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Examining the Spatio-temporal Dynamics of $PM_{2.5}$ in Saudi Arabia Using Satellite-derived Data: A Cluster Study

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Abstract

The study of the concentrations and effects of fine particulate matter in urban areas have been of great interest to researchers in recent times. This is due to the acknowledgment of the far-reaching impacts of fine particulate matter on public health. Remote sensing data have been used to monitor the trend of concentrations of particulate matter by deriving aerosol optical depth (AOD) from satellite images. The Center for International Earth Science Information Network (CIESIN) has released the second version of its global $PM_{2.5}$ data with improvement in spatial resolution. This paper revisits the study of spatial and temporal variations in particulate matter in Saudi Arabia by exploring the cluster analysis of the new data. Cluster analysis of the $PM_{2.5}$ values of Saudi cities is performed by using Anselin local Moran's I statistic. Also, the analysis is carried out at the regional level by using self-organizing map (SOM). The results show an increasing trend in the concentrations of particulate matter in Saudi Arabia, especially in some selected urban areas. The eastern and south-western parts of the Kingdom have significantly clustering high values. Some of the PM2.5 values have passed the threshold indicated by the World Health Organization (WHO) standard and targets posing health risks to Saudi urban population.

Keywords: satellite data; fine particulate matter; air pollution; geographic information system; health risks; spatial analysis; Saudi Arabia

Introduction

Fine particulate matter is one of the important air quality parameters. Recently, fine particulate matter is receiving a lot of attention due to the health, environmental and social implications of increasing particulate matter concentrations. The International Agency for Research on Cancer (IARC) has confirmed the carcinogenicity of $PM_{2.5}$ (Loomis et al., 2013). A positive relationship between exposure to $PM_{2.5}$ and incidences of lung cancer has been found in areas with annual average levels of $PM_{2.5}$ ranging from 10 to 30 $\mu g/m^3$ (Loomis et al., 2013; Hoek & Raaschou-Nielsen, 2014). Even in areas where the concentrations of $PM_{2.5}$ are less than 10 $\mu g/m^3$, there are risks of lung cancer (Loomis et al., 2013). The study by Franck et al. (2014), in Santiago de Chile, indicated that there was a significant impact of exposure to $PM_{2.5}$ on cardiovascular hospital admissions. Nasser et al. (2015) concluded that particulate matter constitutes a risk factor for cardiovascular diseases in the Middle East countries that include Iran, Saudi Arabia, the United Arab Emirates and Qatar. These findings underscore the need to monitor particulate matter concentrations in order to establish means of controlling the concentrations.

Several authors have reported the monitoring of particulate matter at the global and local levels. Brauer (2016) highlighted about 20% increase in the global exposure to particulate matter and about 2.9 million deaths in 2013 attributed to exposure to fine particulate matter. Farahat (2016) examined the variations, causes and effects of the concentrations of pollutants (especially aerosols) over the Arabian Peninsula. In Saudi Arabia, studies (Al-Jeelani, 2009; Aburas et al., 2011; Munir et al., 2013; Rushdi et al., 2013; Shaltout et al., 2013; Habeebullah, 2013) have depicted particulate matter concentrations and compositions in the major cities of the Kingdom such as Riyadh, Jeddah and Makkah. El-Mubarak et al. (2014) identified polycyclic aromatic hydrocarbons (PAHs) in the particulate matter over the city of Riyadh. They found high PAHs and particulate matter concentrations that could be attributed to traffic emissions (El-Mubarak et al., 2014). Also, organic tracers, that could pose toxicity risks, were found in the particulate matter over Dhahran city, Saudi Arabia (Rushdi et al., 2014).

