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Evaluation of the WRF/Chem aerosol models - a dust episode case study

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Abstract

Presented herein is an analysis of an intensive dust intrusion of 8-11 February, 2015. The intrusion has been associated with the development of an intense front over the Middle East. During the episode, dust concentrations in Ahvaz air quality monitoring station in south-western Iran (Khuzestan region) reached over 10000 μg/m3, which was beyond the capacity of air quality sensors to be recorded. In this paper, the performance of WRF/Chem modelling system was evaluated for the west and southwestern Iran as well as the whole model domain. MADE and GOCART models as the main aerosol models implemented in WRF/Chem V3.6 were verified by ground observation data for the specific points. We have taken into account the advantages and disadvantages of MADE and GOCART aerosol models over the study period, by comparing the simulations' results for the specific points with the available dust concentration data. The time series of the area-average of modeled dust column mass density over the test area determined a coherent temporal variation with that of MERRA-2 model which shows the sensitivity of WRF/Chem modeling system for this area with most frequent dust storm events in the Middle East. The validation of WRF/Chem V3.6 modeling system results for the overall model domain is implemented using Hovmoller diagrams. The modeled latitude-average of dust column mass density for the whole model domain showed some discrepancies of dust transport pattern with the results of MERRA-2 model. Although there is a considerable difference between the modelled dust concentrations and the observations especially on the peak values, the temporal variations of the modelled dust concentration with MADE aerosol model is quite consistent with the observations. The results of MADE aerosol model for the dust concentration were more close to the observations of the points inside Khuzestan and surrounding low level plains with aeolian soils. The GOCART aerosol model had more reasonable simulation results for the points through the mountainous terrains of western Iran. It can be concluded that the structure of MADE and GOCART aerosol models can be revised with regard to their relative advantages in specific regions to minimize the error in modeling dust behavior. Scince this study has been employed on a dust episode, and considering that the gaseous air pollutants require the emissions data, the simulations of the gaseous aerosols has not been considered in this study. However, the results of the WRF/Chem model for the dust aerosols could be extended to the other aerosols, especially PM10 and PM2.5 particles.

Keywords: WRF/Chem, Dust, Aerosol models, Middle East

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1 Introduction

In recent decades, sand and dust events are frequent in the Middle East. Western parts of Iran and the alluvial plains of Tigris and Euphrates rivers in Iraq have been experiencing frequent sand and dust storms annually. Various reasons are suggested for this phenomenon, such as soil erosion and degradation, poor hydrological management, and climate change and global warming (Yu et al., 2015). Many dust sources such as Arabian Desert and alluvial and sedimentary basins in Iraq and western Iran have occupied vast parts of the Middle East acting as major sources of dust emission (Prakash et al, 2015). Modelling the atmospheric particulate matters is a crucial task to determine the behavior of sand and dust storms. Numerical air quality modeling can help recognizing various specification of dust storms as well as developing warning systems in order to decrease the damages. Numerical models simulate the transport of dust through the atmosphere by discretizing and solving equations of motion in the atmosphere and parameterizing dust emissions, (In & Park, 2003).

Various numerical schemes can be implemented to simulate the behavior of the particulate matters and their relevant processes such as gravitational settling or wet deposition (Zakey et al., 2006). Simulation and prediction of the air quality is a complicated task including both meteorological factors (e.g. wind and planetary boundary layer) and chemical processes (e.g. aerosol deposition and transport). In the real atmosphere the chemical and physical processes such as the radiation budget and the interaction of aerosols with cloud condensation nuclei are coupled with each other (Grell et al., 2005).

Until recently, modeling of the regional air quality and atmospheric chemistry were mostly performed with offline models. In the offline air quality models, the output of the meteorological model for wind field at the first stage is used as the input or driver of the chemistry transport model in the second stage (Forkel et al., 2014). The model WRF as one of the main atmospheric numerical models could be coupled offline with many air quality models such as CMAQ or CALPUFF. Online coupled meteorology and chemistry models can lead to more accurate predictions in the air quality modeling by considering the impacts of particulate matters on the meteorological variables and vice versa (Baklanov et al., 2014; Grell and Baklanov, 2011). Modeling indirect aerosol effects on cloud microphysics is the important capability of the chemistry-meteorology models (Forkel et al., 2014).

One of the difficulties in evaluating the dust events is lack of the observational data with an appropriate spatial and temporal resolution. Ground-based remote-sensing observations of AERONET networks (http://aeronet.gsfc.nasa.gov) which is a federation of regional networks based on the photometric instruments located at ground stations (currently, more than 400 stations worldwide) for monitoring atmospheric aerosols, including atmospheric mineral dust has high density of the stations over Europe, the Americas and East Asia, but the two most important dust sources in the world (northern Africa – Sahara – and West Asia) have very few photometers. Focusing on West Asia, there is poor, unevenly distributed, network coverage and does not cover dust hotspots and many large cities affected by sand and dust storms (WMO No. 1121, 2013). Satellite data (METEOSAT Dust RGB images) have also been used to determine the geographical regions which have been exposed to the dust storm in this case study. In this study, WRF/Chem online coupled modelling system is implemented for dust transport simulation. The meteorology and chemistry components in WRF/Chem share the same schemes in transport of mass, horizontal and vertical grid distances and temporal resolutions, and physics schemes in the model domains (Fast et al. 2006). The surface resistance is calculated with regard to the characteristics of the soil and plant canopy. The WRF preprocessing system (WPS) geographical input data contains several required data sets for modeling processes such as dust erosion data besides sand and clay fraction data which are crucial in an atmospheric dust modeling (Peckham et al. 2011). The parameterization of the surface resistance is developed by Wesley (1989) and the surface resistance itself depends on the other parameters including sub - layers and aerodynamic resistance. Apart from investigating a dust episode and the model's capability in estimating the simulated dust concentration, this article presents various evaluations methods which could create a precedent for the other studies.

Khuzestan province with more than 4.5 million people is the important and densely populated region in the southwestern Iran which suffers from frequent dust storms annually. Due to the geological aspects of western and southwestern Iran and eastern and southeastern Iraq, which are covered dominantly with alluvial plains and dry deserts with vast areas of unconsolidated sediments, aeolian processes have the major role in dust emissions in this region (Alijani et al, 2016). The intensive dust intrusion of 7 -11 February 2015 was of such intensity that led to the closing of many offices and governmental organizations besides other adverse impacts it inflicted on the local society. During this event the dust concentration in Ahvaz air quality monitoring station reached over 10,000 μg/m3 which was beyond the capacity of the recording sensors. Wu et al. (2017), evaluated the WRF/Chem simulations of the aerosol seasonal variability in California with the aid of satellite data and in situ observations, and found that aerosol modeling is sensitive to model horizontal resolution, with better simulations at 4 km resolution than lower values, which is mainly due to the better representation of the emissions and precipitations in the 4 km simulations.

