unknown spatial values from the points with values by using both degrees of variation and distance (Types of Interpolation Methods, 2019). Kriging formula written as:

$$Z(s_0) = \sum_{i=1}^{N} \lambda i \, Z(s_i) \qquad (1)$$

In above equation $Z(s_i)$ is the measured value, λ_i denote to an unknown weight for the measured value at the location s_0 the prediction of the new site and N is the number of known values (Types of Interpolation Methods, 2019). In the study, there are six points selected with known points values that provide form the National Center of Meteorology in the UAE. Table 2 displays these points with the coordinates (longitude and latitude) and the name of each station.

Table 2 Stations that used in interpolations from 2003 to 2015 in the UAE

	Station Name	Latitude	Longitude
1	Al Ain Airport	24.21583	55.79361
2	RAK Airport	24.77167	55.93917
3	Al Gheweifat	24.12111	51.62694
4	Madinat Zayed	23.83167	53.69861
5	Um Azimul	22.71417	55.13861
6	Al Jazeera B.G	23.29111	52.28889

Additionally, Figure 6 views a map produced by ArcMap with the location of each station in the UAE Land. In this map, it is easy to see the points and spatial distribution of the stations.

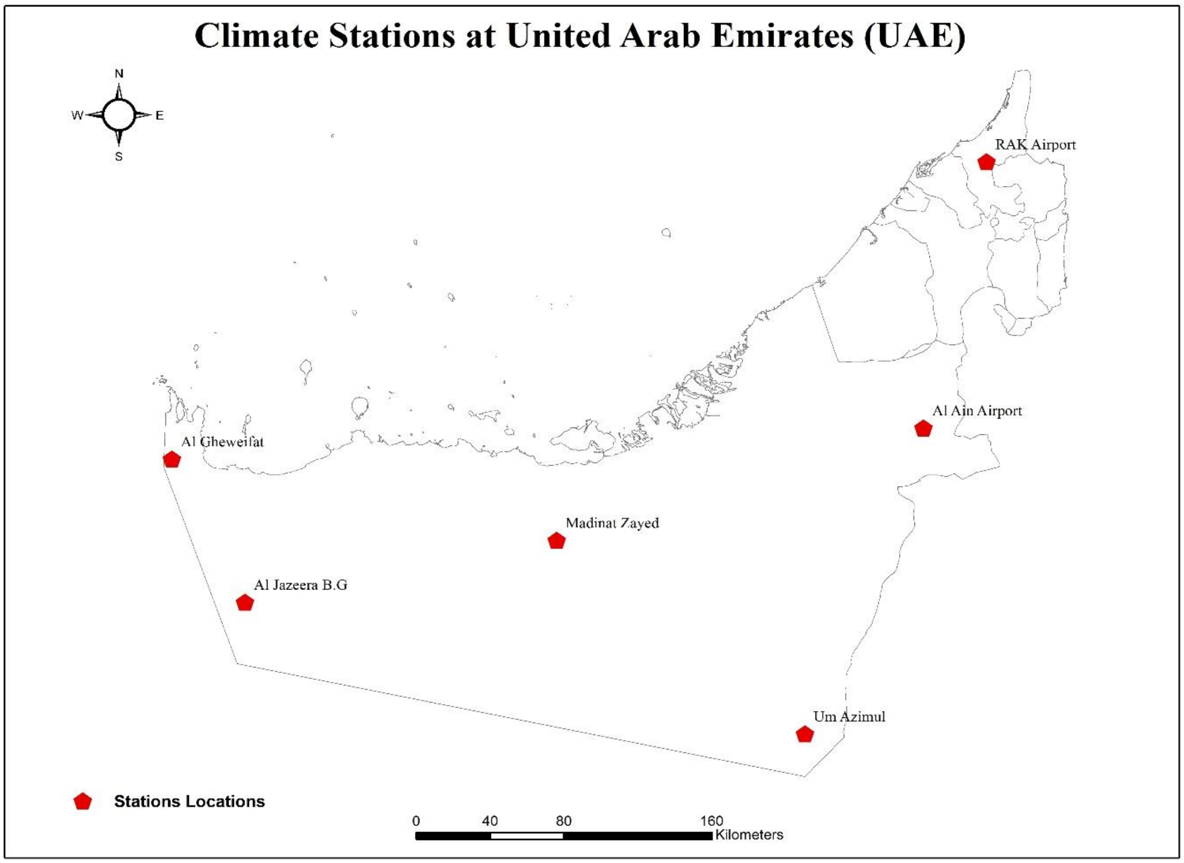

Figure 6 Spatial distribution of metrological stations in the UAE

CHAPTER 5 RESULTS AND FINDINGS

This section from the research will view the findings generated from Aerosol optical depth (AOD) from MODIS Data and Meteorological parameters.

Section 5.1 AOD Maps and Trend

Figures 7 and 8 below the United Arab Emirates map for average aerosol optical depth (AOD). The maps show each year individually with the color ramp that views the areas of high concentration of the AOD across the UAE. From maps easy to notice that a high strength of the AOD is along the coastal line of the UAE where the most urban areas. While the low values of the AOD are speared in the center area of the land and in mountains areas where the dust are less and most topography are create with rocks at north and northeast direction of the UAE.

In contrast, Yang et al. (2019), in their paper, argued that the concentration of the AOD has low values near the coastal area in the China area. Still, they found out the strength AOD is in the urban areas and quiet intensity in the mountain areas as our results. Since the most metropolitan areas in the UAE located near the coastline, then the reason beyond the quit high values of the AOD appear around the coastline from the UAE reasonable where human activities and climate factor play a role in this side.