Data derived from satellite images are used to supplement ground measurements in monitoring particulate matter concentrations. Sinha et al. (2015) used satellite data (Moderate Resolution Imaging Spectroradiometer [MODIS]) and ground-based observations to estimate $PM_{2.5}$ values over Hyderabad in India. In the same vein, Farahat et al. (2015) used multisensor satellite data (including MODIS) and ground observations from AErosol RObotic NETwork (AERONET) to monitor aerosols' dynamics over Saudi Arabia. Recently, efforts have been made to produce satellite-derived global data sets of particulate matter concentrations (Battelle Memorial Institute and Center for International Earth Science Information Network [CIESIN], 2013; de Sherbinin et al., 2014; van Donkelaar et al., 2010, 2015a, 2015b). The first set of the global data (Battelle Memorial Institute and CIESIN, 2013; de Sherbinin et al., 2014) has a spatial resolution of about 50 km while the second set has a resolution of about 10 km. Aina et al. (2014) explored the first set of data in monitoring the changes in $PM_{2.5}$ concentrations of Saudi Arabia especially variations among Saudi cities. The second set of data is finer in resolution and might give different results. Thus, the aim of this study is to reexamine the spatial and temporal variations in $PM_{2.5}$ over Saudi Arabia using the new global data set.

Materials and Methods

Study area

The location of the study is Saudi Arabia. The country covers an area of about 2 million km^2 making it the largest country in the Arabian Peninsula. According to the Kingdom's General Authority of Statistics, the population of Saudi Arabia is about 31 million (2014 estimate) (http://www.stats.gov.sa/en). More than 80% of the population lives in urban areas. The major cities in Saudi Arabia include

Riyadh, Jeddah, Dammam, Makkah and Madinah and the two industrial cities of Jubail and Yanbu (Figure 1). About half of the Saudi population resides in these cities. Though there are other cities with higher populations than the industrial cities, the share of the Kingdom's economic activities at these two cities brings them to prominence.