In the flowing sections, the methodology and the model results will be discussed. In the methodology section, a brief description of the general atmospheric conditions and some model setups are provided. The WRF/Chem capabilities in aerosol modeling are discussed afterwards. In the results section, the WRF/Chem outputs are visualized and verified with the other dataset.

2 Methodology

In this section, the model's configurations and set-up, as well as some general atmospheric conditions and geographical features used in the model have been investigated.

2.1 General atmospheric conditions and model setup

Khuzestan province, which is depicted in the model domain (Figure. 1) is generally a low land on the southwest of Iran, i.e. the extension of the southern Mesopotamia inside the borders of Iran. Khuzestan as well as the other parts of southeastern Iraq consists of vast alluvial and flood plains which classify them as regions with considerable fluvial and aeolian processes (Baltzer et al., 1990).

Using the Era-Interim dataset, 850 hpa and 500 hpa maps of temperature and the geopotential contours over the region of the study have been depicted in Figurer 2, determining the synoptic conditions leading to the studied dust episode. Era-Interim is a global atmospheric reanalysis from 1979, which is going to be replaced by a newer version, called Era5.

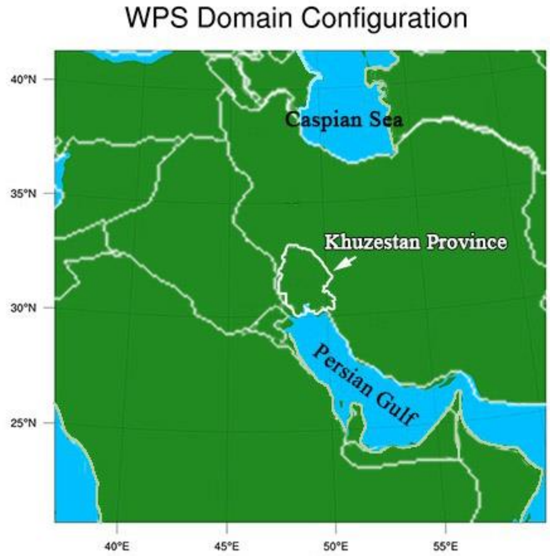
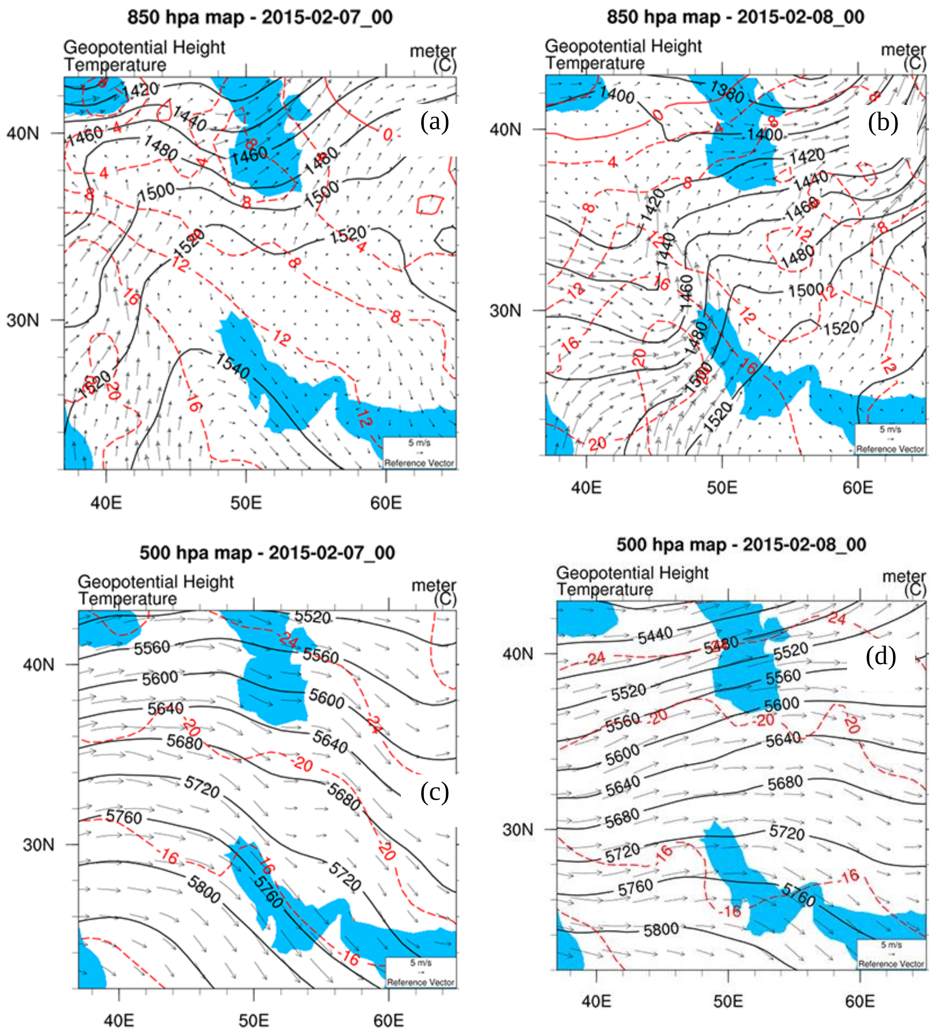


Figure 1. WRF model domain with the location of Khuzestan province.



Figurer 2. Era-Interim 850 hpa and 500 hpa map for the first two days of the period 7-10 Feb 2015, leading to the dust events.

Figurers 2a and 2b show the 850 hpa maps of the geopotential and temperature contours on 2015-02-07_00 and 2015-02-08_00, respectively. Formation of a trough in west and southwest of Iran is evident in Figurer. 2b, which causes a rise in the wind speed. Figures 2c and 2d show the 500 hpa maps of the geopotential and temperature contours. In Figure. 2d, the pattern of the geopotential lines with larger gradients leads to higher wind speeds in comparison to the previous day, shown in Figure 2c.

