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## Air Quality Assessment over Sudan using NASA Remote Sensing Satellites Data and MERRA-2 Model

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### ARTICLE DETAILS

#### Article history:

Received 05 October 2020

Accepted 27 November 2020

Available online 15 December 2020

#### Keywords:

Aerosols

Satellite Data

Giovanni Tools

Reanalysis Data

### ABSTRACT

Satellite remote detecting instruments have been to a great extent used to evaluate air pollutants on the ground and their impacts on human wellbeing. These instruments play an essential job by assessing emanations and air quality models yield. The study concentrated on the analysis of monthly data for the period January 2003 -December 2016 using remote sensing technology and via satellite data products for NASA's Earth navigation satellite. The tools used are Medium Resolution Imaging Spectrophotometer (MODIS), Multi-angle Imaging Spectrophotometer (MISR), the Ozone Monitoring Instrument (OMI), and the Retrospective Analysis of Modern Times for Research and Applications, Version 2 (MERRA-2). Sudan is influenced by airborne particles because of its diverse climate systems, which differ from the desert in the north to poor savanna in the center and to rich savanna in the south. The impact of air pollution is obvious during these years in Sudan. Likewise, OMI trace gas vertical column observations of nitrogen dioxide (NO<sub>2</sub>) watched higher convergences of tropospheric column NO<sub>2</sub> in 2016 than in 2005 over Khartoum that recommends NO<sub>x</sub> emissions have increased in the city over this time period. The most elevated grouping of dust, a particulate matter (PM<sub>2.5</sub>), observed in March 2012 over Khartoum state. The highest concentration of sulfur dioxide (SO<sub>2</sub>) saw by MERRA-2 over Kuwait and South Sudan during December 2015. Noteworthy centralization concentration of black carbon observed over Iraq, Egypt, Central Africa, and South Sudan in December 2015. The most contamination from carbon monoxide watched by MERRA-2 over Iraq and north of Uganda during December 2014.

### 1. Introduction

Human and plant health, in general, relies upon the living conditions encompassing it [1-6] and strongly on the states of air and water quality. The aerosol effect is twofold [5]. The immediate impact is the result of retention and scattering of daylight and infrared radiation. The backhanded effect changes the presence of clouds and the characteristics of cloud condensation. The aerosol is a complex and dynamic mixture of solid and liquid particles from natural and human sources. Natural aerosol, such as fog, forest waste, and geysers vapor, is present in the absence of any human activity, while artificial aerosol, such as dust, air pollutants and smoke, is dominated by human sources. They are emitted directly into the atmosphere or can be formed in the atmosphere by condensation, which is called secondary atmospheric air such as sulfates. The indirect effect of atmospheric air is on the climate by scattering light and changing the reflection of the Earth. Its global impact is usually in opposition to greenhouse gases and causes cooling.

The atmospheric composition of the air quality satellite data has been focused in this paper: aerosol optical depth (AOD), [6], particulate matter (PM<sub>2.5</sub>), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>) and carbon monoxide (CO) [7, 8]. There are many studies in various topics of the use of remote sensing data for air quality applications, such as to measure air pollutants using satellite platforms [9-11], and the use of satellites for estimating air pollutants emissions [12, 13].

Aerosols optical depth is defined as a degree to which aerosols prevent the transmission of light by absorption or scattering of light through the entire vertical column of the atmosphere from the ground to the satellite's sensor [14]. There are also many applications of atmospheric optical depth data: atmospheric correction of remote-sensed surface characteristics, monitoring of atmospheric sources and basins, observation of volcanic eruptions, forest fires, radiation transport model, air quality, health, environment, Earth radiation, and climate change.

AOD derivatives are derived from several sources, including reflection from the Advanced Very High-Resolution Radiometer (AVHRR), [15], reflection from MODIS on Terra (2000 to present) and on Aqua (2002 to date), [16, 17], AOD retrieval from MISR and sunny desert areas [18], as well as direct AOD measurements from Earth Aerosol Robotic Network (AERONET) [19]. A new infrastructure system is designed to help a wide range of users worldwide to access and evaluate data [20]. The NASA Goddard Earth Data and Services Center (GES), whose ultimate goal is to provide scientists and users with a simplified way to access, evaluate and explore NASA satellite data sets, began to be developed by Giovanni in GES DISC [21], which are mainly concentrated in the study of areas of atmospheric composition, atmospheric dynamics, global rainfall, hydrology, and solar radiation.

