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Surface concentration values simulation using WRF models and GOCART scheme in southeast Iran (Case study: December 16-20, 2016 storm)

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A B S T R A C T

Blowing dust is one of the most common natural phenomena in arid and semi-arid regions, which causes a lot of damage every time it occurs. This phenomenon is introduced as a natural hazard in terms of negative effects in natural and human-managed ecosystems, and it is one of the most important problems of societies in arid and semi-arid regions. This research was simulated using the WRF-Chem model and GOCART scheme in the Jazmurian basin in southeast Iran to investigate and analyze this phenomenon. The results showed that the numerical simulation of the dust storm using the WRF-Chem model simulated surface dust concentration values UTC18 on December 17, 2016, in the south of Sistan and Baluchistan province and Hormozgan province were higher than 2500 μg/m^3, and more than 2000 μg/m^3 in the central areas of Jazmurian region. To prevent destructive dust storms and reduce the emission of dust in this region, international protocols are needed for the correction and rehabilitation of degraded lands and activities to prevent desertification to stabilize degraded soils.

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1. Introduction

Today, the phenomenon of dust is one of the basic problems of arid and semi-arid regions. Originating in source areas such as dry wetlands and rivers, dust, by affecting the human respiratory system, causes sometimes irreparable damage to health. The intensity and frequency of this phenomenon are increasing, which is closely related to climate change, as well as to changes in land cover and land use. Climate change includes global warming and changes in parameters such as precipitation and wind speed. These meteorological changes will affect the intensity and frequency of wind erosion and dust storms. The combination of the phenomenon of climate change with human activities increases soil degradation, wind erosion, and desertification, and the continuation of this process causes the loss of soil organic carbon and intensification of dust storms (Sun et al., 2003). It should also be kept in mind that climatic parameters have a great influence on many other indicators used in wind erosion models, including soil type (Matinfar and Maleki, 2011) and vegetation cover (Bayatmovahed, 2011). Climatic factors, particularly the presence of erosive wind, can increase erosion from sensitive surfaces. Increase in droughts as a result of climate change has caused a decrease in vegetation and soil moisture, which also favors wind erosion in the affected areas (Blanka et al., 2013; Mezosi et al., 2013).

As mentioned, the phenomenon of wind erosion occurs parallel to the dryness of the environment and the progress of desertification processes, which can be the result of global warming and climate change. The main sources of dust in Southwest Asia include the Sistan Basin on the border between Iran and Afghanistan, the Makran Plain along the coast of the Oman Sea, the plains of Pakistan to the northwest of India, and the Indian Basin (Alizadeh Choobari et al., 2012). Iran is subject to dust from many of these source regions, notably the Sistan Plain with an area of 15197 km^2 in the east of Iran (Amiraslani et al., 2018). This area has a hot and dry climate and suitable conditions for wind erosion, movement of sand dunes, and the occurrence of dust storms (Shahriar et al., 2018).

The maximum dust emission From the Sistan region in eastern Iran and southwestern Afghanistan and Pakistan occurs in the summer season and these storms load dust from local to regional scale (Rashki et al., 2012). Therefore, finding the origin of and predicting dust storms in this strongly affected region is of great importance. In order to achieve dust forecasts with high accuracy, the phenomenon must first be modeled. The modeling of atmospheric phenomena, including dust lofting and transport, is very complex due to their dynamic nature and the involvement of various factors. Weather models with different goals have been designed in the past to model these phenomena, but one of the most important disadvantages of these models is their limitation in considering all the effective factors, which sometimes causes the accuracy of the results to decrease. The basic output of weather models is atmospheric quantities and parameters, which alone are not capable of simulating and predicting quantities such as the concentration of suspended particles, air pollution, floods, sea waves, and to simulate such quantities, these atmospheric circulation models must be combined with other models such as for atmospheric pollutants, dust, etc. Such composite models can simulate and predict many cases of dust storms. The Weather Research and Forecasting Model (WRF) is a new-generation numerical weather forecasting system designed for research and operational atmospheric forecasting applications. WRF is the basis of the hybrid modeling system WRF-Chem, which can predict the concentration of suspended particles and air quality, which is created by combining WRF with a pollutant sector model.