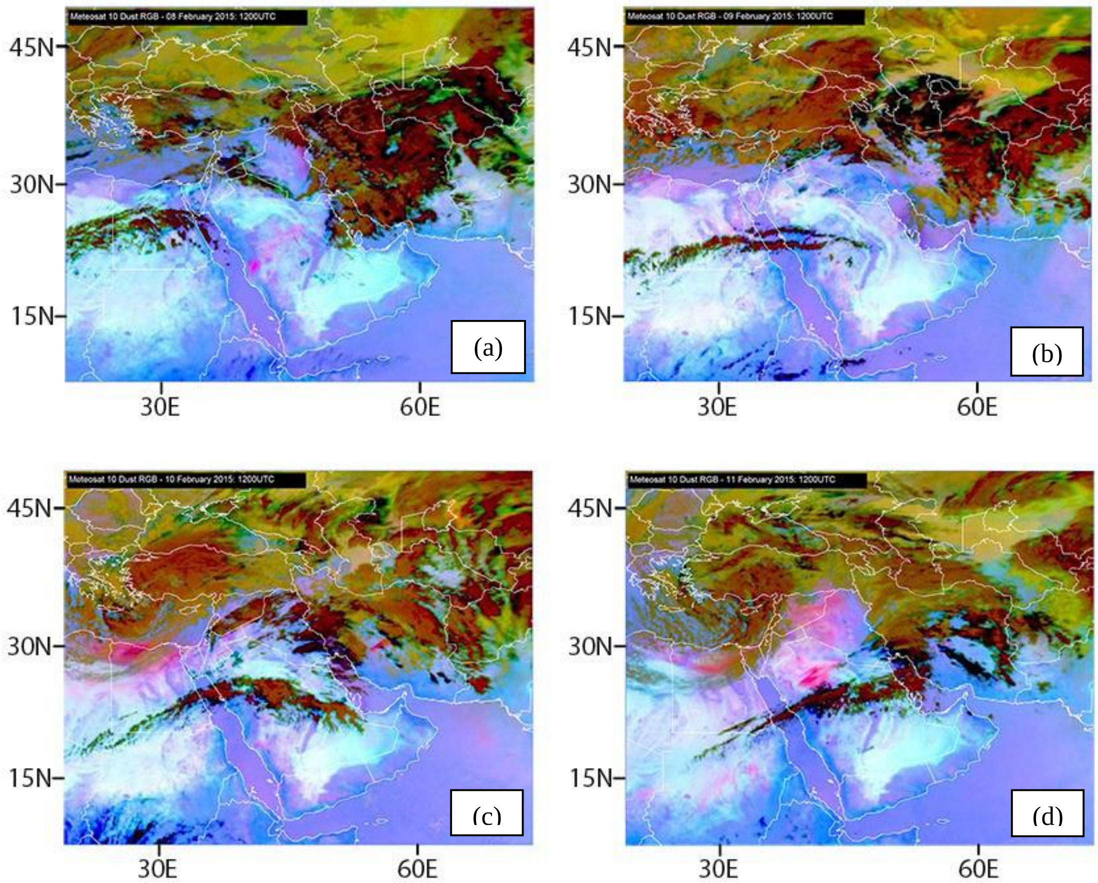


Figure 3. METEOSAT satellite images depicting dust over the study region for (a) Feb 8, (b) Feb 9, (c) Feb 10, and (d) Feb 11, 2015.

With regard to the soil classifications by the United States Department of Agriculture (USDA), the soil texture (clay mineralogy) of the alluvial plain of the rivers Tigris and Euphrates (Figure. 4) is capable to be a source of dust emission. More details about the top soil categories of WRF modeling system are listed in table 1. Since soil texture is a determining factor in dust flux, different aerosol schemes could show different results.

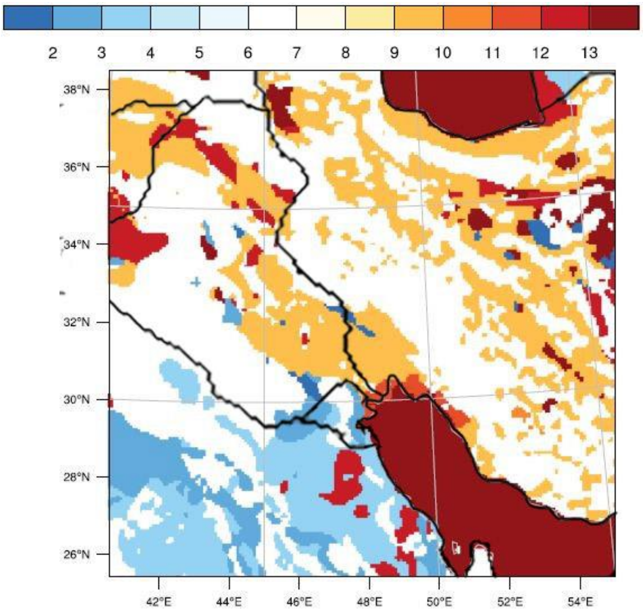


Figure 4. Dominant soil categories of USDA soil texture classification.

Table 1. WRF top soil classifications

ID	1	2	3	4	5	6	7	8
Description	Sand	Loamy Sand	Sandy Loam	Silt Loam	Silt	Loam	Sandy Clay Loam	Silty Clay Loam

9	10	11	12	13	14	15	16
Clay Loam	Sandy Clay	Silty Clay	Clay	Organic Material	Water	Bedrock	Other (land-ice)

The "short-time" winter shamal is relatively common and occurs 2–3 times a month. When a cold front becomes stationary over the region, however, the dust outbreaks can last 3–5 days (Perrone, 1979). Following the EUMETSAT dust RGB images shown in Figure 3, the dust exposure has ceased. These processes can be simultaneously verified by the rise and fall in dust concentration diagrams of Ahvaz station in Khuzestan province.

In general the frontal dust pattern is especially noticeable on the second and fourth days of simulation causing dust emissions in southern Iraq as well as west and southwestern Iran. These regions with high dust column mass density are depicted in Figure. 5 using the Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) dataset with a global reanalysis to assimilate space-based observations of aerosols. MERRA (Reichle et al., 2017; Suarez et al., 2015; Takacs et al., 2014) is a NASA reanalysis project for satellite data using the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5) (Reichle et al., 2017; Suarez et al., 2015; Takacs et al., 2014). The original version of MERRA assimilates only meteorological parameters such as winds and temperature using Goddard Aerosol Assimilation System (GAAS) whereas MERRA-2 includes the assimilation of bias-corrected Aerosol Optical Depth (AOD) from major space-borne sensors such as AVHRR, MODIS, MISR, as well as AERONET AOD data.