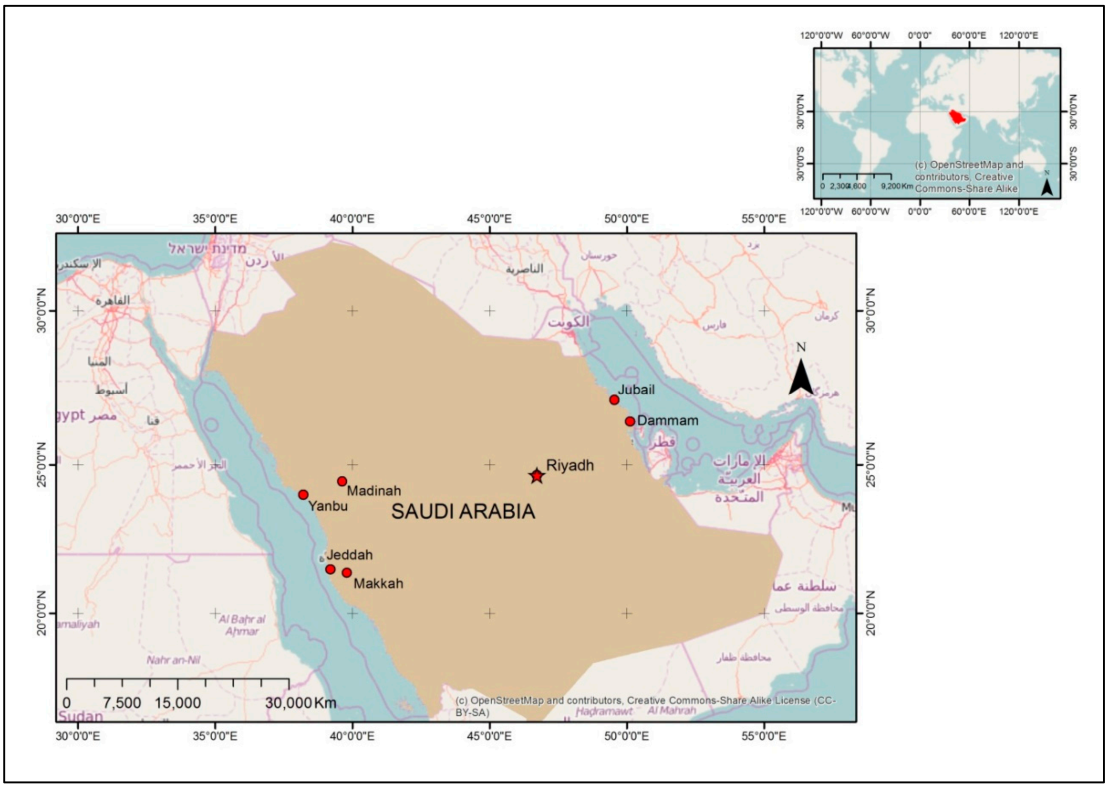

Figure 1. Location of Saudi Arabia and selected major cities

Data acquisition

The PM2.5 data was downloaded from Socioeconomic Data and Applications Center (SEDAC) website hosted by CIESIN (http://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-avg-pm2-5-modis-misr-seawifs-aod-1998-2012). The data provides a satellite-derived (MODIS, MISR and SeaWiFS) global multiyear (1998-2012) continuous surface of PM2.5 concentrations in a series of three-year average grids (1998-2000, 1999-2001,

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2000-2002 and so on) with a spatial resolution of about 10 km (van Donkelaar et al., 2015a). This study adopted the central years (1999 for 1998-2000, 2000 for 1999-2001 and so on). The population data was derived from the population census document (2010 census) from the Central Department of Statistics and Information, Saudi Arabia (http://www.cdsi.gov.sa/english/index.php). The document is a list of Saudi cities inhabited by at least 5000 people. The cities with at least 10,000 inhabitants (about 80% of the Saudi Arabian population) were selected for this study. The location of the cities was derived from Saudi Geological Survey publication (SGS, 2003) and Google Earth as reported in Aina et al. (2014).

GIS Analysis

The analysis was carried out by using GIS (ArcGIS 10.2). The global data was visualized in ArcGIS (1999 and 2011) to the trend of PM2.5 concentrations in Saudi Arabia with other countries. The World Health Organization (WHO) air quality guidelines and targets were used as thresholds for classifying the global data for visualization. After the visualization of the global data, the raster layers of the satellite-derived global data (1999-2011) were clipped to the Saudi Arabian boundary and the cities shapefile was used to extract the particulate matter concentration for each city. Since the data has a higher resolution than the previous version analyzed by Aina et al. (2014), the number of raster cells falling within each city has increased. For example, only two cells intersected with Riyadh according to the 50 km resolution data while about twelve cells intersected with Riyadh by the 10 km resolution data. However, the two cells from the previous study (Aina et al., 2014) was adopted to allow for comparison between the two data sets. Cluster analysis was carried out at the city level using an implementation of Anselin local Moran's I statistic (Anselin, 1995) in ArcGIS (Cluster and Outlier Analysis tool). For the regional analysis, a shapefile of the administrative regions of Saudi Arabia was used to extract the $PM_{2.5}$ values for the regions and ClusterPy (Duque et al., 2011) was used to carry out the cluster analysis (all the data are included from 1999-2011) using a self-organizing map (SOM) algorithm.

Results and Discussion

The new global data has some gaps (missing data) over Saudi Arabia (Figure 2). The $PM_{2.5}$ values of some of the cities had to be estimated by using the neighboring value because of the missing data. The previous version of the data (50 km resolution do not have any gap over Saudi Arabia). The results of the visualization of the global data show that there was an increase in the PM2.5 concentrations over Saudi Arabia from 1999 to 2011 (Figures 3 and 4). In 2011, a large part of Saudi Arabia had concentrations above the WHO target of 35 μg/m^3 than in 1999 (Figures 3 and 4).