Various studies including Sun et al., 2003, Song et al., 2007, Li and Zhang, 2014, Su and Fung, 2015, Munkhtsetseg et al., 2016, Teixeira et al., 2016, Nabavi et al., 2016, 2017, Kim et al., 2017, Rizza et al., 2018, Ju et al., 2018 and Tang et al., 2018 have been carried out with the WRF-Chem model used to simulate climate and atmospheric phenomena, especially dust and environmental pollutants. Also, Soni et al. (2022) estimated particulate matter pollution using WRF-Chem during a dust storm event in India. The results showed that the modeled aerosol optical depth (AOD) (MODELAOD) shows an underestimation by 37% with the value estimated from MODIS satellite sensor data (MODISAOD) over the study region. Therefore, the WRF-Chem model particulate matter (PM_{10}) and AOD were scaled using satellite MODISAOD to provide a better estimation of the particulate.

Thongsame et al. (2024) conducted WRF-Chem $PM_{2.5}$ simulations in Thailand with different anthropogenic and biomass-burning emissions. The results highlighted the challenge of capturing $PM_{2.5}$ diurnal variability, particularly due to inaccuracies in simulating the planetary boundary layer height during nighttime in complex terrains. Their analysis exhibited moderate model performance during the off-haze season while using global and regional anthropogenic emissions in Thailand, emphasizing the need for improving anthropogenic inventories for reliable air quality prediction.

Hassan et al. (2024) compared WRF-Chem model configurations for simulating the April 2022 dust episode in western Iran. They found that the combination of the YSU boundary layer and WSM6 microphysics schemes performed very well in simulating wind fields and dust in western Iran under various weather conditions. Given this previous work, this current research aims to simulate the dust storm of December 16-20, 2016 using the composite WRF-Chem model, focusing on the storm impacts in the Jazmurian basin.

This is very important numerically simulating the dust phenomenon accurately allows us to manage it better and reduce its harmful effects. Using a tool like WRF-Chem, it is possible to model the origins and peak times as well as the direction of dust movement.

2. Materials and Methods

2.1. Study Area

Jazmurian is an endorheic basin located in the provinces of Kerman and Sistan and Baluchistan with the coordinates of latitude 26° 33´ to 29° 36´ N and longitude 16° 56´ to 26° 61´ E and an area of 69374 km2. The average annual rainfall of this basin is about 172 mm. The height of the highest point of this range is 4359 m and the lowest point is 354 m above sea level (Ahmadi et al., 2019). Its lowest point is covered by a seasonal lake. In general, the formations of the studied area are from the Cenozoic era, with a lot of formations from the Quaternary and Tertiary periods. The main land uses include poor pastures and barren lands. It has dried out further in recent decades due to climate change, agricultural exploitation, and water diversion. The geographical location of the studied area is shown in Fig 1.

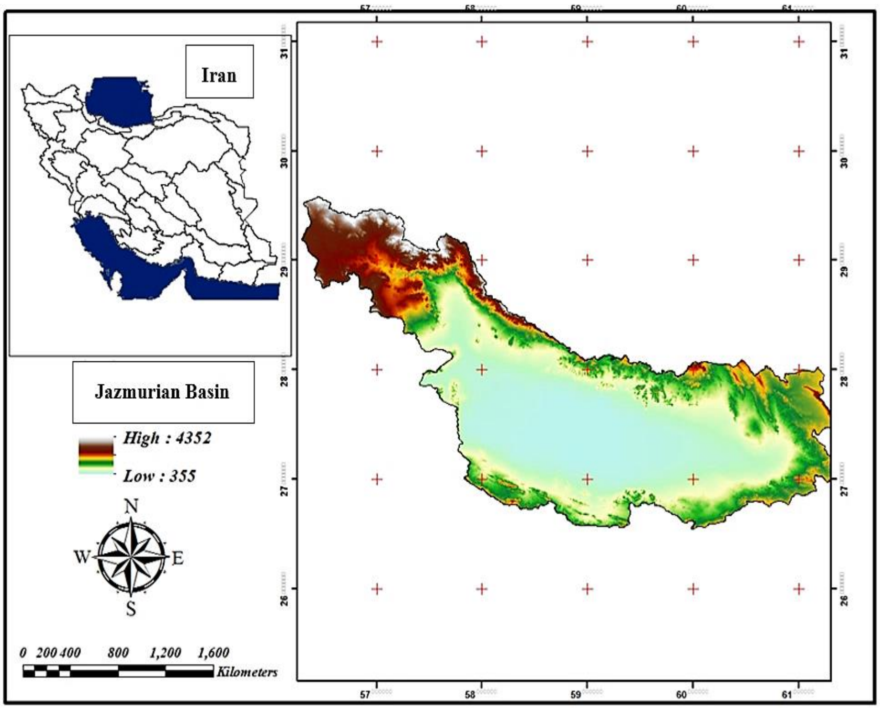

Fig. 1. Geographical location of the studied area.