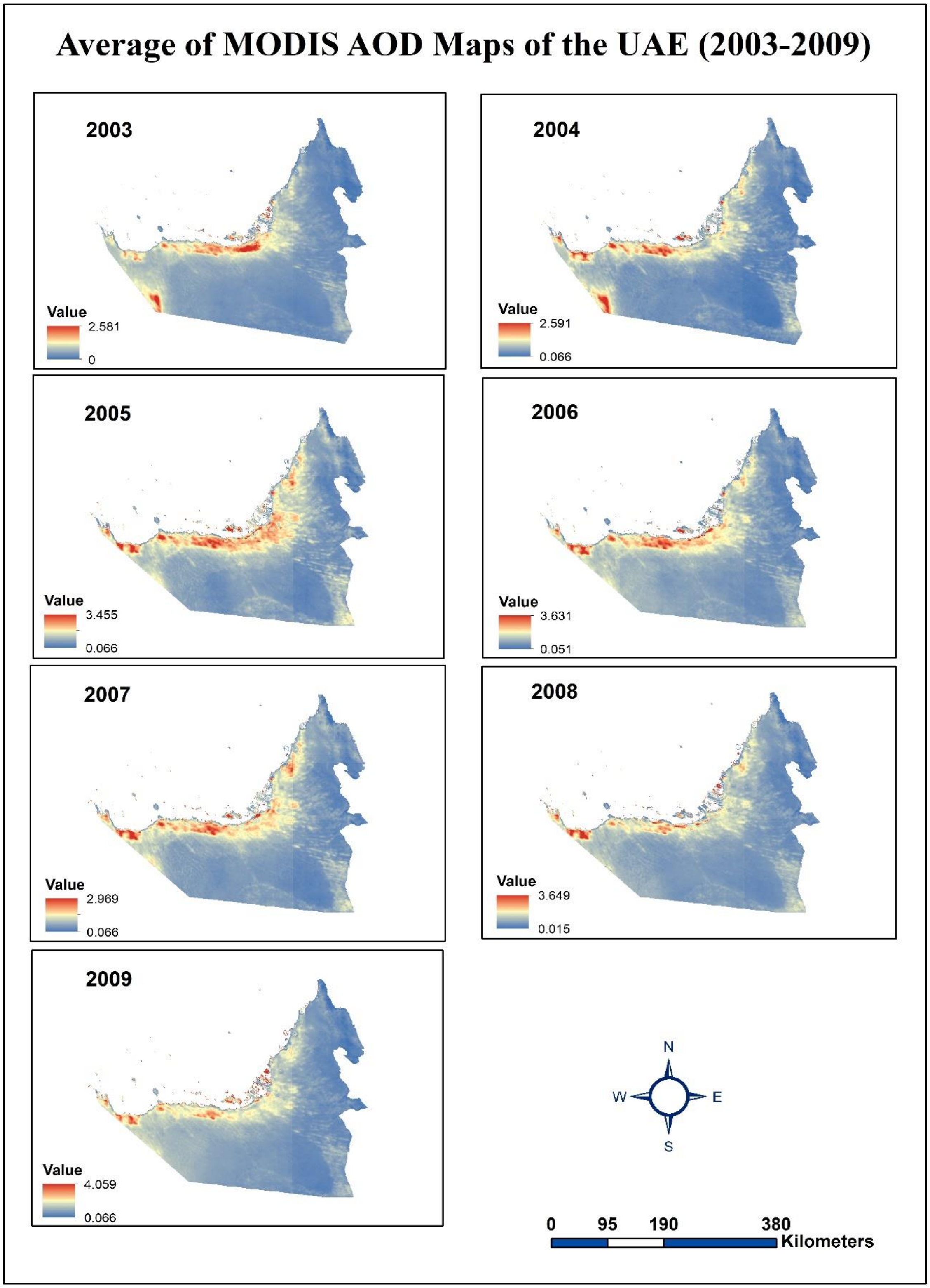

Figure 7 Average AOD maps of the UAE from 2003 to 2009

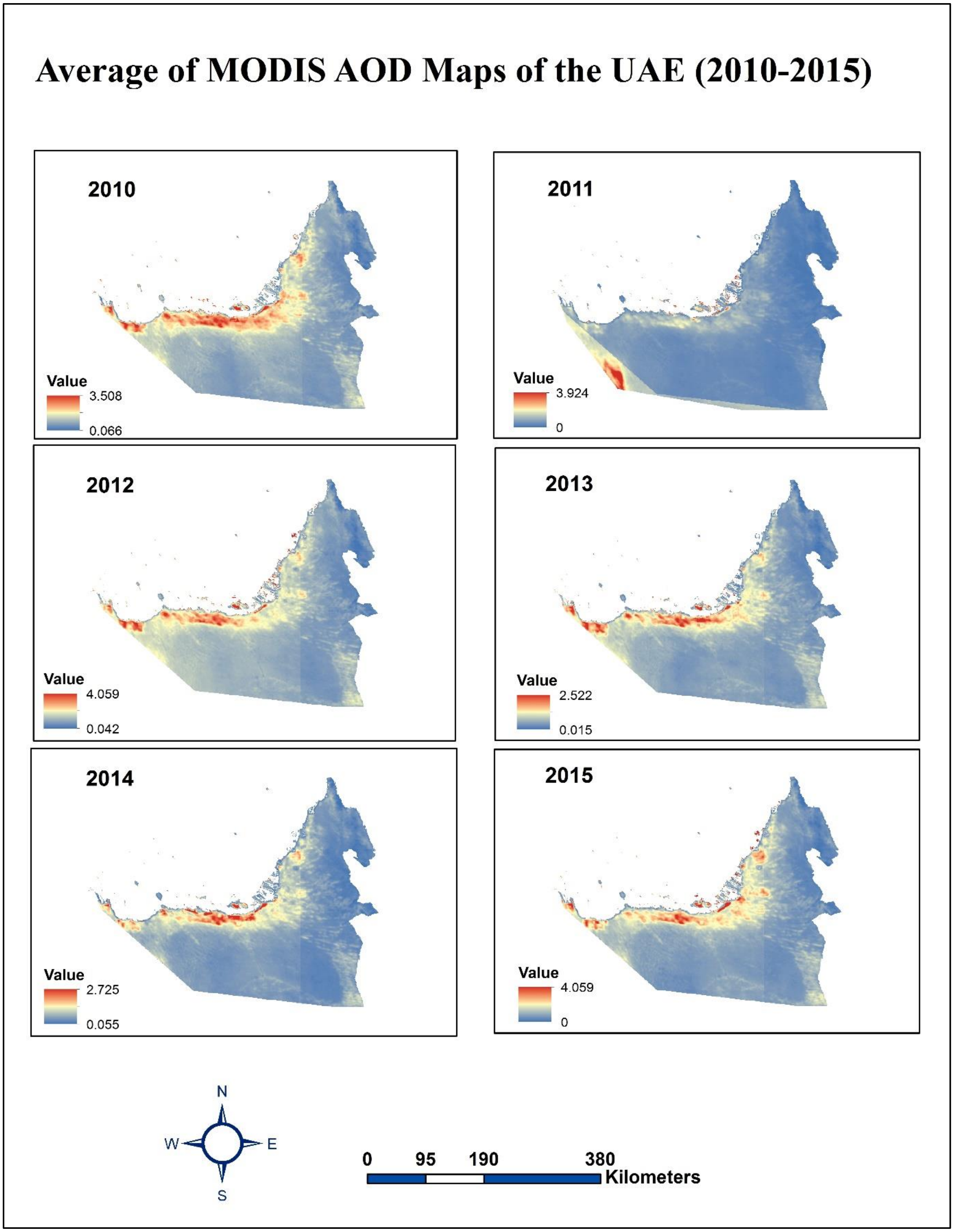

Figure 8 Average AOD maps of the UAE from 2010 to 2015

As the Maps of average MODIS AOD from 2003 to 2015 show the concentration of the AOD across the UAE. The high amount of AOD focus on the coastal area along the gulf. The second strength values of AOD noticed in the southwest direction of the UAE near to the border of the Kingdom of Saudi Arabia mainly in 2011 map to become unique than other years whereas, the lowest values of AOD were in the desert areas of the country where most deserts are located. The reason for this AOD distribution in the UAE is related to several things. Firstly, the coastal line, especially in the summer influence by the high-temperature degree, which could reach 50; this temperature leads to evaporate the gulf water hugely to increase the relative humidity. Thus, water vapor with the humidity causes the main intention to hold more dust and particles in the air then increase AOD value in those areas. Hamza et al. (2011), in their paper, mentioned that enormous dust storms took place in the coastal areas of the gulf as a result of strong monsoon winds during spring and summer seasons (March-August). According to the report of the National Center of Meteorological and Seismology (NCMS) in the UAE, on March 2, 2010, the dust moved from the central areas in the UAE toward the Arabian Gulf. This observation evidence of the strength values of AOD along the coastal line too.

Furthermore, in the southwest area, the possible cause of AOD intensity is petroleum fields there, which increase the hydrocarbon industry emissions for these fields and contribute to raising the amount of the particles in the air. Moreover, the winds have a role in AOD value since the UAE affected by the extension of surface thermal low pressure over the Rub Al Khali desert. The temperature increase and cause southern and southwestern wind, which lift the dust, and the sand on it is peak (National Center of Meteorological and Seismology, 2011).

On the other hand, the low value of AOD dominated in the open desert areas in the center of the UAE. The dry weather inside the desert far away from the water bodies when compare it with the coastal areas. During the summer season, the dry reaches the peak in the desert with increasing the temperature and winds speed aid to move the dust fast. As well the air pressure increase with the high temperature in the desert area. The NCMS report (2011), stated that a dust storm in the center of the UAE moves toward the coast due to the wind speed.

Figure 9 below will show the average of MODIS AOD trend over the UAE form 2003 to 2018. The time series of AOD fluctuated over the year, and the highest value of the AOD was in 2018 with 0.47µm, followed by 2012 and 2011 with 0.43 µm while the minimum AOD values were in 2004 presented with 0.31µm. The tendency of the AOD in the UAE affected by several natural and anthropological reasons that depend on weather conditions during the whole year in the selected duration.

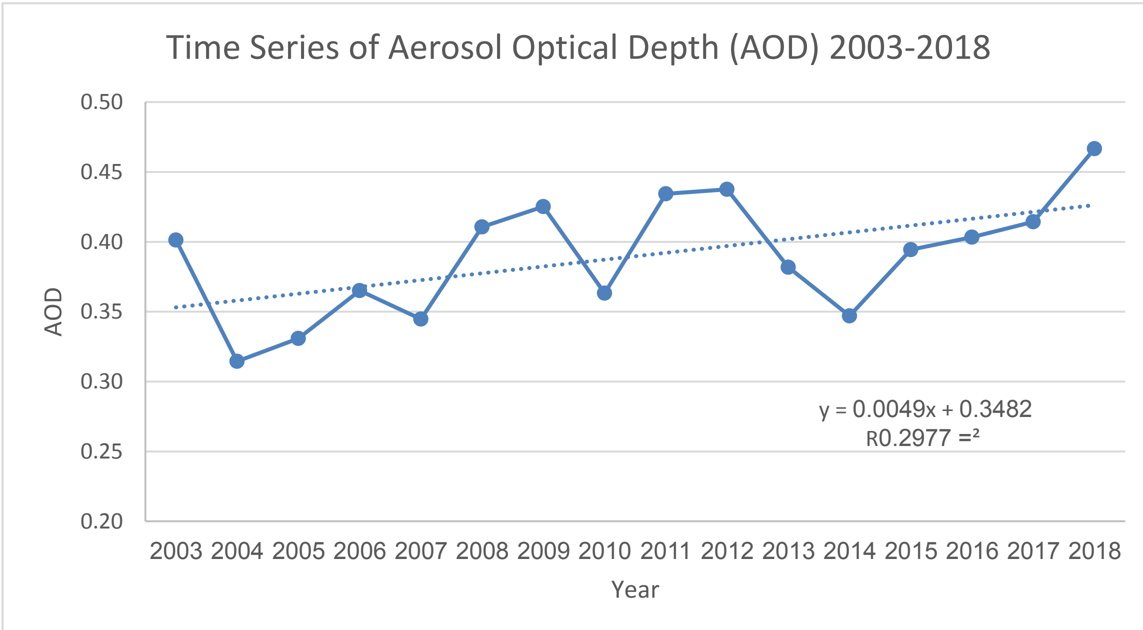

Figure 9 AOD time series trend from 2003 to 2018

The linear trend of the AOD valued in duration shows the increase over the years with R^2 = 0.297 as the time series shows the trend increase by the years until 2018. The significant values of AOD observed in 2003, 2008, 2009, 2011, and 2012 which means these years have the active year of the dust storms in the area. Major dust storm episodes took place in 2003 in the UAE, which came from Iran and Afghanistan (National Center of Meteorological and Seismology, 2011). Figure 10 shows the dust direction toward the UAE.

In 2008 and 2009, there were extremely active dust storm in the Middle East region that lead to an increase in the strength of the AOD. Maghrabi et al. (2011) discussed dust storms in the Arabian Peninsula that occurred during 2009, and in their results, the AOD values had the strength in the storm days. Figure 11 illustrates the dust storm over the coast in the UAE in 2009. In addition to that, 2011 was active with many dust storms that hit the region and especially in the UAE. Kazim et al. (2011), they reported that several sandstorms blow the UAE, fell the trees, and brought extreme winds with speed around 100km/h in some parts of the UAE. Basha et al. (2019), in their study, argued that 2012 has massive dust storms, and Abu Dhabi city had major dust episodes during that time of the year.