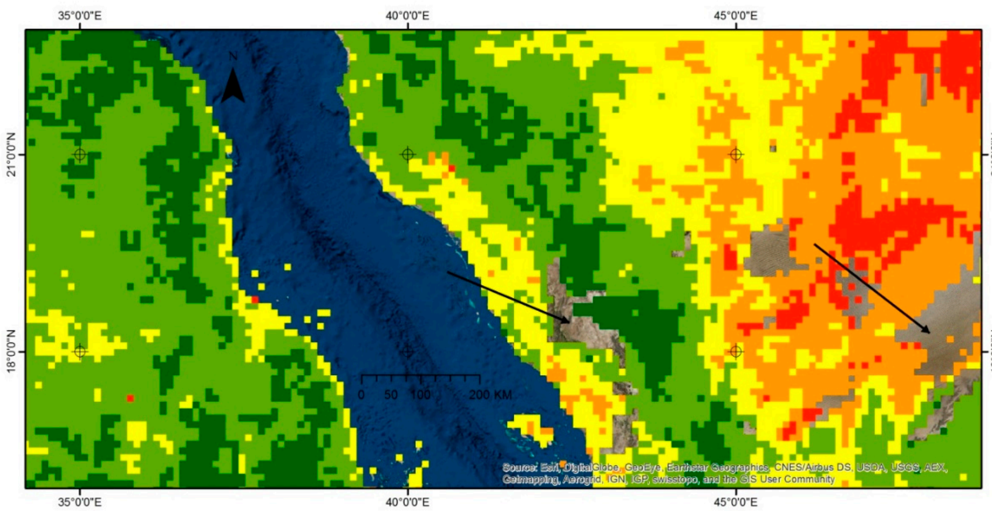

Figure 2. Gaps in the global data (1998 – 2011)

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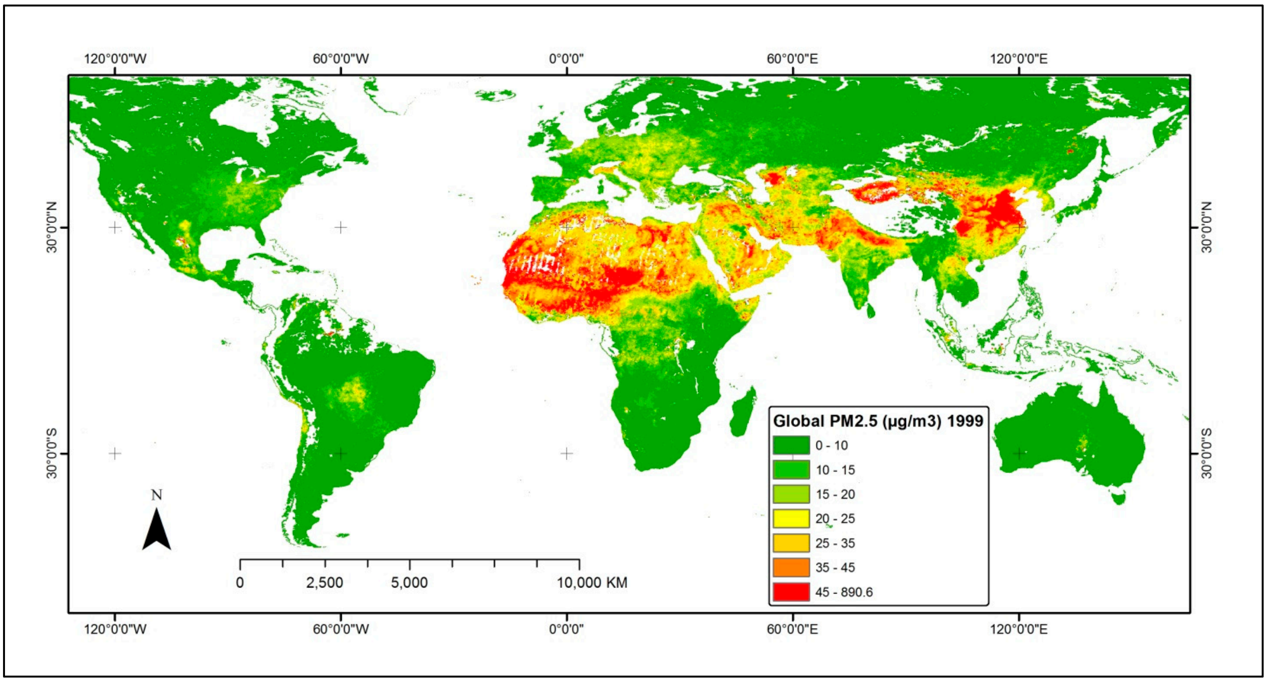