Sudan, which is located in northeastern Africa, lies between latitudes 8° and 23°N. The terrain is generally flat plains, broken by several mountain ranges. Its neighbors are Chad, the Central African Republic to the west, Egypt and Libya to the north, Ethiopia and Eritrea to the east, South Sudan to the south, with an area of 1,886,068 km<sup>2</sup>. It is the third-largest country on the continent (after Algeria and the Democratic Republic of the Congo) and the sixteenth-largest in the world. Khartoum, the capital, is located in central Sudan at the confluence of the White Nile with the Blue Nile to form the Nile, which flows northwards through Egypt to the Mediterranean Sea. Sudan's climate is diverse, including a desert in the north, a poor savanna in the middle and a rich savanna in the south, with a dry season occurring during the winter. The amount of rainfall increases towards the south. Desertification is a problem in Sudan, which is rarely influenced by climate change. This result is similar to the findings of many previous studies have been published for Africa [22-26], and for the Middle East [27-29].

The overall objectives of this work are: (1) to identify sites with the highest levels of pollution and (2) to use time series analysis to identify sites that have statistically significant trends and (3) to determine the size of trends.

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## 2. Experimental Methods

### 2.1 Satellite Observation Data

Satellite remote sensing has been used to monitor regional air quality where earth observation stations are not available or sparsely distributed [30–34]. A useful training on how to use remote sensing instruments for air quality are freely available from NASA Applied Remote Sensing Training (ARSET); (<http://arset.gsfc.nasa.gov/>). MODIS [30, 35] provides the vast majority of AOD observations that are included in MERRA-2, especially after 2002, when data from both Terra and Aqua satellites became available. Prior to 2000, AVHRR reflections on the ocean were only used in MERRA-2 [36]. AOD for both MODIS and AVHRR is derived from cloud reflections using a neural network procedure obtained in AERONET measurements [37]. By construction, these AOD retrievals are unbiased with respect to AERONET observations. AOD from MISR and AERONET notes are used without bias correction.

### 2.2 MERRA-2 Model Description

MERRA-2, a retrospective analysis of modern times for research and applications, is one of the most recent models of atmospheric analysis in our modern era, produced by NASA Global Modeling and Assimilation Office (GMAO) [38]. The MERRA-2 analysis is a key step towards an integrated analysis of terrestrial systems, which includes aerial, marine and land observations, by providing an accurate and consistent scientific description of the state of the Earth system and how it is currently evolving.

Production of MERRA-2 began in June 2014 in four processing phases, which were reduced to one in mid-2015. It was produced using the GEOS-5 Atmospheric Model, and from the data collection system [39], 3DVAR analysis and Network Statistical Interpolation Scheme (GSI) and Meteorological Analysis Scheme [40, 41]. In addition to meteorological observations, MERRA-2 now includes the absorption of AOD at 550 nm from various platforms [37].

### 2.3 Giovanni Data Summary

Giovanni was initiated and developed for faster and easier access to data sets at the GES DISC after collecting and analyzing feedback from user support [21, 42]. Users have access to commonly practicing analytical methods and visualization, various search capabilities and file formats that support GIS data exploration. Analysis, and also choice of tools, spatial or temporal accuracy, or other categories based on the satellite mission (TRMM, GPM), or from the rest of the satellites included in the multipurpose web. Input and output data can easily be downloaded. All data files included in the Giovanni can easily be downloaded and the output image formats are PNG, GeoTIFF and Keyhole Markup Language (KMZ). All input and output data are available in the Network Common Data Form (NetCDF) formats, which can be handled by many off-the-shelf software packages.

## 3. Results and Discussion

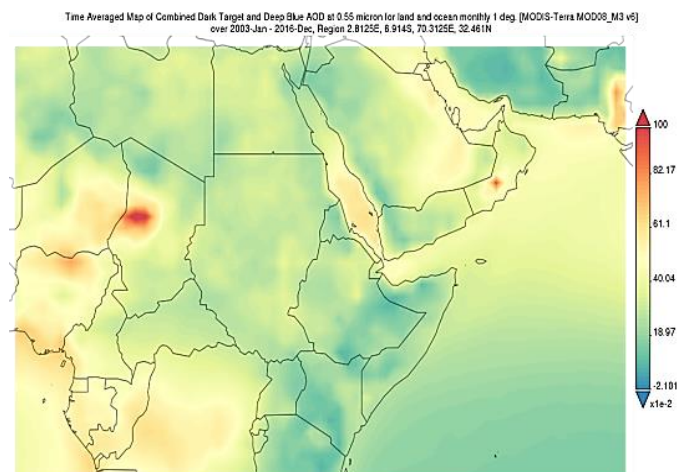
### 3.1 Aerosol Optical Depth (AOD)

Fig. 1(a) shows the AOD map using the MODIS-Terra instrument (Combined Dark and Deep Blue, version 6, Global Level 3 Aggregates  $1^\circ \times 1^\circ$ ) averaged in the period from January 2003 to December 2016, over a region encompassing Sudan.