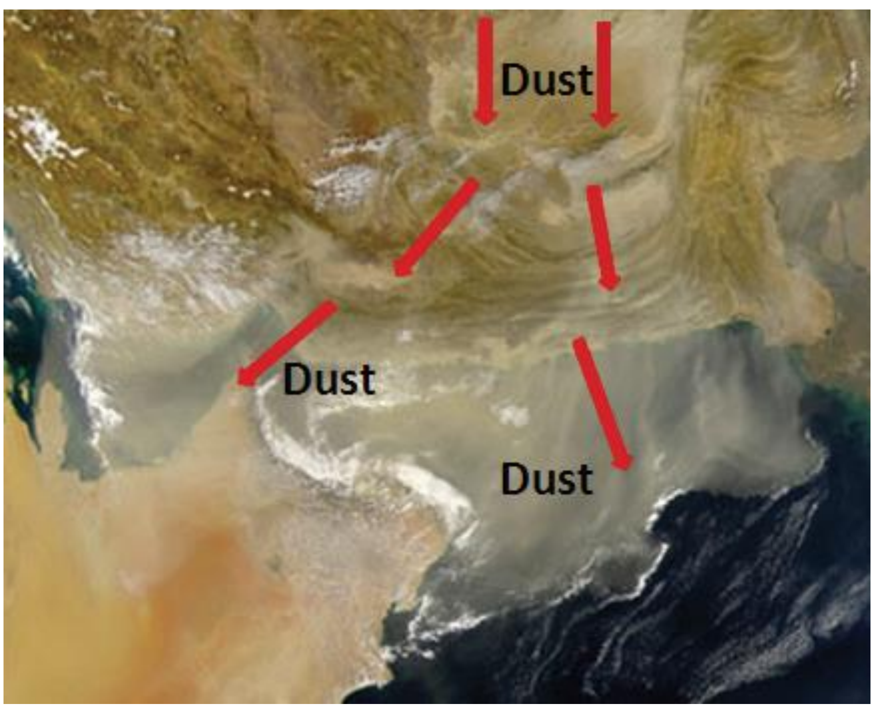

Figure 10 Dust storm came from Iran to the UAE in 2003 (NCMS, 2011)

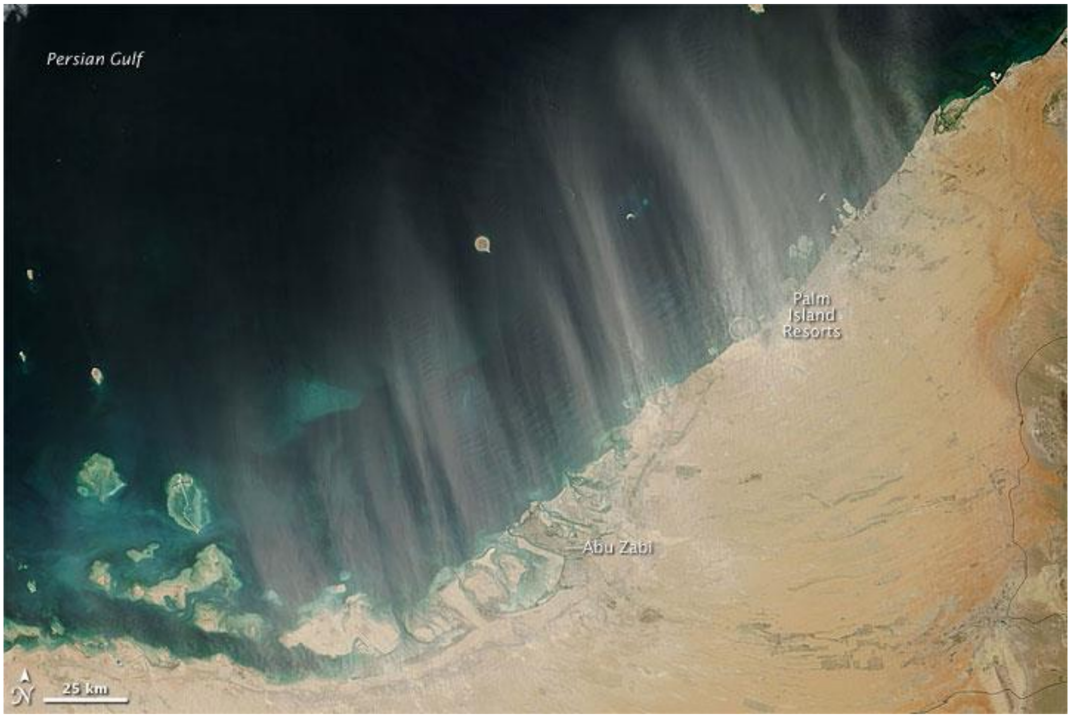

Figure 11 Dust storm over the UAE in 2009 (NASA, 2009)

As the MODIS AOD maps show that 2011 AOD distinctive than other years in distributions of the AOD values where the high AOD appears in the southwest of the UAE, followed by the coastline and the lowest amounts of AOD found in the central zones. In an attempt to explain this pattern in the AOD 2011, the monthly measurement of MODIS data and ground measurements of climate stations utilized to figure out the main reason that affects the southwest area during this period. Figure 12 display the monthly AOD values in 2011.

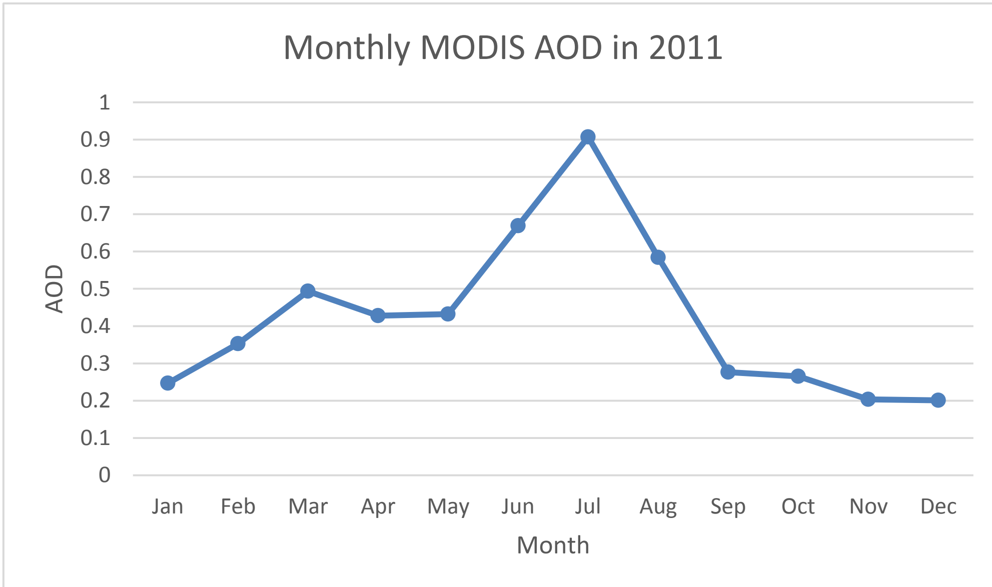

Figure 12 Monthly MODIS AOD for 2011

From the above figure, the AOD in 2011 reaches the peak in the summer season (July), increasing in the values of AOD started from April and May when the season of dust storms season beginning in the Middle East region until the drop-down in September. Air temperature a great deal of influence on the amount of dust and particles in the air that affects the AOD value. The temperature during April to September from ground measurements station (in situ)located in the southwest direction of the UAE as following; April (30 C), May (34.9 C), June (36.7 C), July (38C), August (37.4 C), September (34 C). Figure 13 below compare between temperatures from two climate stations, first in the coastal line the second in the southwest. From the graph, the temperature variations between these two different spatial distribution stations confirm that temperature during

2011 plays a significant role in raising the level of AOD from place to another, especially from April to September. NCMS report (2011) that the extreme highest temperature recorded in the summer month chief to more arid and dry weather conditions then many dust storms started in the area. Figure 14 gives us a glance at the linear relationship between AOD values in 2011 and ground measurement temperature in the same year.