2.2. Method

2.2.1. WRF-Chem

The WRF-Chem model, Version 3, is a state-of-the-art research and operational model for, among other things, simulating and predicting the concentration of air pollutants in the atmosphere caused by natural mechanisms and human activities. It can simulate the emission of dust in different size classes, and the way it spreads and deposits. The WRF-Chem model has diverse applications such as numerical weather forecasting, data evaluation studies, physical parameterization research, climate simulation, air pollution modeling, and coupled ocean-atmosphere systems, and its modular structure makes the model flexible to different input data and applications. The WRF-Chem model advanced numerical capabilities, and due to its higher resolution compared to typical global atmospheric models, it can simulate local effects more accurately Unlike most similar models, the WRF-Chem pollutant chemistry and transport model is coupled with an atmospheric model and calculates its required atmospheric quantities online (including their interaction with pollutants such as dust), so in addition to the quantities related to atmospheric chemistry, atmospheric quantities such as wind at the surface. It also provides pressure and geopotential height as the output of the model. The structure of the WRF-Chem model is shown in Fig 2.

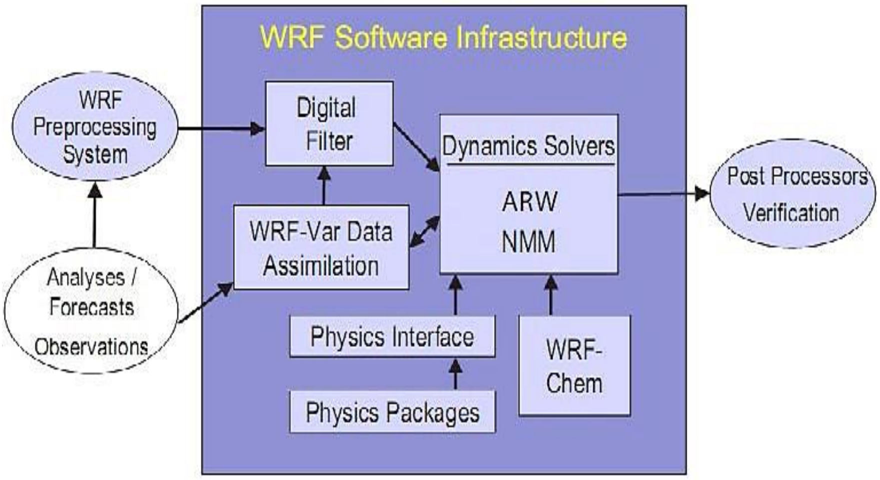

Fig. 2. Structure of the WRF-Chem model.

2.2.2. WRF-Chem model configuration

In this research, version 3.9.1 of the WRF-Chem model was used for the numerical simulation of dust storms. Boundary and initial conditions are obtained from the global climate model GFS (NOAA) with a horizontal resolution of 1°*1°. Static geographic data such as surface roughness height, soil characteristics, fraction of vegetation, and land use were used from United States Geological Survey (USGS) data. Table 1 shows the schematics and modules used in the implementation of the WRF-Chem model.

Table 1. of schemas used in the implementation of the WRF-Chem model.