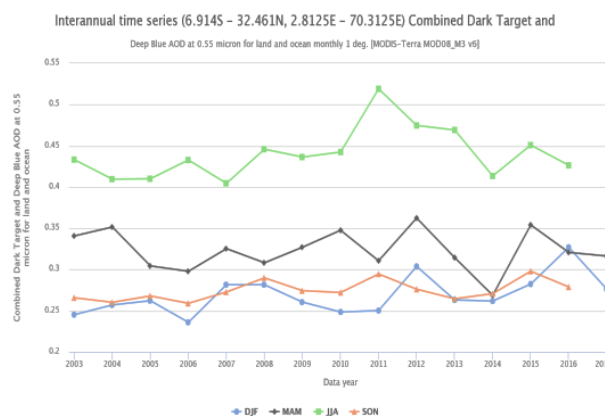
Fig. 1(b) shows the time series of seasonal averages over the same period and region (with the months represented by the first letter). Enhanced AOD values are observed in the South-West of Sudan and over the Arabian Peninsula. The highest peak is located over Lake Chad, due to the chemical pollution caused by industry, mining, agriculture, and also due to the lack of shrinks according to high levels of evaporation during the dry season. Regarding the seasonal cycle, the highest AOD is reached during summer ( $\sim 0.45$  of the combined dark target and deep blue AOD), the lowest in autumn and winter ( $\sim 0.25$ ).

The period with the highest AOD is the summer of 2011 ( $> 0.5$ ). The year 2014 is characterized by relatively low values both in summer and spring. A more detailed analysis of the years 2011 and 2014 is carried out in what follows, together with the year 2015, which is regarded as representative of an "average year".

The Model AOD has broadly the same features of the observations, but has generally lower values and less steep gradients, especially over hot spots such as over Lake Chad. The annual and seasonality are also well reproduced by the model, with lower values in autumn and winter, intermediate values in spring and higher values in summer. The highest peak in the series is in the summer of 2011, as in the observations. <https://doi.org/10.30799/jespr.207.20060302>



**Fig. 1(a)** Map of AOD at 550 nm from MODIS/Terra (Combined Dark Target and Deep Blue retrievals) in a region encompassing Sudan, averaged over the years from 2003 to 2016

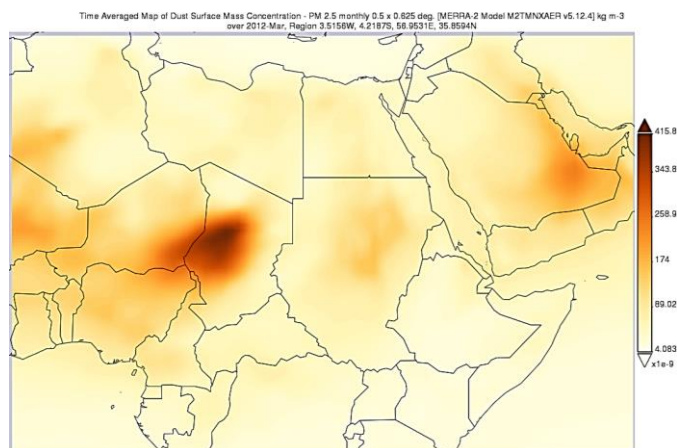


**Fig. 1(b)** A time series of a seasonal average of AOD from MODIS/Terra averaged over the same region. The highest peak is in July 2011. Created by: (<https://giovanni.gsfc.nasa.gov/giovanni>)