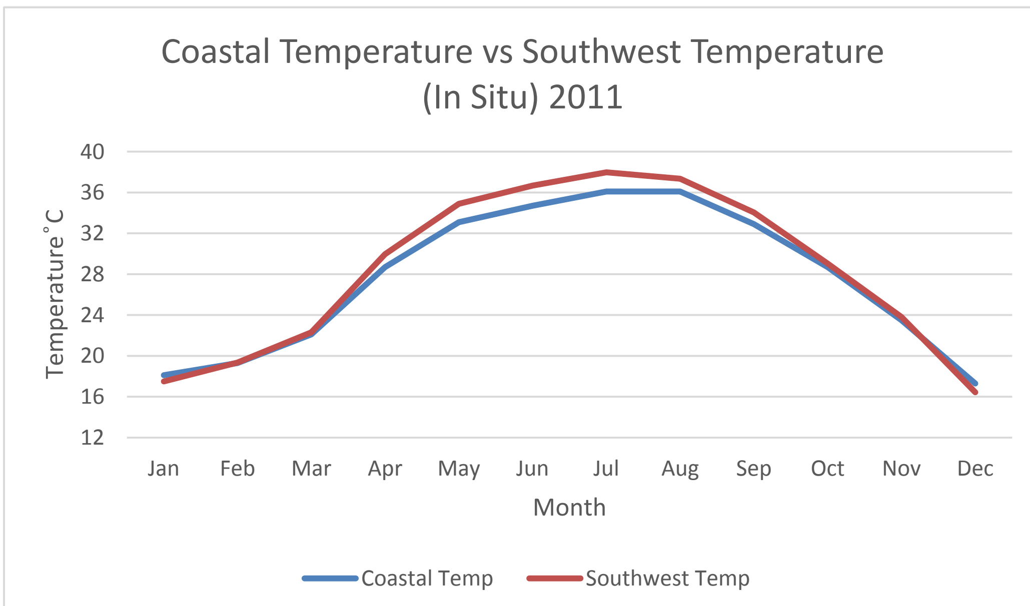

Figure 13 Coastal and Southwest temperature in 2011

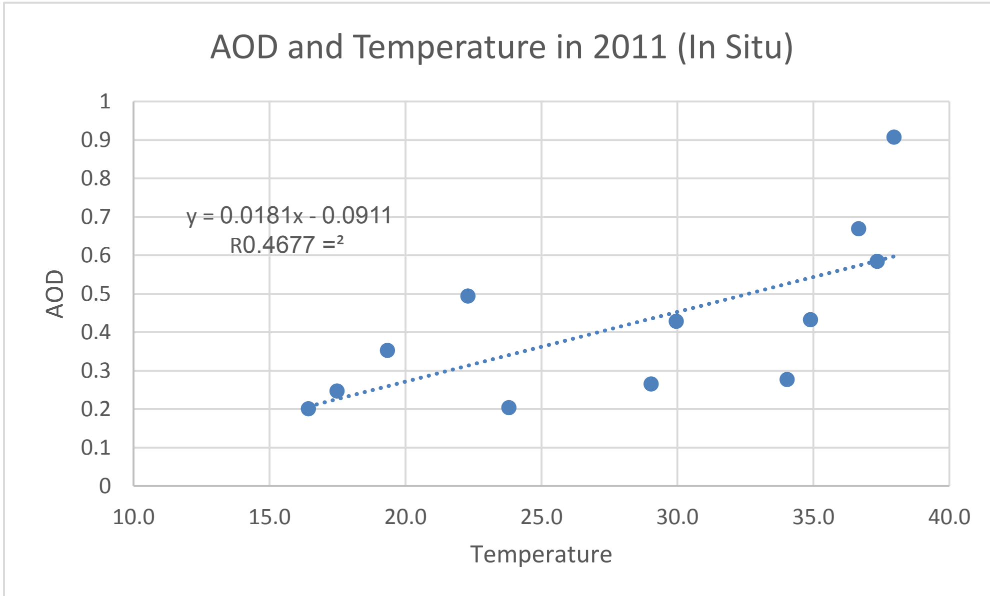

Figure 14 Ground measurement (southwest) temperature and AOD in 2011

Figure 15 demonstrations the variations in air pressure for both coastal and southwest area in the UAE. As the chart, the air pressure from May until August declines slightly, the back to increase even reach the high value during December. Importance to mention that, as the UAE is aired/ desert country, then the summer start from May, and the weather return to become cooler. NCMS, in their report (2011), declared that the Middle East region affected by diverse pressure systems. These extended from all geographical directions (east, west, north, and south). The UAE by itself influence with 12 pressure systems that make the processes and predictions much difficult (National Center of Meteorological and Seismology, 2011). Similarly, Cachorro et al. (2008), stated that low pressure in the source region of dust events such as Niger and South Algeria indicate convective activity and strong winds transport the dust toward the Africa coast. This explains the strong negative relationship between AOD and air pressure in 2011 (Figure 16).

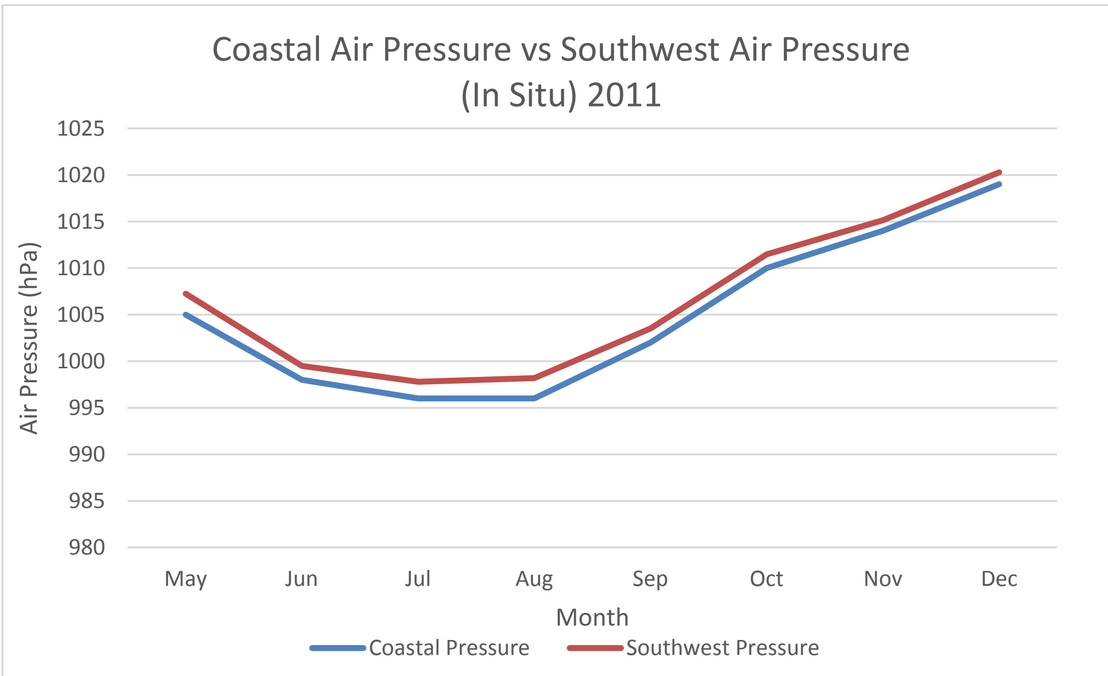

Figure 15 Coastal and Southwest air pressure in 2011

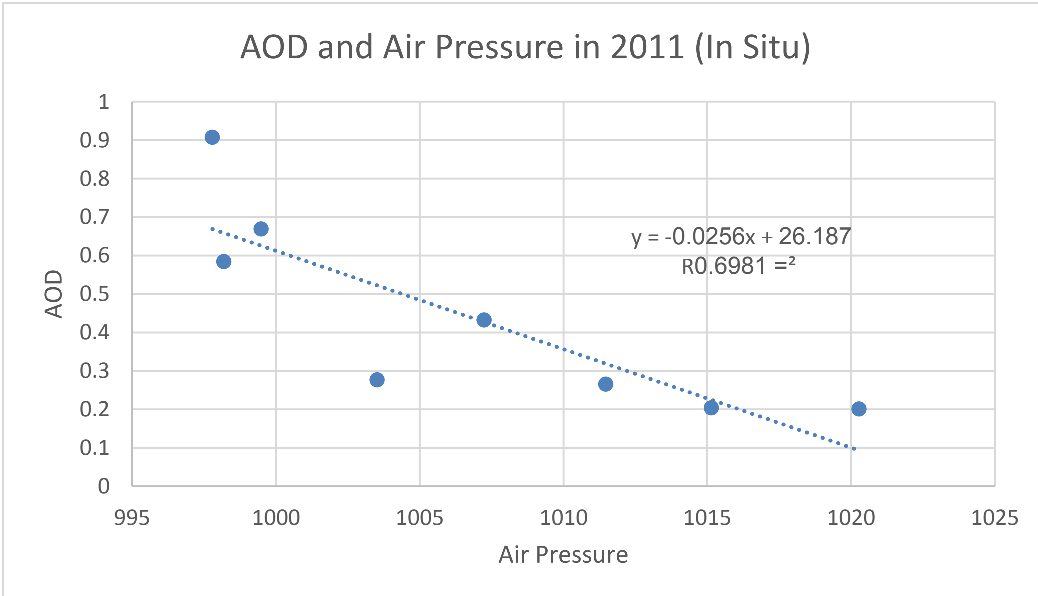

Figure 16 Ground measurement (southwest) air pressure and AOD in 2011

In figure 17, the wind speed in the southwest direction from the UAE higher than the wind speed in the coastal area. This trend of the winds related to several sources that generate the speedy wind. Since the southwest areas are close to the Kingdom of Saudi Arabia, so it is influenced by the topography, dust storm, and the winds from Saudi Arabia toward the west side of the UAE (National Center of Meteorological and Seismology, 2011). Correspondingly, Cachorro et al. (2008) found the dust mobility from the southern Saharan desert toward southwest Europe in a dust storm plumed.

Chudnovsky et al. (2017), argued that high AOD values related to prevailing winds direction and impacted by dust storms. Northern winds are the primary source of dust storms in the Arabian Peninsula, and it is divided into two types. The first type is called "Northerly summer winds," which begins with summer season plume every day within 120 days (June-September). Moreover, the features of northerly winds lead to creating a convergence area in tropical between the Arabian Peninsula and Iraq (National Center of Meteorological and Seismology, 2011). The second type is northerly winter winds, which drive to enormous dust storms during winter months. All these storms assist and support to increase the level of AOD in the area. Figure 18 represents the relationship between the AOD and wind speeds in the ground measurement station located on the southwest side of the UAE. Figure 19 illustrates the direction of the dust storm in March 2011 that came from Iran and Afghanistan regions toward the UAE and Saudi Arabia.