Figure 3. Global $PM_{2.5}$ concentrations -1999

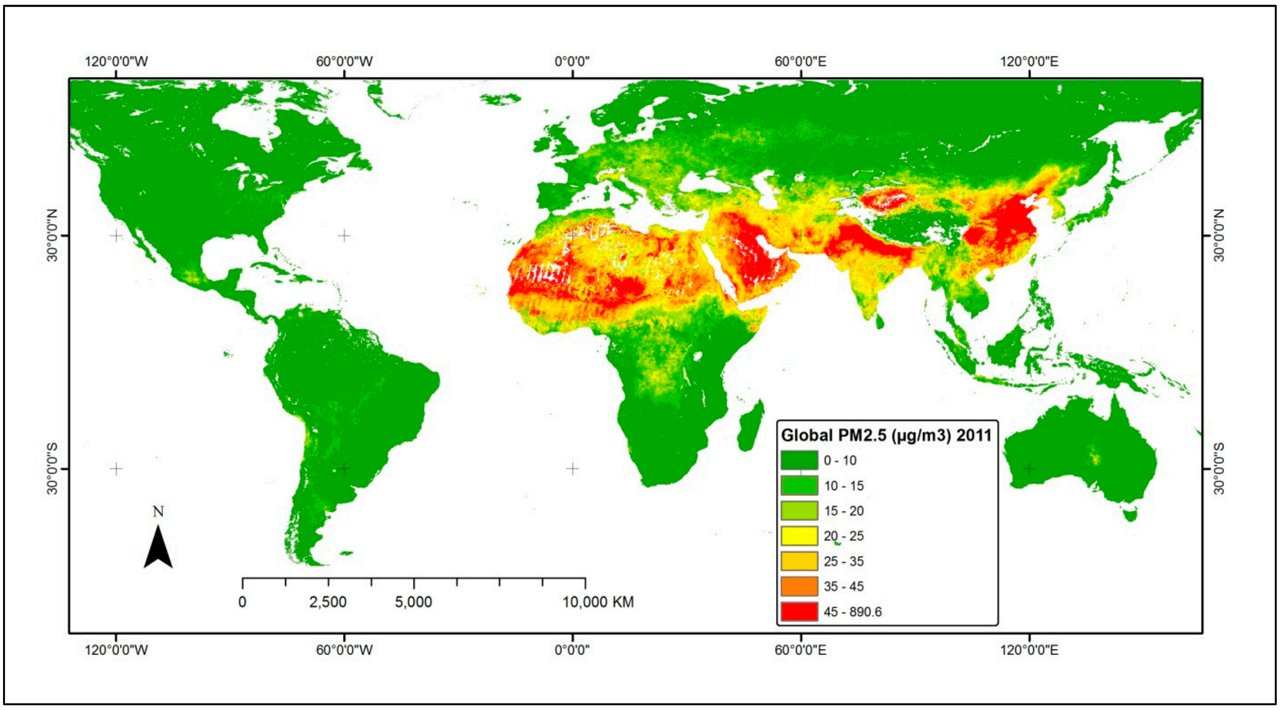

Figure 4. Global $PM_{2.5}$ concentrations – 2011

Table 1 and 2 show the result of the $PM_{2.5}$ values of some selected cities from 1999 to 2011. Though the results depict a trend of increasing particulate matter