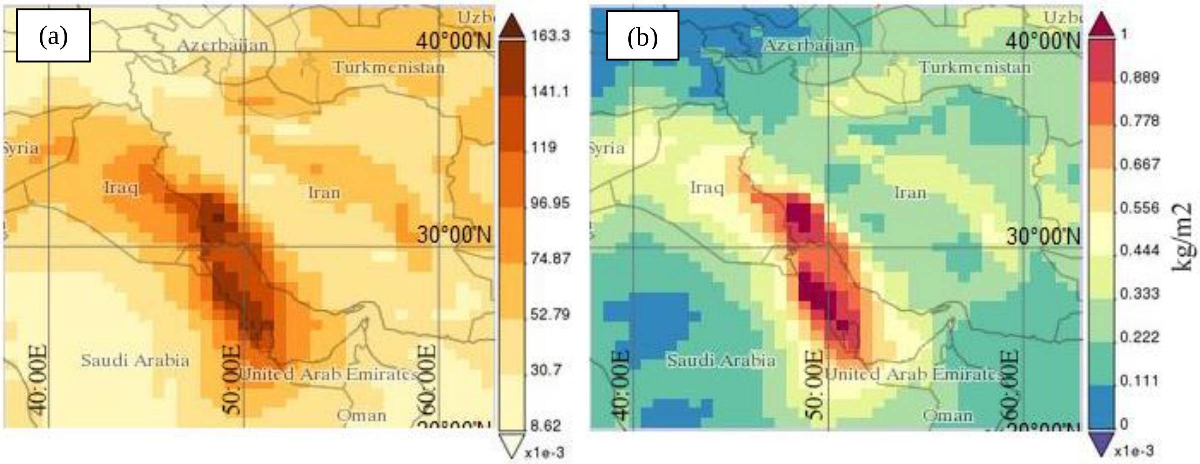


Figure 5. MERRA-2 Model time average map over Region 38E, 20N, 63E, 42N for (a) Dust Scattering AOT 550 nm - PM 1.0 µm, and (b) Dust Column Mass Density, 2015-02-07 00Z - 2015-02-11 23Z.

The locations of the air quality stations with available data (PM10 concentration) as well as the test area (45E, 29N, 51E, 35N) for the evaluation of WRF/Chem results are shown in Figure. 6. These stations are selected through the west and southwest of Iran, which according to Figurers 1 and 5 are exposed to the highest dust concentrations over the studied period.

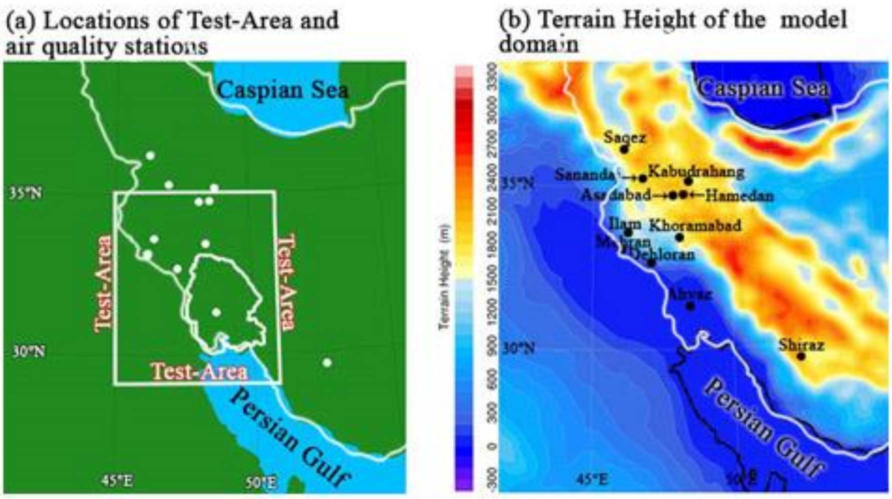


Figure 6. (a) Locations of the Test-Area (45E, 29N, 51E, 35N) and the air quality stations, and (b) Terrain height of parts of the model domain used in the evaluation of WRF/Chem results.

2.2 Aerosol models and numerical simulation

Modeling atmospheric aerosols requires the modeling of planetary boundary layer and atmospheric microphysical processes. The modal and sectional aerosol models are two major approaches commonly used in the air quality models to represent the particle size distribution. In the modal approach, the particle size distribution is approximated by several modes, and particle properties are assumed to be uniform in each mode (Salma et al., 2002; and Voutilainen et al., 2002). In the sectional approach, the size distribution is classified into specific sections, and the properties of the particulate matters in each section are assumed to be nearly constant (Park et al., 2002; and Frederix et al., 2016). This assumption is necessary for the simplification of aerosol modeling (Zhang et al. 2015). In this study, the WRF Single-Moment 5-class is employed for cloud microphysics scheme which considers mixed-phase processes. Furthermore, the Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model (Ginoux et al, 2001) and The Modal Aerosol Dynamics Model for Europe (MADE) (Schell et al., 2001) as the main aerosol models in WRF/Chem are applied for the modeling of dust transport. The Advanced Research WRF (ARW) dynamical core considers several approaches including model initialization, boundary conditions, physics options, and grid-nesting techniques in the numerical modeling (Skamarock et al. 2008). Physical and PBL parameterization is required for the modelling of small scale processes such as the precipitation which generally cannot be numerically discretized by the model.

MADE aerosol model is a modification of the Regional Particulate Model (Binkowski and Shankar, 1995). As a complementary component, Secondary Organic Aerosols (SOA) has been incorporated into MADE aerosol model by means of the Secondary Organic Aerosol Model (SORGAM) (Schell *et al.*, 2001). MADE is a modal model describing the Aitken mode (nucleation mode <0.1 μm diameter), the accumulation mode (0.1-2 μm), and the coarse mode (>2 μm) by log-normal distributions.

In MADE aerosol model, the distribution of the aerosols with regard to the particle size is represented by two log-normal distributions, showing each mode as follows:

$$n(lnd_p)\frac{N}{\sqrt{2\pi}ln\sigma_g}exp\left[\frac{-1}{2}\frac{\left(lnd_p-lnd_{pg}\right)^2}{ln\sigma_g{}^2}\right] \quad (1)$$

Where N is the number of concentration [m^{-3}], d_p the particle diameter, d_{pg} the median diameter, and σ_g the standard deviation of the distribution (Ackermann et al., 1998).

In the GOCART aerosol model as a sectional model, 5 effective radii for dust particles (0.5, 1.4, 2.4, 4.5, and 8 μm) are included in the aerosol modeling. The accumulation of the dust concentrations of all 5 dust bins can be represented as PM10 concentration in the case of sand and dust storms (Mashayekhi et al., 2010). Dust flux, F_p in the GOCART model is approximated formulas by equation (2):

$$F_p=\begin{cases}CSs_pu_{10m}^2(u_{10m}-u_t) if u_{10m}>u_t\\ 0 otherwise\end{cases} \quad (2)$$

In the above equation, C is constant, S corresponds to the fraction of the alluvial soils and erodibility, s_p is the fraction of each size bins, u_{10m} and u_t are the horizontal wind speed at 10m and the threshold wind speed, respectively.