WRF Single-Moment 5-class	Microscale physics
RRTM	Long wave radiation
Goddard shortwave	Short wave radiation
Noah Land Surface Model	Surface physics
YSU	Boundary layer
Grell 3D	Convection

2.2.3. GOCART dust Scheme

This scheme, used in WRF-Chem and other modeling frameworks, considers potential sources of dust based on erodibility. The vertical dust flux from the surface is calculated as follows (Eq. 1):

$$F_p = C_G S s_p U_{10}^2 (U_{10} - U_t\ ) U_{10} > U_t \qquad (1)$$

Where CG is an experimental constant and is equal to 1/9 (µgs^2)/m^5, U10 is the wind speed at 10 meters level, Ut* is the threshold speed for particle wind erosion of the size p, at speeds lower than which there is no emission, sp is the fraction of each category of dust, which is considered equal to 0.1 for the smallest particle size and 0.25 for other sizes. S is the erodibility function obtained by the following relation (Eq. 2):

$$S = \left(\frac{z_{max} - z_i}{z_{max} - z_{min}}\right)^5 \qquad (2)$$

In which, S is the probability of accumulation of sediments at point i of the network with height Zi. Zi is the height of the grid cell, Zmax and Zmin are, respectively, the maximum and minimum height of the topography at a distance of 10 degrees by 10 degrees from the center of the grid cell. In this scheme, five different sizes for spherical dust particles with radii from 0.1 to 10 micrometers are considered. The effective radii of the particles in each class are taken to be 0.73, 1.4, 2.4, 4.5, and 8 micrometers, respectively, and all calculations are done for each class separately.

3. Results and Discussion

Fig. 3 shows the surface concentration values of the WRF-Chem model simulated dust particles at 12 UTC on December 17, 2016. At this time, the simulated surface dust concentration in the south of Sistan and Baluchistan province and Hormozgan province is higher than 1600 µg/m^3, and in the eastern areas of the Jazmurian region, the dust concentration is higher than 1200 µg/m^3.

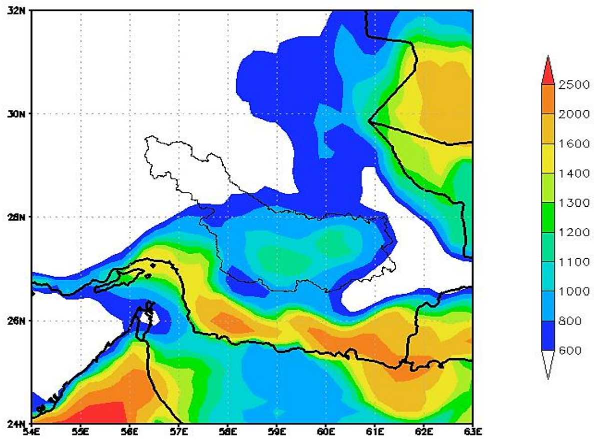

Fig. 3. Simulated surface concentration values (μg/m^3) of dust at UTC12 on December 17, 2016.

Fig. 4 shows the surface concentration values of the WRF-Chem model output at UTC18 on December 17, 2016. The surface dust concentration in the south of Sistan and Baluchistan province and Hormozgan province is higher than 2500 μg/m^3, and in the central areas of the Jazmurian region, the dust concentration is higher than 2000 μg/m^3. The concentration of dust shows a significant increase compared to 6 hours earlier.

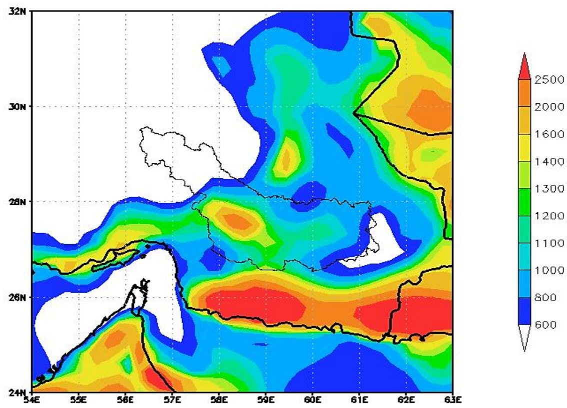

Fig. 4. Surface concentration values of WRF_Chem model output particles at UTC18 on December 17, 2016.

Fig. 5 shows the surface concentration values of the WRF-Chem model output at UTC00 on December 18, 2016. The surface dust concentration in the south of Sistan and Baluchistan province and Hormozgan province is still higher than 2500 μg/m^3, and in the central areas of the Jazmurian region, the dust concentration is simulated to be higher than 1400 μg/m^3, which is a decrease compared to the previous time shown.