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concentrations over Saudi Arabia like the 50 km resolution data (Figure 5), the $PM_{2.5}$ values are higher than that of the previous data. For instance, the lowest $PM_{2.5}$ value derived from the previous data is 10.1 µg/m^3 and the highest is 40.4 µg/m^3 (Aina et al., 2014) while the lowest and the highest values for the new data are 16.5 and 62.6 µg/m^3. Also, some cities that have low values according to the previous data (Makkah, Madinah and Jubail) have got high $PM_{2.5}$ concentrations while using the new data. Figures 6 and 7 show that there is only one cluster of high value in the 1999 data while in the 2011 data there are many clusters. The clusters occur in the eastern part of Saudi Arabia where considerable oil production activities take place. In the 2011 data, clusters of low values occur in the western part of the Kingdom.

Table 1. $PM_{2.5}$ concentrations (in µg/m^3) in selected Saudi cities (1999-2005)

Cities	**Population 2010**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Riyadh	5,188,286	30.65	37.30	39.30	40.55	39.60	40.20	40.20
Jeddah	3,430,697	27.35	27.80	27.75	27.75	34.20	35.65	33.85
Makkah	1,534,731	17.20	22.0	25.70	25.70	30.40	30.50	30.50
Madinah	1,100,093	15.60	22.10	25.30	25.30	25.30	25.00	24.50
Dammam	903,312	48.20	37.40	30.50	30.50	31.10	31.10	31.10
Jubail	142,825	35.20	38.40	40.00	40.00	41.60	52.20	44.90
Yanbu	73,000	16.50	19.50	21.10	25.70	28.60	25.70	16.50

Table 2. $PM_{2.5}$ concentrations (in μg/m³) in selected Saudi cities (2006-2011)

Cities	**Population 2010**	2006	2007	2008	2009	2010	2011
Riyadh	5,188,286	42.50	44.90	53.35	53.35	52.50	52.10
Jeddah	3,430,697	33.20	33.20	33.40	39.60	36.80	39.35
Makkah	1,534,731	31.60	31.90	36.50	36.50	36.00	36.00
Madinah	1,100,093	25.00	25.00	28.40	29.90	29.90	32.20
Dammam	903,312	31.70	34.30	39.70	39.70	40.50	41.00
Jubail	142,825	48.90	48.90	58.10	58.50	58.50	62.60
Yanbu	73,000	25.40	25.40	24.00	30.00	25.10	28.80