Geological and terrain features, such as the soil texture and land use are the leading causes of dust emission in the Middle East. The role of geological patterns and aeolian processes besides the meteorological conditions in lifting dust particles over the model domain is inspected in this study. The performance of WRF numerical model in wind simulation has a vital role in dust emission and consequently influences the model results for the dust concentrations (Mattar et al., 2016; Carvalho et al., 2012).

Two methods are employed for the evaluation of the WRF/Chem model output. The modelled dust concentration in the specific points is compared with the available ground data in western parts of Iran which is exposed to the dust storm. The ground based observations are obtained from the Iranian Department of Environment. Moreover, the hourly variations of the dust column mass of the "Modern-Era Retrospective analysis for Research and Applications, Version 2" (MERRA-2) is compared with the WRF/Chem output for modelled dust behavior. Figure. 5 depicts the dust storm event of 7 to 11 February 2015 by time averaging maps of the MERRA model for (a) dust scattering AOT 550 nm and (b) dust column mass density over the region. As shown in Figure. 5, the accumulation of the dust particulates are significant in the west and south-west of Iran for this dust episode between 7 and 11 February 2015.

In this study, by implementing WRF/Chem v3.6.1 modelling system and using the Global Forecast System (GFS) data with a resolution of 0.5° in geographical scale and 10×10 kilometers for the model grid spacing, the numerical modelling of the dust concentrations is carried out. The number of the grid points is set to 228 for west-east and south-north directions, with 30 vertical levels. The model domain is part of the Middle East, which encompasses western Iran and Khuzestan province. WRF/Chem is an online-coupled modelling framework which simultaneously models both meteorological processes and atmospheric chemical reactions. The chemical part of the model is compiled simultaneously as a separate program with the main WRF model. It consists of several modules capable of modeling and parameterizing the chemical processes in the atmosphere.

A four-day period of the simulation has been run by the model WRF/Chem and the output was compared with the observational data, measured by meteorological stations, located in Ahvaz (The capital of Khuzestan) and several other stations along western and south-western Iran. The running start time of the model has been set before the occurrence of the dust episode. The near real and historical GFS data with 0.5° × 0.5° spatial resolution were provided from National Oceanic and Atmospheric Administration (NOAA) National Operational Model Archive & Distribution System (http://nomads.ncdc.noaa.gov/). The WRF horizontal grid spacing is set to 7km with 105 hours of the simulation between 7 and 11 February 2015. Khuzestan province and western Iran is in the center of the model domain.

The physics option for the planetary boundary layer was set to YSU (Yonsei University) (Hong, Noh and Dudhia, 2006). RRTM (Rapid Radiative Transfer Model) scheme was chosen for the long wave radiation and Goddard shortwave scheme (Two-stream multi-band scheme with oz one from climatology and cloud effects) for the short wave radiation. Noah land surface model was the scheme for the Land Surface physics option which is a Unified NCEP/NCAR/AFWA (National Centers for Environmental Prediction, National Center for Atmospheric Research, and Air Force Weather Agency, respectively) scheme with soil temperature and moisture in four layers. The physics options were chosen by default. Spin up time is included in the run process, by setting the start time a day before the dust outbreak.

3 Model results and discussion

A comparison of the results of the two aerosol models (GOCART and MADE) of WRF/Chem modelling system for surface dust concentration and the results of MERRA model for dust column for the 8th of February is shown in Figure. 7. The spatial variation of dust concentrations of GOCART and MADE aerosol models are almost consistent with the pattern of dust column mass of MERRA model. Both aerosol models in the WRF/Chem modelling system show the maximum dust concentrations on the western parts of Iran. According to Figure. 7, the temporal variation of dust concentrations for

GOCART and MADE aerosol models have a logical consistency with the results of MERRA model (maximum values on 2015-02-08_15:00:00 UTC). It should be mentioned that Figure. 7 is used to compare the dust spatial pattern which for the most cases is concentrated near the surface. Therefore the column mass of dust in a good approximation could be a representative of dust concentration on the surface.