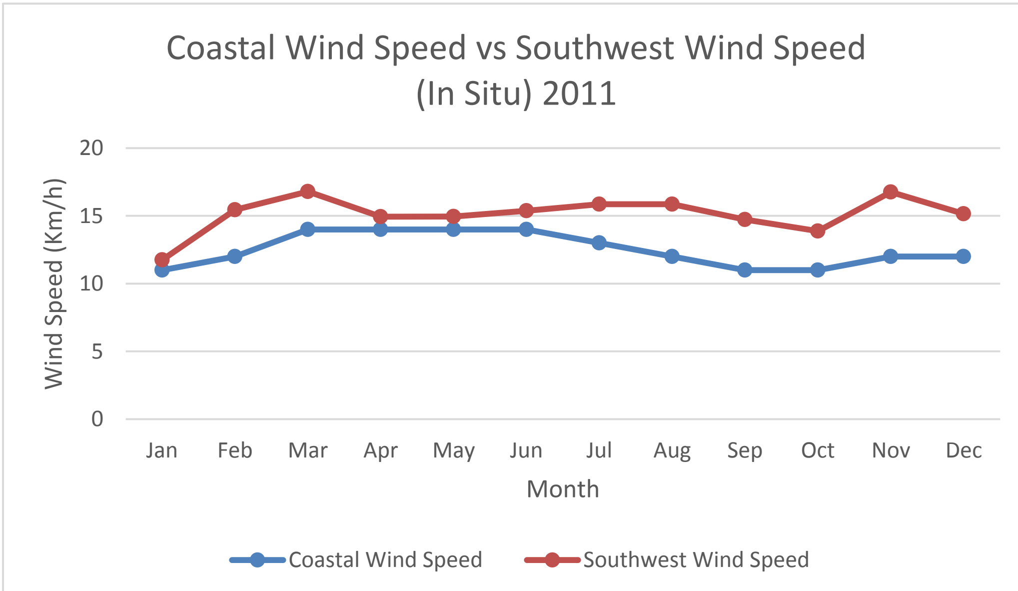

Figure 17 Coastal and Southwest air pressure in 2011

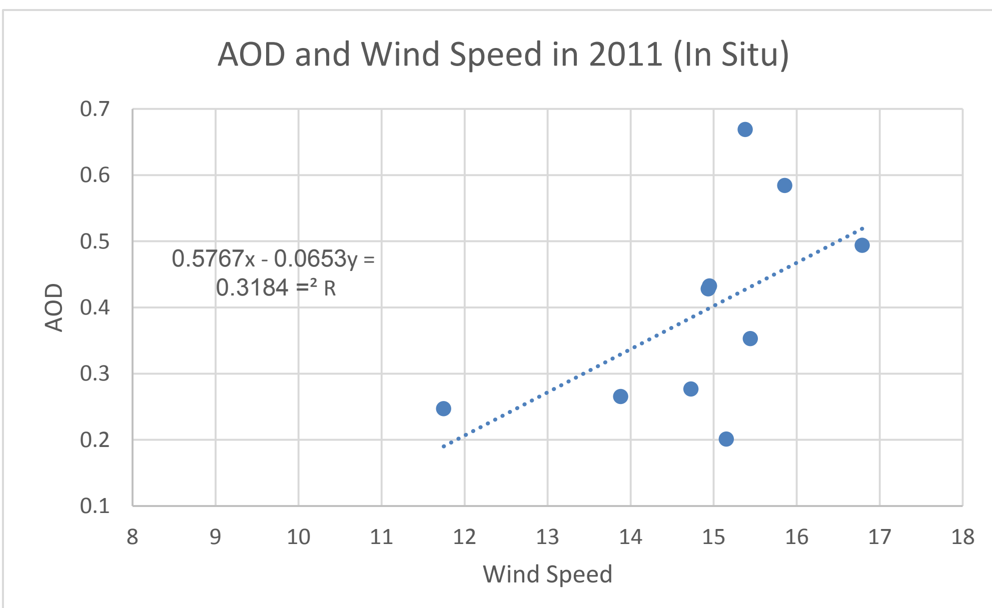

Figure 18 Ground measurement (southwest) wind speed and AOD in 2011

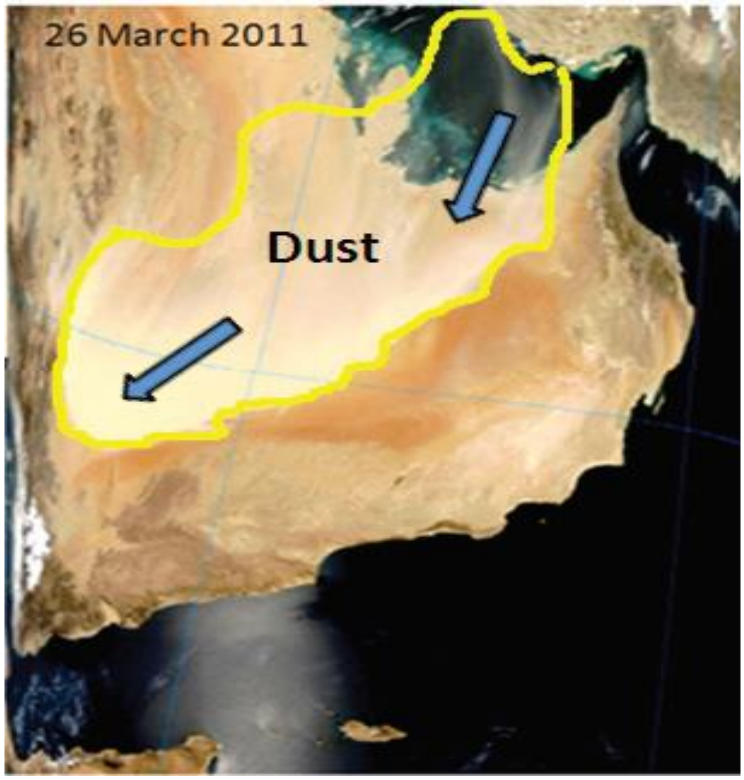

Figure 19 Strong dust storm movement to south-west in 2011 (NCMS, 2011)

Section 5.2 Meteorological Interpolation for Annual (2003-2015)

In the ArcMap software, the interpolation was done by using the kriging method to produce meteorological maps for temperature, wind speed, and pressure in the UAE. This step is vital to test the relationships between each climate parameter and the AOD. Then figure out which are mostly influence and not among these three parameters. Table 3 illuminates the results of the interpolation of kriging methods applied in the three major meteorological parameters (temperature, wind speed, and air pressure) for the study area in the same years that selected in this research.

Table 3 Results of kriging interpolation of meteorological parameters

Year	Wind Speed	Temperature	Air Pressure
2003	16.7459	17.7346	1017.953
2004	12.0801	19.6863	1015.883
2005	11.9152	17.3857	1018.323
2006	11.6821	17.8236	1018.266
2007	11.7882	16.3682	1020.318
2008	12.1773	16.938	1017.32
2009	10.6559	16.1195	1018.783
2010	10.1941	18.2063	1018.689
2011	11.239	18.7362	846.6034
2012	11.2465	17.7318	1017.189
2013	12.0857	18.7738	1018.248
2014	10.8701	17.3326	1020.493
2015	10.4244	18.5783	1020.08

Figure 20 (a) gives us a glance at how the AOD and wind speed act with each other from 2003 to 2015. As the chart view, the average wind speed was quite little while the AOD has a high concentration, except in 2003 and 2004, the opposite trend appears in the chart the AOD less in values while the wind speed has greater values.

Winds play an essential role in moving the particles and dust in the atmosphere. Chudnovsky et al. (2017) mentioned that strong wind speeds associated with the great movement of the dust in a particular zone. The result shows there are low in wind speeds from 2005 to 2015, which mean less dust move from the area, then the dust will suspend in the same area in high values during the time. In contrast, both 2003 and 2004 have a high wind speed than the selected period, especially in 2003 it was reached 17 km/h. The notice is throughout these two years, the AOD concentrations were low, as in figure 20 (a), while the wind speeds had high values. NASA (2003) stated that a thick dust storm was blown over the Middle East with the MODIS satellite image in May 2003. Moreover, the NCMS report (2011) illustrated a dust storm that attacked the UAE in December 2003 in the border region between Iran, Afghanistan, and Pakistan.

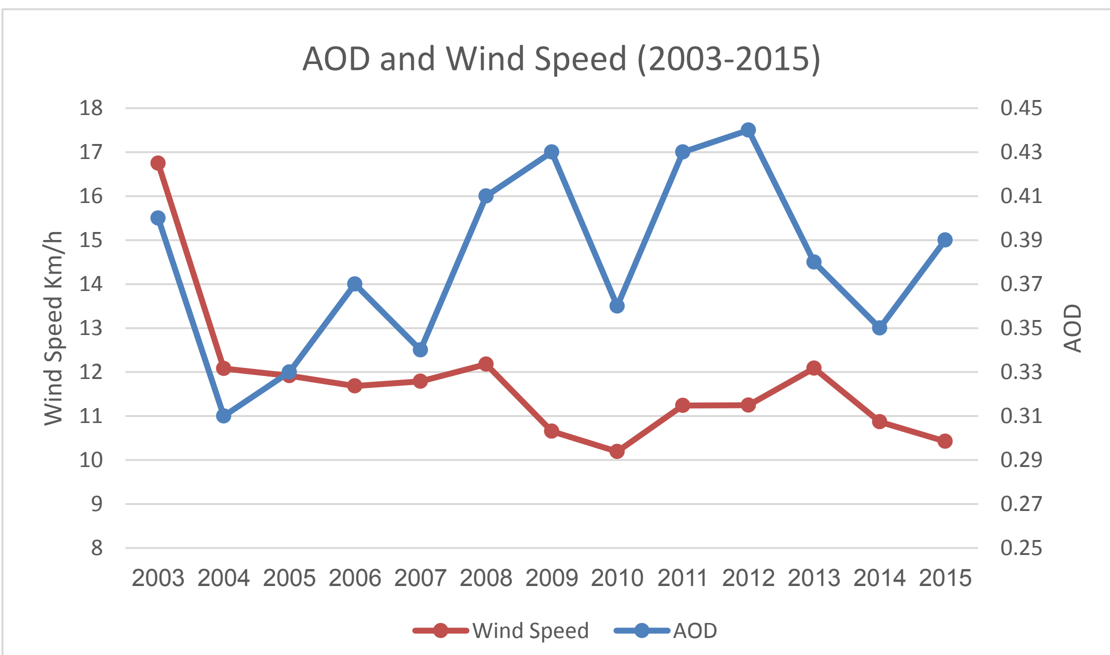

Figure 20(a) AOD and wind speed trend

In figure 20 (b) below, we can see the trend of both AOD and temperature. From the graph, when the temperature increases, the AOD intensity decrease while the AOD value appears it was raised with a low-temperature degree in some years, such as 2012; the AOD has the most exceptional values between the other years in the duration. Maghrabi et al. (2011), in their paper, noticed that dust storms occur in 2009 in Saudi Arabia neighbor country to the UAE affect the air temperature and decrease it, while the AOD percent increased. That also appears in figure 20(b) since both the UAE and Saudi Arabia located in the same region (Middle East Region).