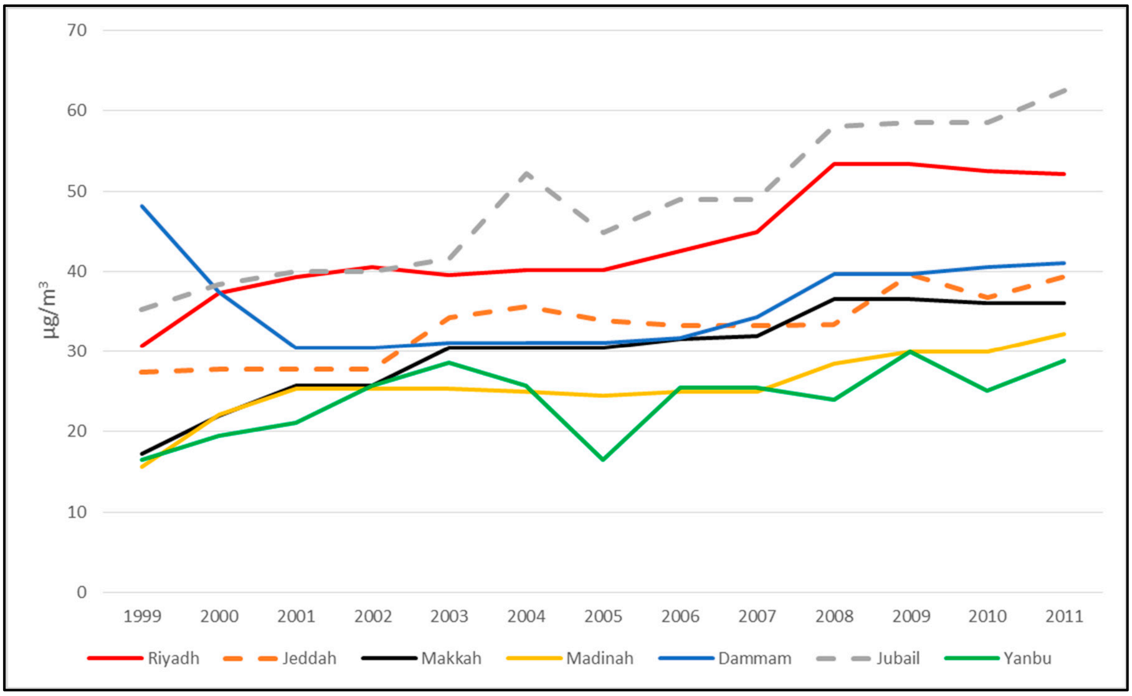

Figure 5. $PM_{2.5}$ concentrations (in μg/m³) in selected Saudi cities (1999-2011)

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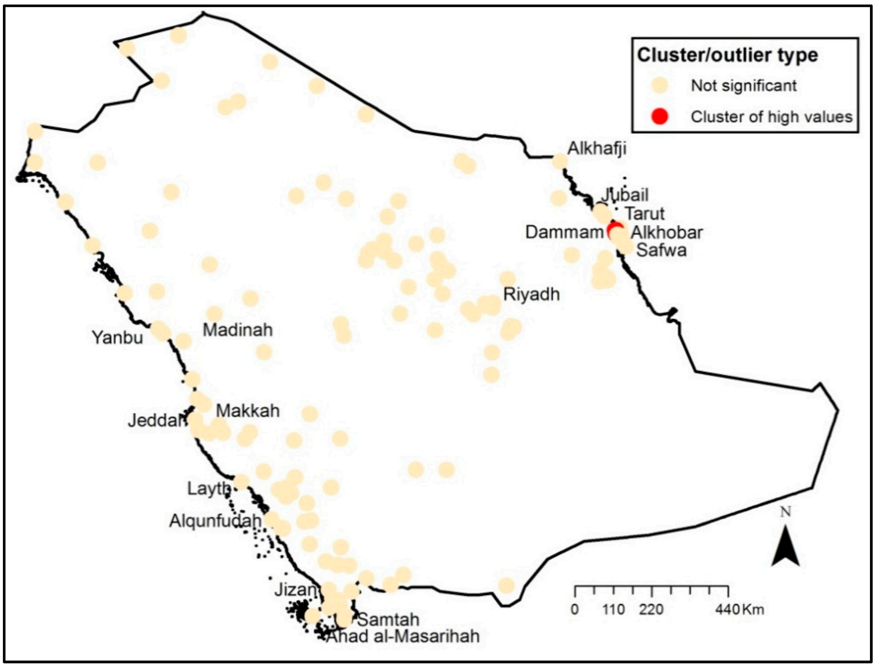