### 3.2 Particulate Matter ( $PM_{2.5}$ )

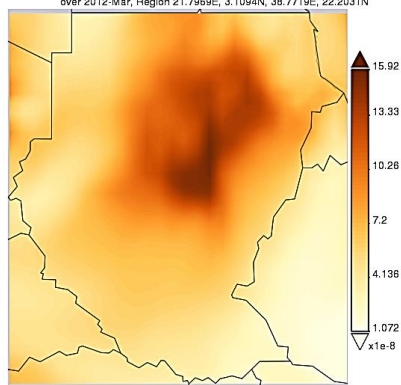
Particulate matter (PM) air pollution includes  $PM_{2.5}$ , which is known as atmospheric aerosol particles with aerodynamic diameter  $\leq 2.5 \mu\text{m}$  and  $PM_{10}$ , which is known as atmospheric aerosol particles with aerodynamic diameter  $\leq 10 \mu\text{m}$ . The World Health Organization (WHO) designates airborne particulates are the most harmful form of air pollution due to their ability to penetrate deep into the lungs and bloodstreams unfiltered, causing heart attacks, respiratory disease, and premature death, particularly  $PM_{2.5}$  regarded as deadly [43], with a 36% increase in lung cancer per  $10 \mu\text{g}\cdot\text{m}^{-3}$  as it can penetrate deeper into the lungs [11, 44]. The highest pollution observed in this study in March 2012 was over Lake Chad, as shown in Fig. 2(a), with a maximum value of  $66.3 \mu\text{g}\cdot\text{m}^{-3}$ .

In Sudan, most pollutants are due to dust storms and grassland fires. The hot spot observed over the northern part of Sudan including Khartoum state, as shown in Fig. 2(b), in March 2012 with  $62 \mu\text{g}\cdot\text{m}^{-3}$ .



**Fig. 2(a)** The averaged monthly of dust surface map concentration over a region including Sudan, in the period March 2012

Time Averaged Map of Dust Surface Mass Concentration - PM 2.5 monthly 0.5 x 0.625 deg. [MERRA-2 Model M2TMNXAER v5.12.4] kg m<sup>-3</sup> over 2012-Mar, Region 21.7969E, 3.1094N, 38.7719E, 22.2031N

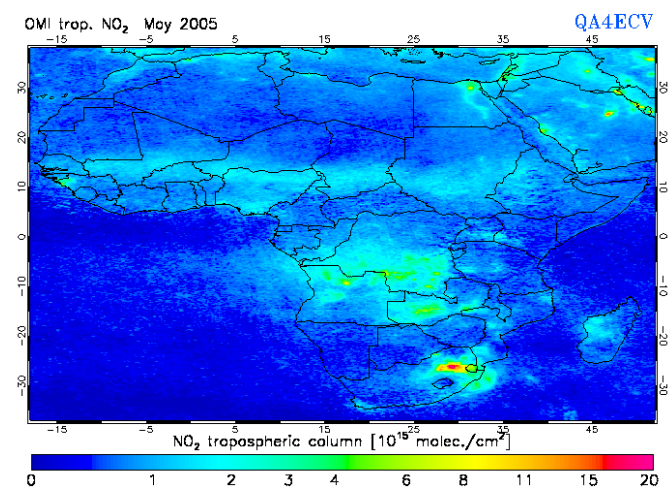


**Fig. 2(b)** The averaged map of dust surface mass concentration over Sudan for the period of March 2012

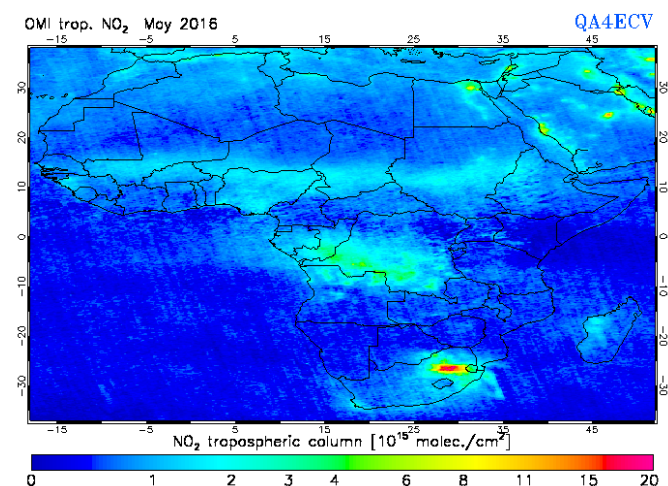
### 3.3 Nitrogen Dioxide (NO<sub>2</sub>)

The most prominent sources of NO<sub>2</sub> are internal combustion engines burning fossil fuels. Outdoors NO<sub>2</sub> can be a result of traffic from motor vehicles as emissions from cars, trucks and buses, power plants, and off-road equipment. Indoors, exposure arises from cigarette smoke, and butane and kerosene heaters and stoves [45]. It's toxic gas and increased respiratory symptoms in people with asthma and plays an important role in absorbing sunlight and regulating the chemistry of the troposphere, especially in determining ozone concentrations.