Previously, discussion the years with active storms from the time series of AOD, such as 2008 and 2009. Dust storms and aerosols had high contributions during the duration of the study. Because of the properties of the storm, the air temperature influence. When the dust storm takes place, that means a great deal of solar radiation from the sunlight will block from the land surface so that the land surface will become cooler. In this research, the ground measurement stations used to generate temperatures by interpolation in ArcMap for each year. This is one reason to have a low temperature when the AOD values high. Miller and Tegen (1997) found that dust aerosols diminish the solar radiation that heating the surface. In this case, temperature decrease around 1 C. In a similar way, the aerosols are solid or liquid, and the particles diffuse the sunlight and absorb it, hence the temperature drop with the dust storms (Lim & Kim, 2018).

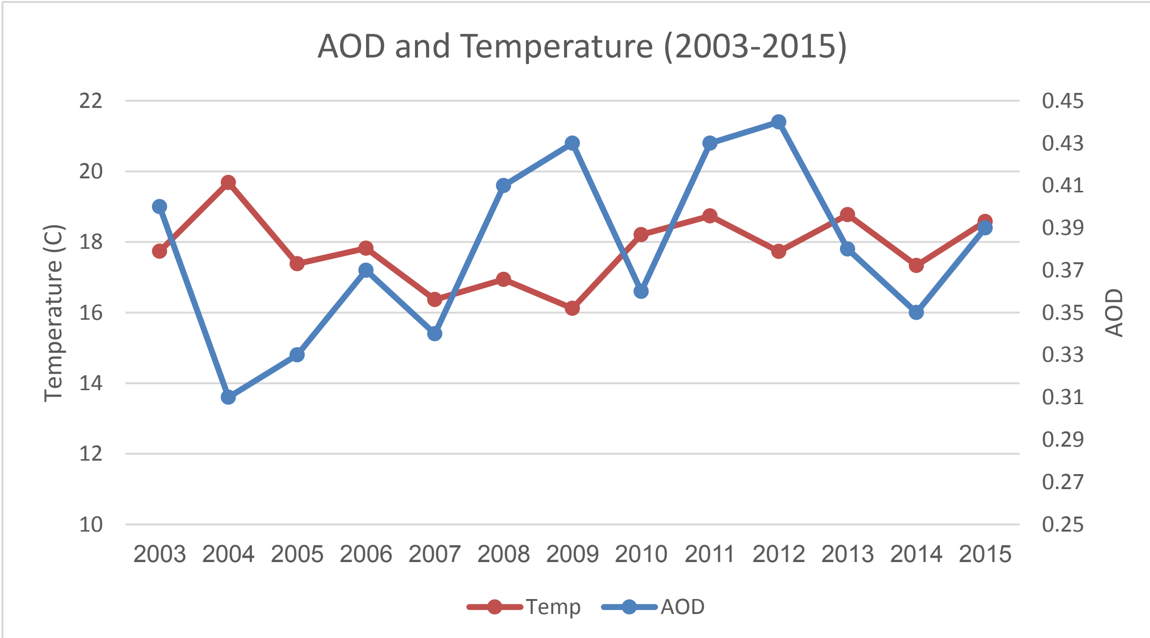

Figure 20(b) AOD and temperature trend

Figure 20 (c) the air pressure average from interpolation shows the values of air pressure are steadily over the years except in 2011, and the AOD stays in low intensity in some years and increases in the other such as 2009 and 2011. Importance to mention that even the air pressure values were constant, but there is a sharp decline in air pressure in 2011 with an increased in the AOD. The explanation of high air pressure and low AOD is related to the winds that formed due to the high pressure (Karagulian et al., 2019). The wind speeds transport the dust and particles from high pressure to low-pressure areas. Therefore, the value of AOD remains quiet with the high-pressure amount. Moreover, Maghrabi et al. (2011) found in the dust storm in 2009, the pressure increase, and the AOD increase. Hence, the result in figure 10(c) is true, as the same approach happened in 2009 between air pressure and AOD value. NCMS mentioned in their report that the UAE located in 12 pressure systems that make a challenge in predictions and could be influenced by other factors.

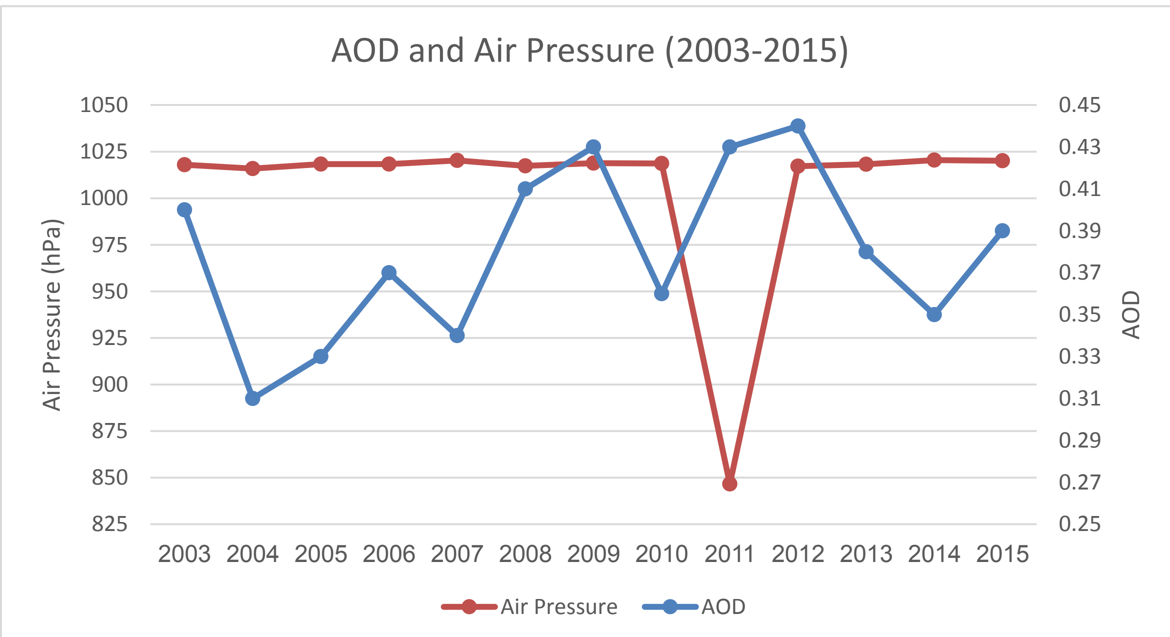

Figure 20(c) AOD and air pressure trend

Section 5.3 AOD and Meteorological Parameters in Monthly Observation

In table 4 below the monthly observation of 2015 is tested from January to December to understand the trend and relation between the climate parameters and AOD over this year from the duration.

Table 4 Monthly AOD and climate parameters for 2015

Month	AOD	Pressure	Temperature	Wind Speed
Jan	0.212783	1019.97	18.38	10.65
Feb	0.280355	1015.57	21.66	14
Mar	0.368476	1014.82	24.43	14.5
Apr	0.622775	1010.97	29.03	14.03
May	0.434032	1006.92	34.91	14.33
Jun	0.518333	1000.61	35.89	15.59
Jul	0.717248	998.4	37.9	14.4
Aug	0.409681	1001.38	37.51	13.28
Sep	0.348815	1006.66	34.22	12.7
Oct	0.310682	1012.1	30.94	11.27
Nov	0.250553	1015.91	25.36	12.23
Dec	0.223848	1020.15	19.83	12.45

In Figure 21 (a-b), the AOD and temperature of 2015 appear. In the (a), the rise of the air temperature is associated with an increase of AOD. This was expected, particularly if AOD monthly variability was climatically related. In Figure 21 (b), the relation between AOD and temperature in 2015. Figure 21(b) attempts to build a linear relationship between the two variables (positive correlation).

The temperature began to increase in April, where the most dust storms start in the Middle East region include the UAE, Saudi Arabia, Kuwait, Iraq, and Iran. April recorded a high value of AOD that related to the dust/sand storm on April 10, 2015 (NASA, 2015). According to NASA (2015), the spring storm and strong winds (northwesterly) lift dust to hundreds of kilometers. Since the dust blocks the sunlight and reduces the solar radiation by absorbing and scattering (Lim & Kim, 2018), the temperature in April 2015 was low than AOD value. During the summer month, July holds the highest amount of AOD, that back to air temperature and water vapor from the gulf lead to suspending the dust for a long time. Moreover, the lack of precipitation in the summer associated with an increase in the AOD. However, increasing in temperature related to generate more dust storms and increase AOD value.