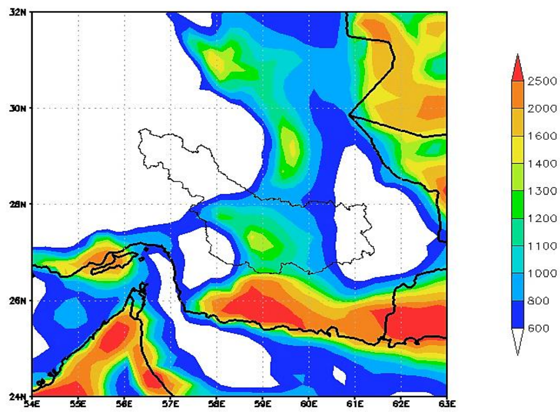

Fig. 5. Surface concentration values of WRF-Chem model output particles at UTC00 on December 18, 2016.

Fig. 6 shows the surface concentration values of the WRF-Chem model output particles at UTC06 on December 18, 2016. The area with a surface dust concentration higher than 2500 µg/m^3 has decreased in the south of Sistan and Baluchistan province and Hormozgan province, and in the central areas of the Jazmurian region, the dust concentration is simulated higher than 1000 µg/m^3, which is compared to the previous figure. It has decreased drastically in the Jazmurian region.

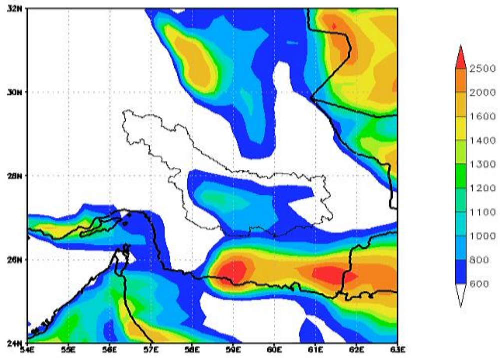

Fig. 6. Surface concentration values of WRF_Chem model output particles at UTC06 on December 18, 2016.

Fig. 7 shows the surface concentration values of the WRF-Chem model output at UTC12 on December 18, 2016. The surface dust concentration has been greatly reduced in the south of Sistan and Baluchistan province and Hormozgan province, except for the southern areas of the Jazmurian region where the dust concentration between 600 and 800 µg/m^3 has been simulated, while surface dust is not observed at the 600 µg/m^3 threshold in other areas of this region.

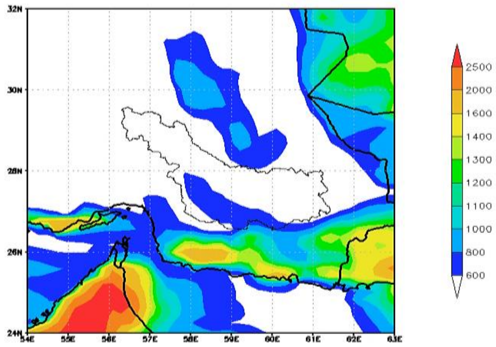

Fig. 7. Surface concentration values of WRF_Chem model output particles at UTC12 on December 18, 2016.

Fig. 8 shows the surface concentration values of the WRF_Chem model output particles at UTC18 on December 18, 2016. The surface dust concentration is higher in the south of Sistan and Baluchistan province and Hormozgan province compared to the previous Fig. Also, in most of the southern half of the Jazmurian region, the concentration of dust has exceeded 2500 µg/m^3.

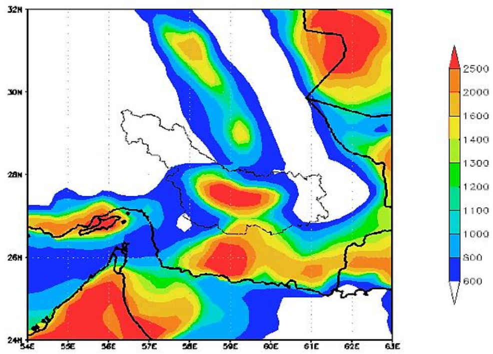

Fig. 8. Surface concentration values of WRF_Chem model output particles at UTC18 on December 18, 2016.

Fig. 9 shows the surface concentration values of the WRF_Chem model output at UTC00 on December 19, 2016. The surface dust concentration has increased in the south of Sistan and Baluchistan province and Hormozgan province compared to 6 hours ago. Also, the surface concentration of dust has increased in most of the central and southern areas of the Jazmurian region.