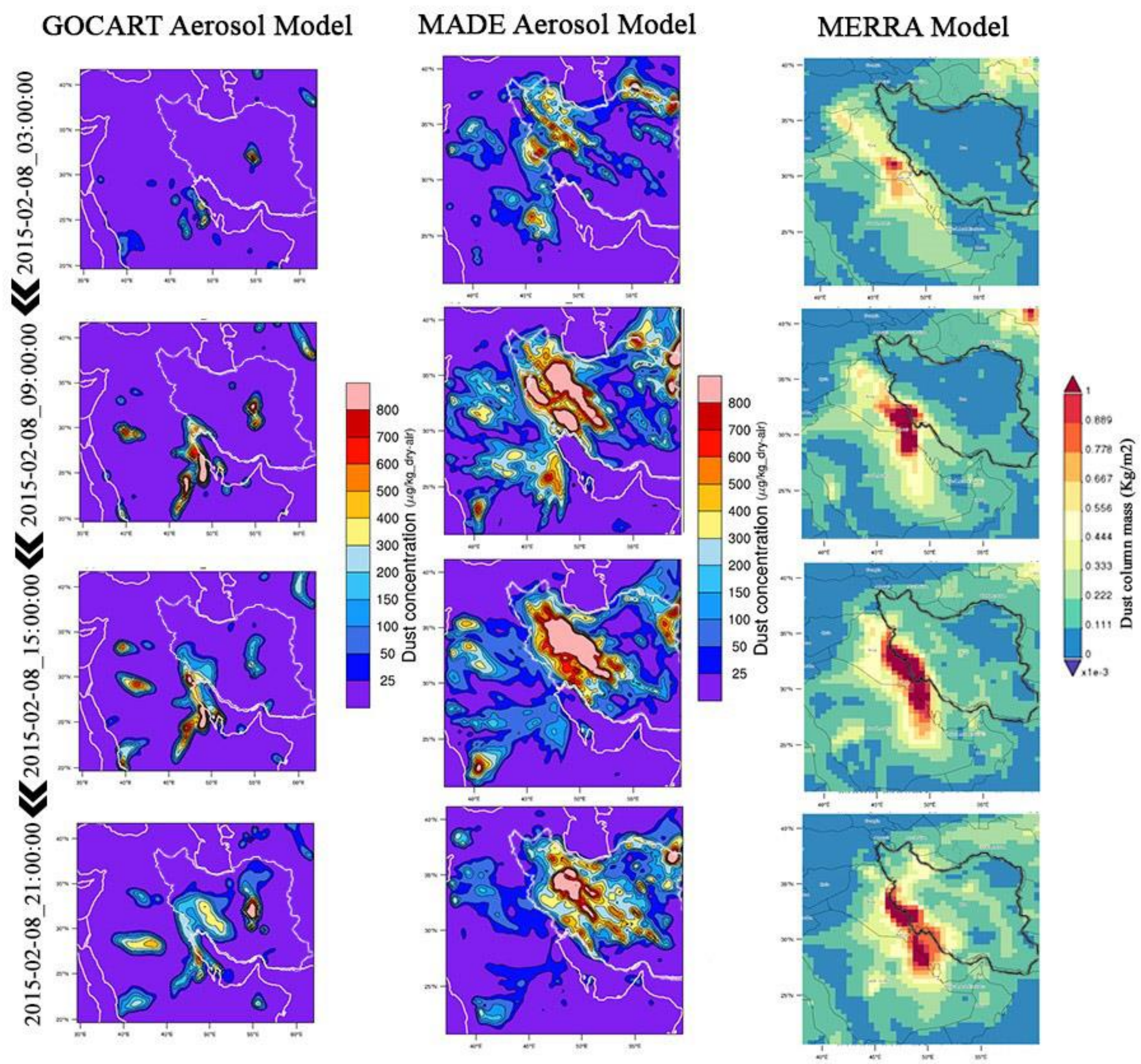


Figure 7. Results of WRF/Chem surface dust concentrations and MERRA-2 dust column mass during a period of 2015-02-08_03:00:00 - 2015-02-08_21:00:00 UTC by 6 hour interval.

Due to the geographical and geopolitical importance of Khuzestan province and Ahvaz as a capital city, the comparisons of the modelled dust concentrations as the results of GOCART and MADE aerosol models with the ground observational data and visibility (for MADE aerosol model) for Ahvaz are shown in Figure. 8. Ground observations have been provided from the ground stations of the Iranian Department of Environment. The visibility data as a criterion for the air pollution level, have been provided from the Iranian meteorological organization. $\mu g/m^3$

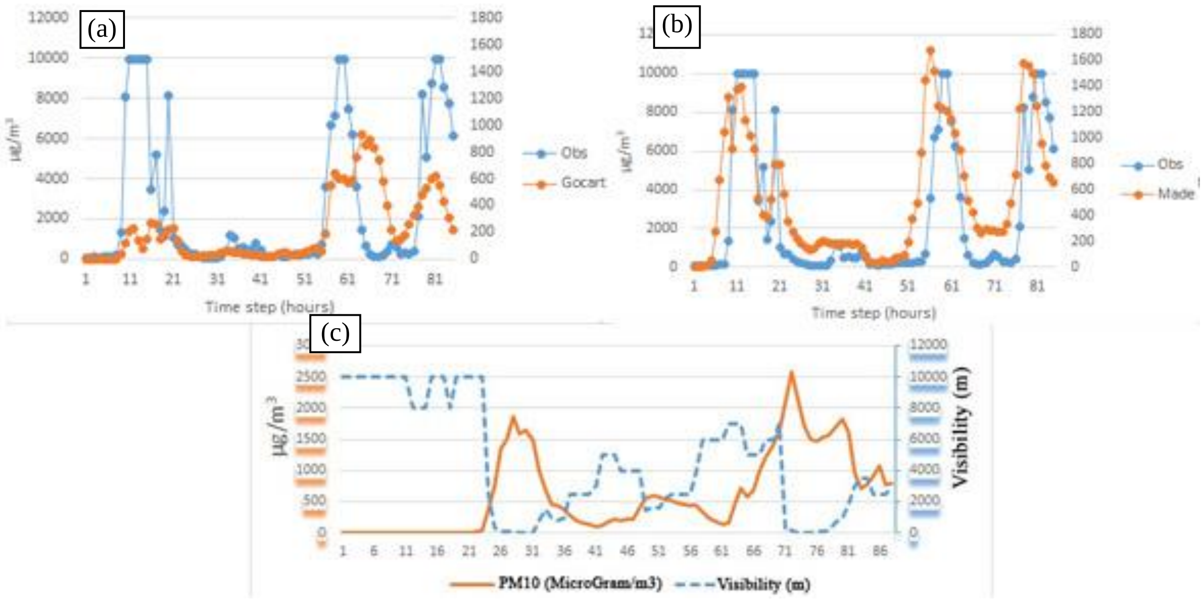


Figure 6. (a) GOCART Aerosol Model versus observations, (b) MADE Aerosol Model versus observations, and (c) MADE Aerosol Model versus visibility at the Ahvaz Station.

As shown in Figure. 8, although there is a considerable difference between the modelled dust concentrations and the observations especially on the peak values, the temporal variations of the modelled dust concentration with MADE aerosol model is quite consistent with the observations. Figurer 8c shows a high negative correlation between the modeled dust concentration and visibility in Ahvaz station. The difference between the modeled dust concentrations and the observations are obvious in the diagrams of Figure. 9.

Regarding the diagrams in Figure. 9, the results of MADE aerosol model are closer to the observed data rather than the GOCART aerosol model. The evaluations of WRF/Chem modelling system for other stations are shown in Figure. 9 which are orographically different from Khuzestan. Other stations are in a mountainous' terrain (Zagros Mountains), whereas Ahvaz station elevation is 20 meters.

Figurer 9 shows that the results of the modelled dust concentrations from MADE aerosol model for Ilam, Mehran, and Dehloran stations besides/together with Ahvaz station are closer to the observational dust concentrations rather than GOCART aerosol model which shows better simulations for other stations. The mentioned stations with better results for MADE aerosol model are located either totally outside the Zagros mountain range or at its boundary whereas the results of GOCART aerosol model determines more reliable results for the other stations by mountainous topography.

Another fact for the stations which show better results of MADE aerosol model rather than GOCART model, is the proximity of these stations to the massive erodible soils (Figure. 4) in west and southwestern Iran. This characteristic, besides the low elevation of this region, has a significant contribution to the better performance of MADE aerosol model in dust simulation in Ahvaz.