The Ozone Monitoring Instrument (OMI) trace gas vertical column observations of nitrogen dioxide (NO<sub>2</sub>) observed higher concentrations of tropospheric column NO<sub>2</sub> in 2016, Fig. 3(b), than in 2005, Fig. 3(a), over the Eastern part of South Africa, and over Khartoum that suggests NO<sub>x</sub> emissions have increased in the city over this time period. Data has been obtained from NASA Air Quality Applied Sciences Team (AQAST); (<http://acmg.seas.harvard.edu/aqast/>).



**Fig. 3(a)** The monthly satellite map of nitrogen dioxide observed by OMI in May 2005



**Fig. 3(b)** The monthly averaged map of nitrogen dioxide observed by OMI for the same region in May 2016

<https://doi.org/10.30799/jespr.207.20060302>

Cite this Article as: Muntasir A. Ibrahim, Gabriele Curci, Farouk I. Habbani, Air quality assessment over Sudan using NASA remote sensing satellites data and MERRA-2 model, J. Env. Sci. Pollut. Res. 6(3) (2020) 438–441.

### 3.4 Sulfur Dioxide (SO<sub>2</sub>)

It is a toxic gas and produced biologically as an intermediate in both sulfate-reducing organisms and in sulfur-oxidizing bacteria by volcanoes, coal, and petroleum in various industrial processes [46]. Higher concentrations observed over the Arabian Peninsula megacities in December 2015, and the highest concentration observed over Kuwait with a value of 0.92 μgm<sup>-3</sup>. In Sudan highest pollution observed up to the border with Uganda, for the same time and period, with a value of 1.08 μgm<sup>-3</sup>.

### 3.5 Carbon Monoxide (CO)

Carbon monoxide is colorless, odorless, and highly toxic [47]. It is produced from the partial oxidation of carbon-containing compounds; it forms when there is not enough oxygen to produce carbon dioxide (CO<sub>2</sub>). In the atmosphere, carbon monoxide is produced from the burning of fossil fuels and biomass, and most of it comes from the chemical reactions with organic compounds emitted by human activities and plants. The higher pollution is observed over Iraq and north of Uganda during December 2014 with a value of 121.10 ppbv. High concentration over South Sudan during December 2014, with a value of 148.62 ppbv.

### 3.6 Black Carbon (BC)

It is harmful to human health, and plays an important role by absorbing sunlight and reduces the planetary albedo when suspended in the atmosphere, and also indirectly causes changes in the absorption or reflection of solar radiation through changes in the properties and behavior of clouds [48]. The most polluted areas observed are over Iraq, Egypt and Central Africa during December 2015 with a value of 0.49 μgm<sup>-3</sup>. The highest pollution observed over South Sudan in December 2015, with a value of 0.65 μgm<sup>-3</sup>.

## 4. Conclusion

Using observations of satellite remote sensing instruments and MERRA-2 model to assess air quality, to specify the distributions and concentrations of AOD, PM<sub>2.5</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, and BC over Sudan and the neighboring countries. The main conclusions are listed as follows. Enhanced AOD values are observed in the South-West of Sudan and over the Arabian Peninsula. The highest peak is located over Chad, associated with Lake Chad. The highest AOD is reached during summer (~0.45), the lowest in autumn and winter (~0.25). The period with the highest AOD is the summer of 2011 (>0.5). Model AOD has broadly the same features of the observations, but has generally lower values and less steep gradients, especially over hot spots such as over Lake Chad. The seasonality is also well reproduced by the model, with lower values in autumn and winter, intermediate values in spring and higher values in summer. The highest peak in the time series of the model is in the summer of 2011 as in the observations. OMI satellite observed higher concentrations of tropospheric column NO<sub>2</sub> in 2016 over Khartoum, Sudan that suggests NO<sub>x</sub> emissions have increased in the city over this time period. MERRA-2 model observed increase of dust, with the highest concentration of PM<sub>2.5</sub> observed over Lake Chad and Khartoum, Sudan in March 2012. The highest concentration of sulfur dioxide observed by MERRA-2 is over Kuwait and South Sudan during December 2015. Highest pollution from carbon monoxide observed by MERRA-2 is over Iraq and north of Uganda during December 2014. The most polluted areas of black carbon observed by MERRA-2 are over Iraq, Egypt, Central Africa and South Sudan during December 2015.

## Supplementary Materials

Contact Corresponding Author to get more details about the results.

## Acknowledgment

This work was supported by the Ministry of Higher Education and Scientific Research of Sudan, the University of Blue Nile (Sudan), the University of L'Aquila (Italy), and the International Center for Theoretical Physics (ICTP) through the Training and Research in Italian Laboratories (TRIL) and Associate Scheme visiting programs. Many thanks to NASA for providing the observation satellite data through Giovanni tools.

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