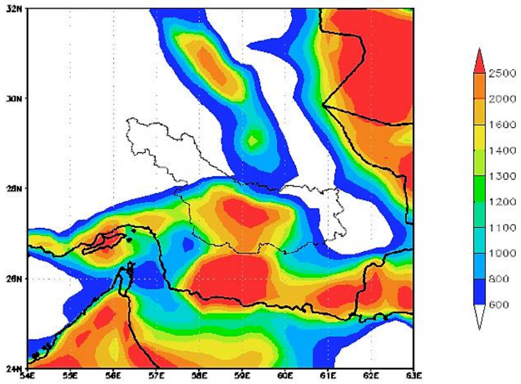

Fig. 9. Surface concentration values of WRF_Chem model output particles at UTC00 on December 19, 2016.

Fig. 10 shows the surface concentration values of the WRF_Chem model output at UTC06 on December 19, 2016. The surface concentration of higher dust in the south of Sistan and Baluchistan province and Hormozgan province has decreased in some places compared to 6 hours ago. Also, the surface concentration of dust in most of the central and southern areas of the Jazmurian region is greatly reduced.

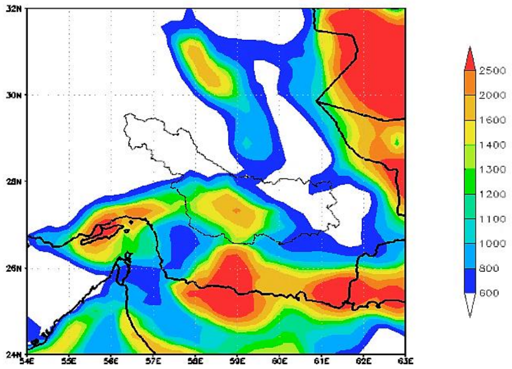

Fig. 10. Surface concentration values of WRF_Chem model output particles at UTC06 on December 19, 2016.

Fig. 11 shows the surface concentration values of the WRF_Chem model output particles at 12 UTC on December 19, 2016. The surface dust concentration is higher in the south of Sistan and Baluchistan province, while Hormozgan province and the Jazmurian region have decreased sharply. The dust concentration in the southern half of the Jazmurian region has reached below 1000 μg/m^3.

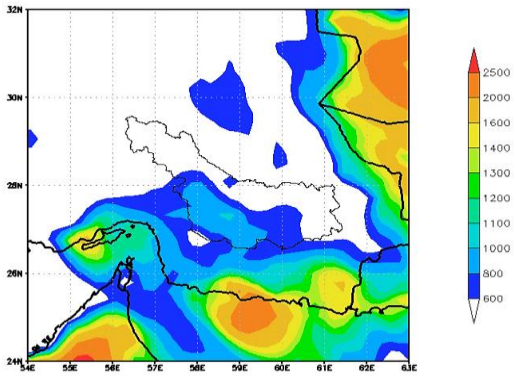

Fig. 11. Surface concentration values of WRF_Chem model output particles at UTC12 on December 19, 2016.

Fig. 12 shows the surface concentration values of the WRF_Chem model output particles at UTC18 on December 19, 2016. The surface dust concentration is higher in the south of Sistan and Baluchistan province, Hormozgan province and Jazmurian region has decreased sharply. The surface concentration of dust in the southern half of the Jazmurian region has reached below 1000 µg/m^3.

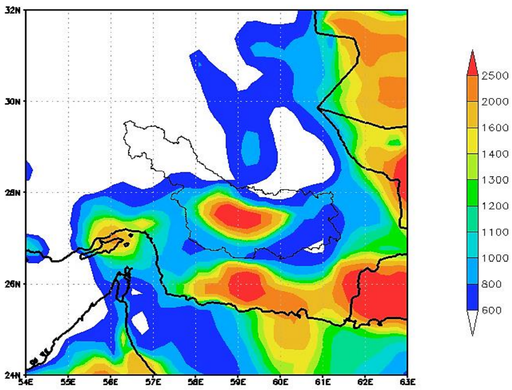

Fig. 12. Surface concentration values of WRF_Chem model output particles at UTC18 on December 19, 2016.