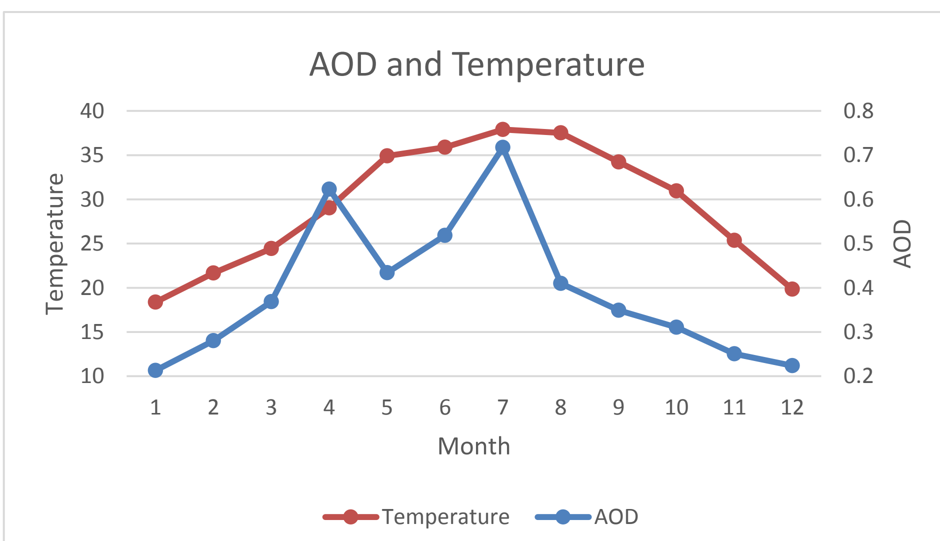

Figure 21(a) AOD and temperature in 2015

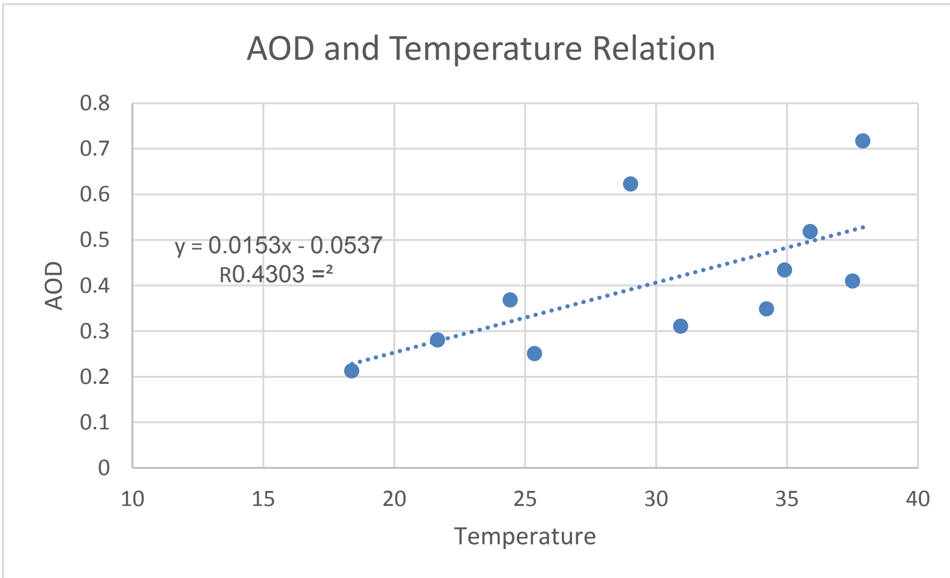

Figure 21(b) Relation between AOD and temperature in 2015

Figure 22 (a-b) view the AOD and wind speed which has a positive, strong correlation (R^2 =0.71). Since the UAE is the desert environment, the rise in wind speed leads to the formation of dust/sand storms and transport. These particles matter (PM) in the atmosphere as a result increase the amount of the AOD suspended in the air.

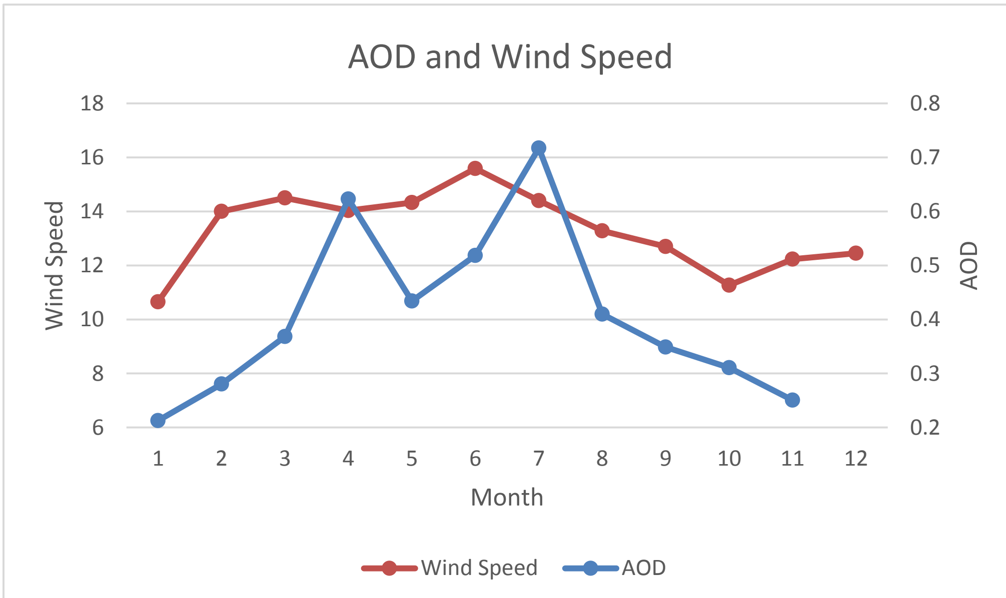

Figure 22(a) AOD and wind speed in 2015

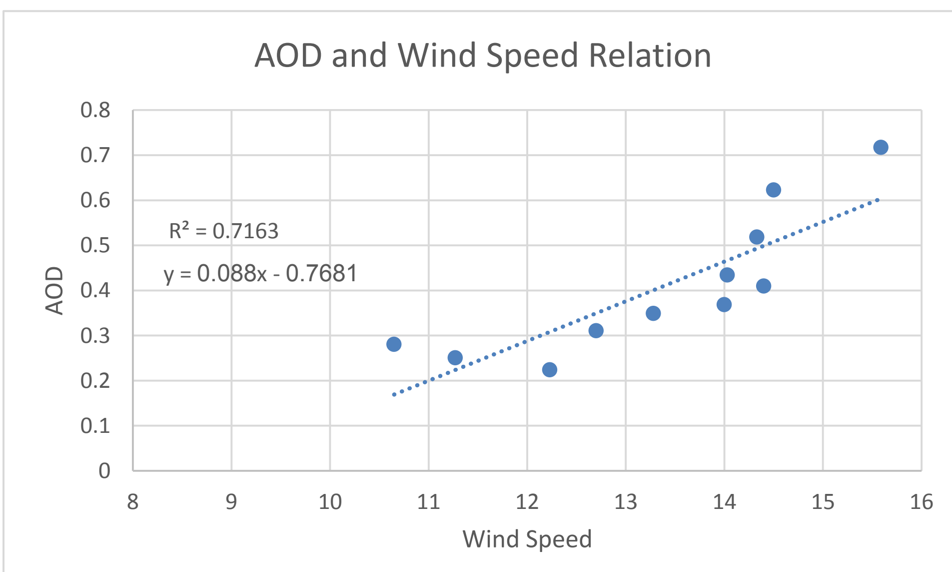

Figure 22(b) Relation between AOD and wind speed in 2015

Figure 23(a-b) the AOD and air pressure tend oppositely to each other. When the air temperature decreases, the AOD amounts increase. Interestingly, the air pressure and AOD depicts fair negative relation. This was not expected to find. Air pressure refers to the force of a column of air on a surface due to its mass. One would thus expect that as such mass decline or rise, the AOD would follow a similar pattern, as atmospheric particles would significantly contribute to the total air mass.

Because of the high temperature during summer months (June-August), the warm air will rise and create a low-pressure system than other seasons, as figure 23(a). This pattern helps to replace the warm air with dust and particles to move from a high-pressure system to low pressure. Thus, in July, embrace the highest AOD value when the pressure was in the lowest value. The inverse happened in the high-pressure the AOD was in less intensity. However, April is exceptional in 2015, where AOD and air pressure values almost close to each other. April 2015 was active with intense dust storms, which increase the AOD and reduce the pressure relatively (Karagulian et al., 2019). the physical principle of dust storm movement from high-pressure to the low-pressure area is the most possible in AOD values since the area has a complex pressure system (National Center of Meteorological and Seismology, 2011)