Figure 6. Clusters of $PM_{2.5}$ values over Saudi Arabia – 1999

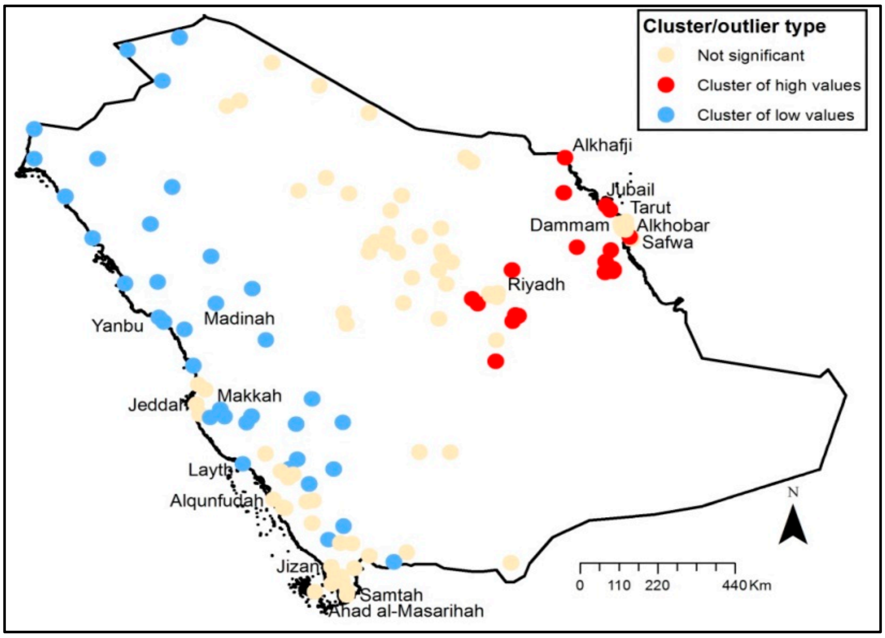

Figure 7. Clusters of $PM_{2.5}$ values over Saudi Arabia – 2011

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As regard the SOM analysis, the result depicts four clusters (Figure 8). The clusters of high values are depicted in the eastern and the south-western part of the country. The clusters of low values are highlighted in the western and north-western part of the Kingdom. Some of the high concentrations of particulate matter might be due to natural factors such as sandstorm. It is noticeable from figure 8 that the "empty quarters" or the Rub'al Khali desert that is virtually uninhabited is included in the cluster of high values.

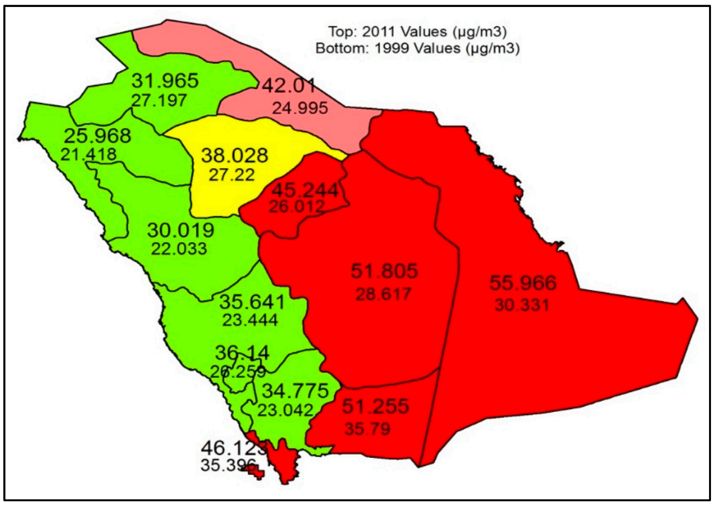

Figure 8. Regional clusters of PM2.5 values over Saudi Arabia (1999-2011)

Conclusion

The study reexamines the $PM_{2.5}$ concentrations over Saudi Arabia using the new global satellite-derived data. It highlights the differences between the previous version of the data and the new version. Though the new version has some data gaps, it capable of depicting the particulate matter concentrations of the Kingdom. It is probably more accurate than the previous version due to the higher values derived for Saudi cities. Aina et al. (2014) opined that the earlier version might have underestimated particulate matter concentrations. As regard the concentrations over Saudi Arabia, an increasing trend has been observed in all the

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cities and regions. Further research can be carried out to validate and improve the accuracy of the values derived for Saudi Arabia. Other satellite data, such as nighttime data, can be combined with particulate matter data to ascertain the effects of economic activities and urban expansion on particulate matter concentrations.

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