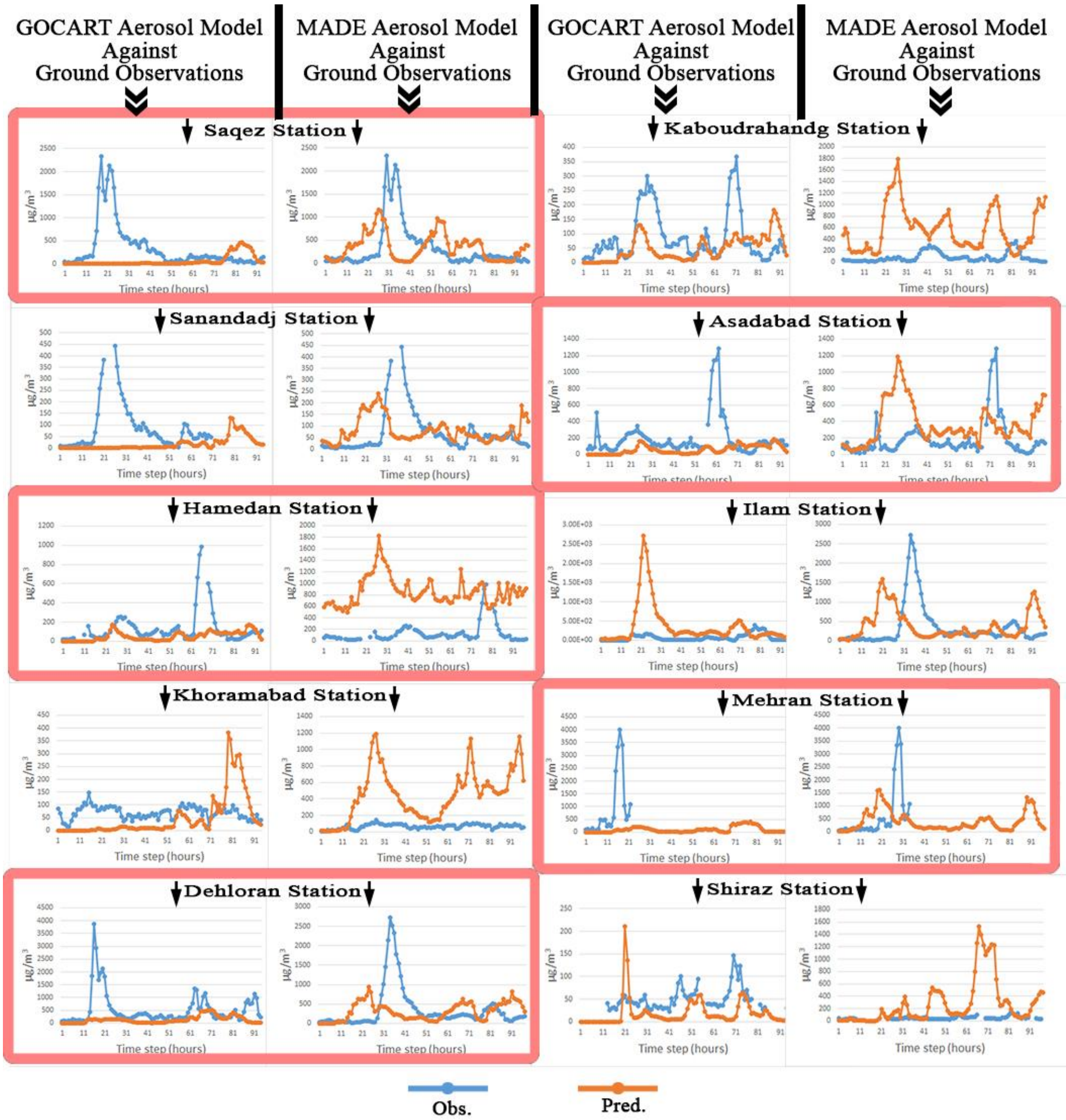


Figure 7. Comparisons of WRF/Chem modelled dust concentrations (GOCART and MADE Aerosol Models) versus ground based observations for different stations.

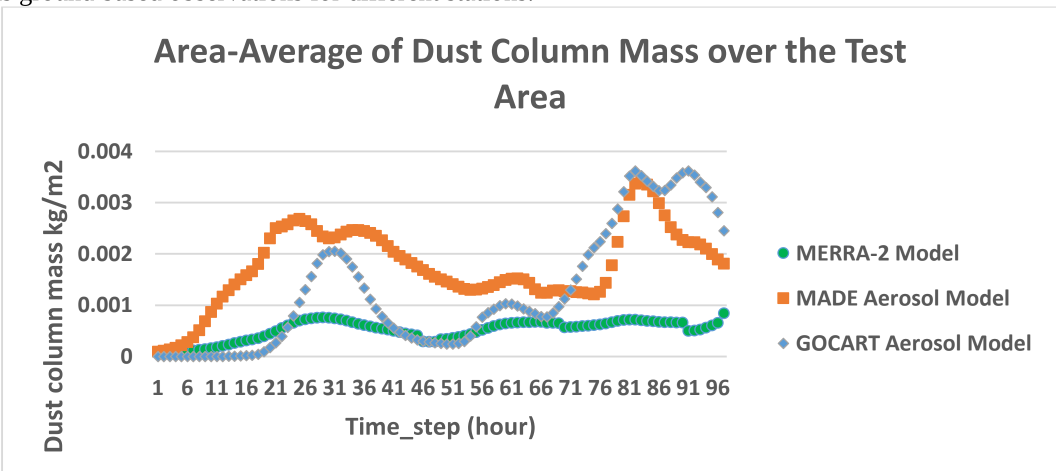


Figure 8. Time series of the area-average of dust column mass density for the modelled results (GOCART and MADE aerosol models) and MERRA-2 model over the region of the Test-area (45E, 29N, 51E, 35N), and during the WRF/Chem simulation area period (7 – 11 Feb 2015).

Figure 10 shows the area-averaged time series of dust column mass density over the test-area (Figure. 6) and compares WRF/Chem model results of the two aerosol models (GOCART and MADE) with MERRA-2 model. The examination of Figure. 10 shows a fairly consistent manner in temporal variations of the modeled time series (red and blue diagrams) of dust column mass density with the results of MERRA-2 model. Apparent discrepancies between WRF/Chem and MERRA-2 results on the peak values are found in Figure. 10 which are similar to Figurers 8 and 9 of the comparisons of the modeled results with the ground observations.