Fig. 13 shows the surface concentration values of the WRF_Chem model output at UTC00 on December 20, 2016. The surface concentration of higher dust in the south of Sistan and Baluchistan province, Hormozgan province has increased sharply and has reached more than 2000 µg/m^3. The surface concentration of dust in the southern half of the Jazmurian region is often between 1400 and 1600 µg/m^3.

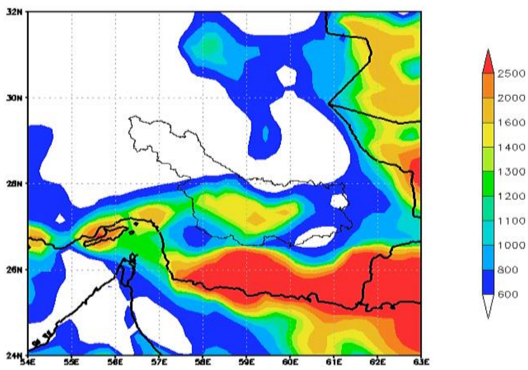

Fig. 13. Surface concentration values of WRF_Chem model output particles at UTC00 on December 20, 2016.

Fig. 14 shows the surface concentration values of the WRF_Chem model output at UTC06 on December 20, 2016. The surface concentration of dust is higher in the south of Sistan and Baluchistan province, Hormozgan province and, the Oman Sea above 2000 µg/m^3. The surface concentration of dust in the southern half of the Jazmurian region has decreased and is between 1200 and 1300 µg/m^3.

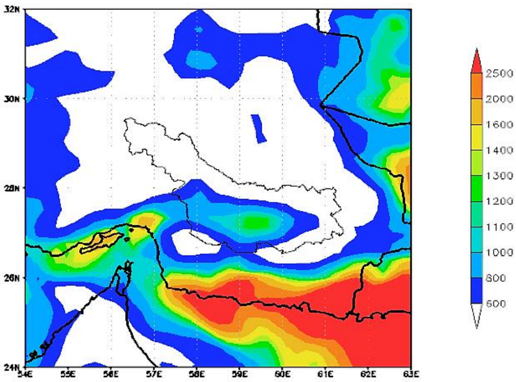

Fig. 14. Surface concentration values of WRF_Chem model output particles at UTC06 on December 20, 2016.

The surface concentration values of the output particles of the WRF_Chem model were simulated at different hours of the incident. The simulated surface concentration of dust at some hours and regions, such as in the south of Sistan and Baluchistan province, Hormozgan province, and Oman Sea, was well above 2000 $\mu g/m^3$. For example, the values of the surface concentration of particles output from the WRF-Chem model at UTC18 on December 17, 2016 show that the surface concentration of dust in the south of Sistan and Baluchistan province and Hormozgan province was higher than 2500 $\mu g/m^3$, and in the central areas of Jazmurian region, the dust concentration is higher than 2000 $\mu g/m^3$ is simulated. Also, the surface concentration values of WRF-Chem model output particles at 18:00 UTC on December 18, 2016, in most of the southern half of the Jazmurian region, the dust concentration has exceeded 2500 $\mu g/m^3$.

4. Conclusions

Using the WRF-Chem model, the dust storm in southeastern Iran was simulated from December 16 to 20, 2016. Numerical prediction and simulation can help in locating the origin of dust in the region. Also, it is very important to determine the peak hours of dust transport and concentration and the movement path of particles. In general, there are two sources of dust, internal sources and external sources. By simulating the dust storm and the transport of dust from other basins, it is also determined that for the simulated storm period, dust centers in the east, southeast, and south of Iran, which are the countries of Afghanistan (Hamon Plain) and the Arabian deserts in the south, are active. Therefore, many dust storms in the Jazmurian area can become more intense if the direction of the wind is from the east or the south. In other words, the Jazmurian basin is the source of dust in southern Iran during droughts if dust storms occur when the external foci (Hirmand plain in Afghanistan and Arabian deserts) are activated because of wind trajectories and low humidity that support dust transport to Iran, the intensity of this phenomenon in Iran will increase. The necessity to prevent damaging dust storms in this region requires international protocols for the correction and restoration of degraded lands, including the release of water and watershed management and desertification prevention activities to stabilize the degraded soils and reduce dust emissions.

Acknowledgments

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