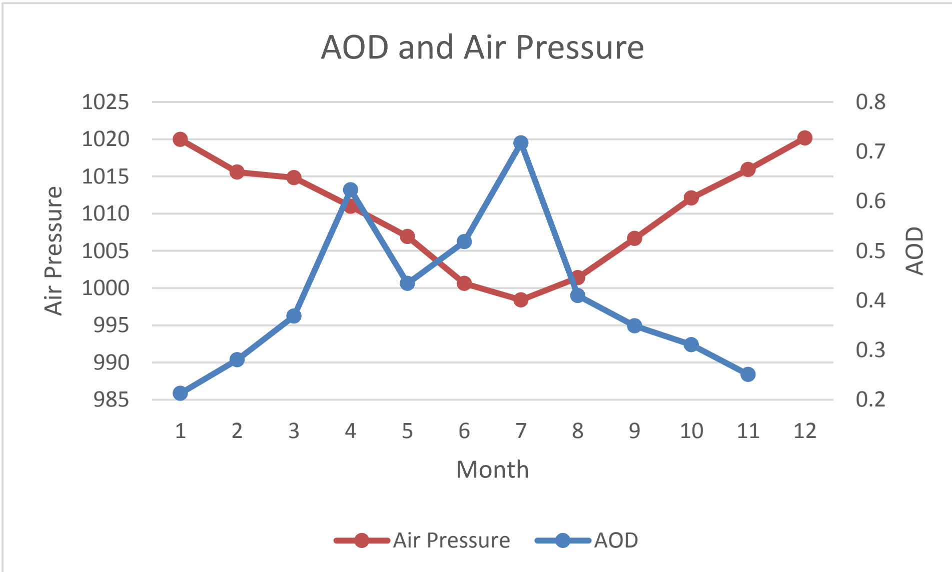

Figure 23(a) AOD and air pressure in 2015

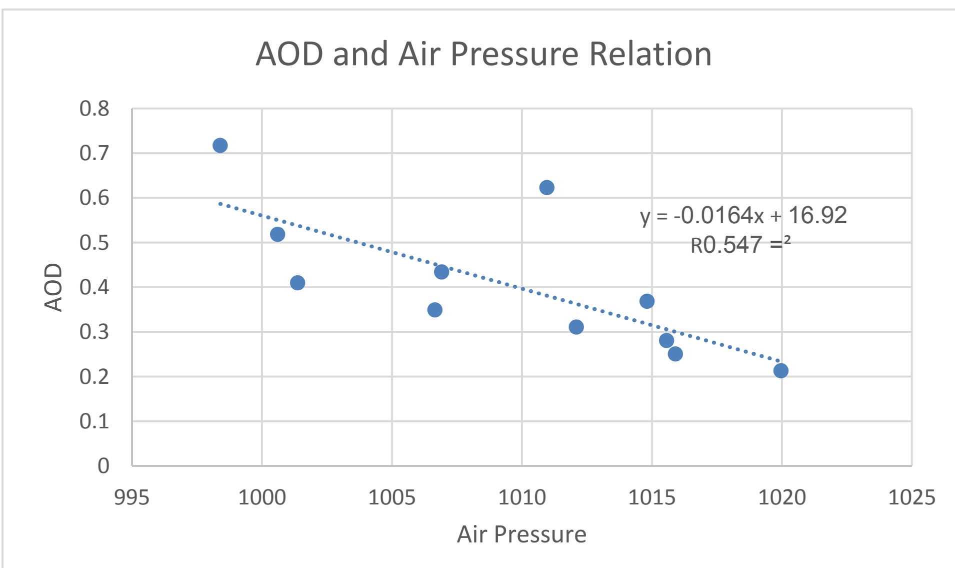

Figure 23(b) Relation between AOD and air pressure in 2015

Section 5.4 Seasonal AOD from 2013 to 2015

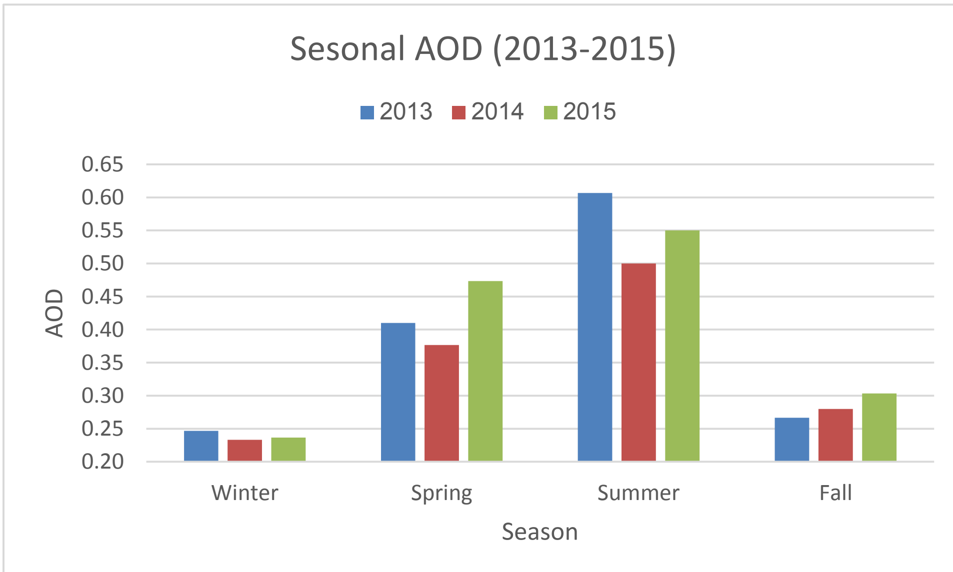

Figure 24 Seasonal AOD from 2013 to 2015

Figure 24 above shows the seasonal pattern of AOD in the UAE as the graph views the most dominate of AOD in the summer season, followed by spring. Summer starts in the UAE from June to August, while spring from March to May. The high temperature during summertime increases the water body surrounds the UAE (Gulf water). Water vapor in the air aid in suspending a large amount of the dust. Moreover, it contributes to increasing the relative humidity value, which causes to hold more particular matter (PM) in the air. In winter (December to February) and fall (September to November), the lowest AOD can observe when the temperature in minimum degree over the year.

The dust storms in the UAE beginning in spring seasons, especially in April until the end of summer seasons. These storms are intense with dust and variate from year to another. In figure 24, 2013, has the greatest AOD during summer, which means most dust storms occurred from June to August, and there were active. NASA's Aqua satellite captured a satellite image of the intense dust storms in the gulf area in 2013. Moreover, illustrations a dust blow extending from eastern Saudi Arabia to the United Arab Emirates and over the ocean. Similarly, in 2015, for spring season was the highest because the storms initiate from April 2015. Another reason is the strong monsoon winds promote dust storms over the Gulf area in both spring and summer (Hamza, Enan, Al-Hassi, Shuut, & Beer, 2011).

Section 5.5 Daily AOD Time Series in 2011

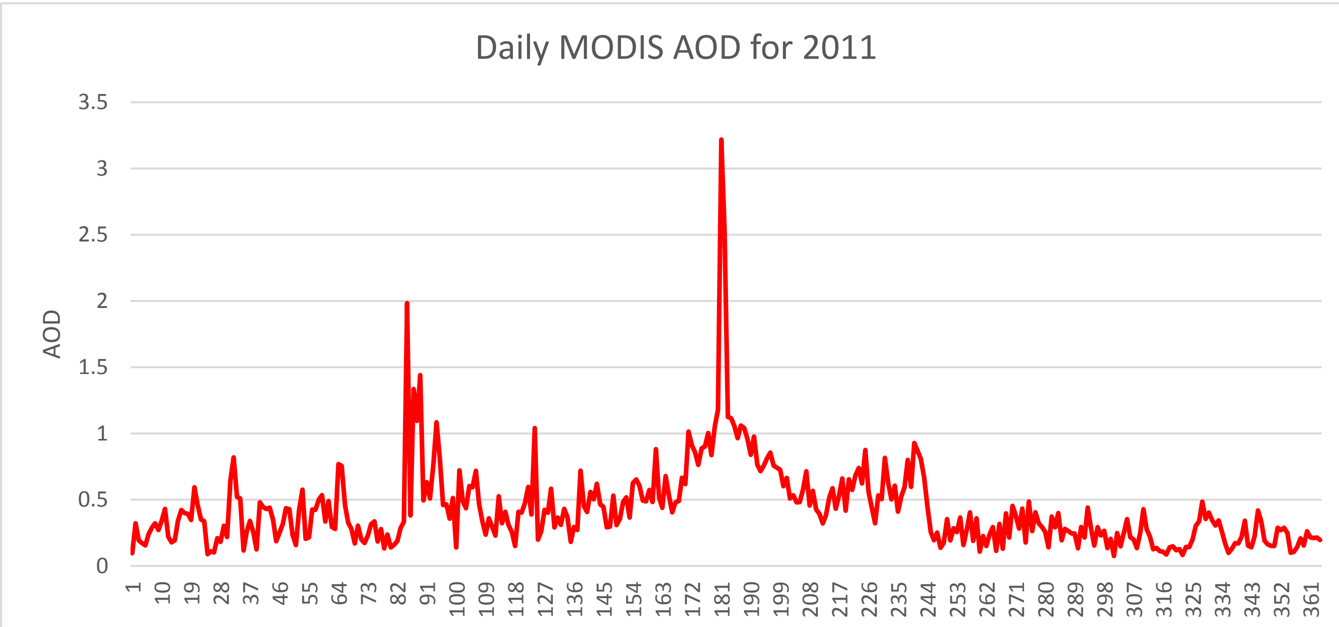

Figure 25 Daily MODIS AOD for 2011

Figure 24 above displays the 2011 AOD for daily measurement from MODIS Satellite. A great deal of days has ≥ 0.5 µm, especially in spring, summer, and fall seasons. Whereas less than 0.5 µm dominated in the winter days. In the time series, the high amount of AOD notices in day 85 with around 1.98 µm. This day represents the end of March, which had an intense dust storm in 2011 was between March 25 and March 27(NCMS, 2011). This dust storm patented from Iraq and Kuwait in the southeast borders brought massive amounts of dust and particular matters, and the wind speed 90 to 57 km/h (National Center of Meteorological and Seismology, 2011). In summer, the highest value of AOD appears in the time series around 3.21 μm in day 181, which represents the last day of June. The strength of AOD in summer due to high temperature, which created wind and dust storms in arid weather. Another reason is the strong monsoon winds promote dust storms over the Gulf area in both spring and summer

CHAPTER 6 DISCUSSION AND CONCLUSION

AOD concentration reaches the peak during summer months in the UAE in the monthly observations, and the amounts fluctuated over the years from 2003 to 2015. AOD maps generated from MODIS data in the duration tend to get the highest concentration of AOD along the coastline. The explanation of this tendency is related to that meteorological conditions which affect each other. Water vapor plays a significant role in the coastal areas, especially during the summer season, when the temperature increase in evaporating the Gulf water. The water vapor aid the AOD to suspend in the air leads to an increase in the amount of AOD over the coastal. In addition to that, relative humidity seems essentials to examine in the UAE are due to the high values in the coastal line. Maghrabi et al. (2011), mention in their paper that the AOD in 550nm growth to hit 330% directly after the dust storm that happened in Saudi Arabia. The rapid increase in the amount of AOD related to rising in both relative humidity (RH) and air pressure, during the reduction in the general temperature (Maghrabi, Alharbi, & Tapper, 2011).

The research has investigated the monthly and annual variability of AOD levels in the UAE in relation to corresponding meteorological observations of air temperature, wind speed, and air pressure. According to results, the monthly observation of AOD is much better than the annual observations because the monthly trend brought the positive and linear relationship between the AOD and the meteorological variables (temperature, wind speed, and air pressure). Plots of monthly meteorological observations and estimated AOD display a strong positive relation between air temperature, wind speed, and AOD. This confirms the primary hypothesis that the variability of AOD within the study area is mostly due to climatic and seasonal weather conditions.

From the seasonal observation, the summer and spring seasons contribute to the most extent of AOD in the UAE country. In contrast, the lowest records of AOD found in the winter season. This beyond the temperature difference in each season and effect of the air temperature in the water body, especially during summer months. The high strength of AOD in coastal areas where the lowest values noticed in the interior space where the air drier.

For future works, extend the study with more meteorological variables such as relative humidity and precipitation can assist in better understand of AOD variations in the coastal and interior areas. Moreover, used different data can show other possible results to support what found or enhance it. Connect the AOD with water, energy, and food security of the country to provide information about how AOD can affect the safety and how to use or solve it.

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