Figure 11 shows the Hovmoller diagrams of the latitude-average of the modeled dust column mass density of MADE and GOCART aerosol models as well as MERRA-2 model towards the zonal direction of the simulation domain (38E to 60E) between February 7, 2015 and February 11, 2015). The general patterns of Figure. 11b and Figure. 11c show a fairly similar variation to that of MERRA model (Figure. 11a). The beginning of the dust storm is noticeable around 50E in Figurers 11b and 11c which is consistent with Figure. 11a of MERRA-2 model. According to Figure. 11b, high dust particulates of MADE aerosol model results are transported through the eastern model domain (from 50E moving to the east) over Zagros mountain ranges. This pattern is rather different from the results of GOCART aerosol model (Figure. 11c) which determines the maximum dust accumulations along 40E to 50E of the model domain. The patterns of Hovmoller diagrams of modeled dust column mass can be noticed in the results presented in Figurers 8 and 9 for the selected air quality stations over the western parts of Iran.

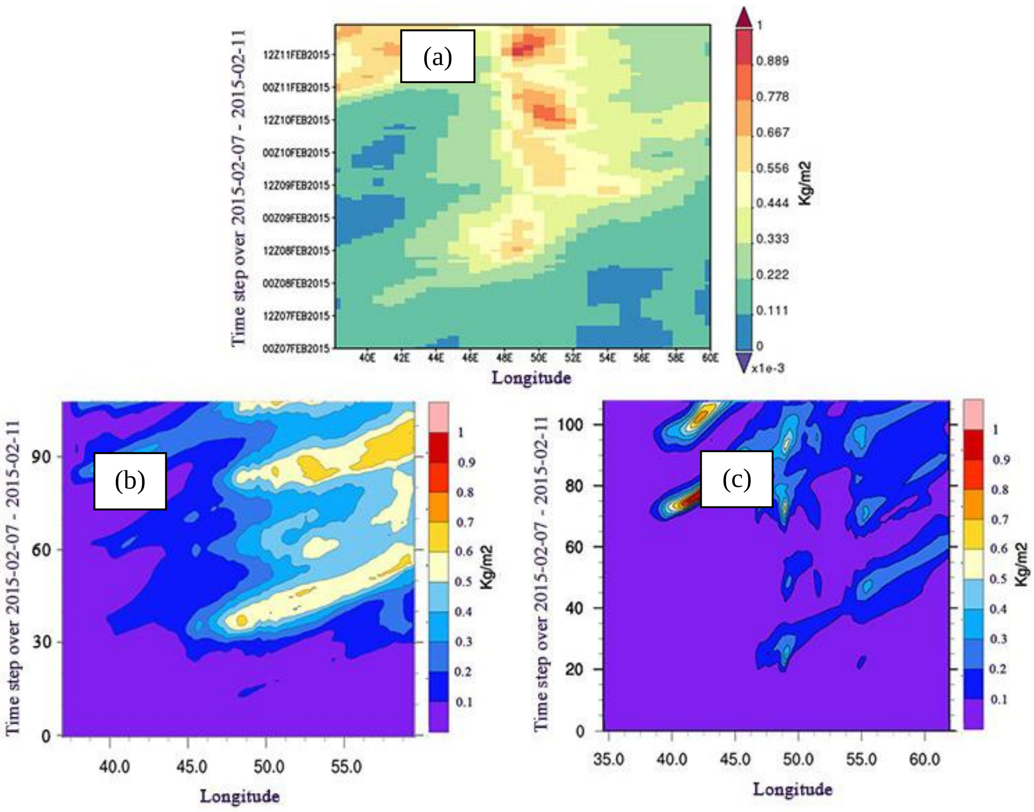


Figure 9. Hovmoller diagrams, Latitude-average of dust column mass density from 38E to 60E between 2015-02-07 and 2015-02-11, for (a) MERRA-2 model, (b) WRF/Chem, MADE Aerosol Model, and (c) WRF/Chem, GOCART Aerosol Model.

Our comparisons showed that for the flat terrains of Khuzestan and its neighboring regions along the western boundary of Zagros Mountains with an erodible soil texture, the results of MADE aerosol model were more consistent with the observations; whereas, for the stations inside the regions of Zagros mountain ranges, GOCART aerosol model produced better performance in the simulation of the dust concentrations.

4 Conclusion

In this study we assessed the accuracy of two major aerosol models implemented in WRF/Chem V3.6 modelling system in the simulation of dust concentration of a dust episode, as a case study for western parts of Iran which are exposed to frequent sand and dust storms annually. Several verifications were performed in order to analyze the model results. We examined the results of MADE and GOCART aerosol models for dust concentrations in comparison to the ground observations as well as the assimilated satellite observations (MERRA-2 model) using several spatial and temporal analyses. Modelled dust concentrations have been compared with two kinds of dataset: the MERRA reanalysis data, and ground based observations.

The motivation of our study was to inspect the different results of MADE and GOCART aerosol models in relation to topographical features and the soil texture. The simulations' result for the specific points with the available air quality data were validated. We put forward the advantages and disadvantages of MADE and GOCART aerosol models for the model domain by comparing the simulations results of the specific points with the available dust concentration data. This difference is not necessarily due to the soil texture, but the aerosol models themselves employ different methods in the calculation of dust transport, which could be another cause of the the difference in the model results.

We considered a test area representing the region with the most dust column mass with regard to the real satellite data of MERRA-2 model. The time series of the area-average of modeled dust column mass density over the test area determined a coherent temporal variation with that of MERRA-2 model which shows the sensitivity of WRF/Chem modeling system for this area with the most frequent dust storm events in the Middle East. The validation of WRF/Chem modeling system results of the overall model domain is implemented using Hovmoller diagrams. The modeled latitude-average of the dust column mass density for the whole model domain showed some discrepancies of the dust transport pattern with the results of MERRA-2 model. Modeled dust column mass density by MADE model is accumulated on the eastern model domain which quantitatively makes considerable overestimations on the model results over the mountainous terrains of western Iran, whereas the results of GOCART aerosol model were relatively and quantitatively better representation for the behavior of dust simulation over the western mountainous regions of Iran.

In order to gain a more precise validation of WRF/Chem modeling system, our future studies would include the altering and correction of the soil texture which have a direct effect on dust emission leading to more realistic simulation of the dust concentration. Due to the complexity and long term projects of the correcting soil textures with field measurements, using statistical methods to improve soil classifications used in WRF/Chem modeling system is suggested. More fundamental works on the effects of various WRF planetary boundary layer parameterizations in wind field as a key factor in dust emission are among our future studies over the Middle East.

5 Acknowledgements

Analyses and visualizations used in this study were produced with the NCAR Command Language, the Giovanni online data system, and Meteosat Second Generation satellite data, which are developed and maintained by NASA GES DISC, UCAR/NCAR/CISL/TDD, and EUMETSAT respectively.

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