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The study of a severe dust storm over Persian Gulf, the Gulf of Oman and parts of the Indian Ocean with two operational dust forecasting models

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ABSTRACT

Introduction: The entry of dust particles into water areas, which has increased sharply in recent years, causes a lot of environmental damage. The Persian Gulf and the Gulf of Oman are among the water areas that are covered with dust many times of the year.

Materials and methods: In this study, a severe dust from July 27 to 31, 2018 is analyzed, in which a large part of the Persian Gulf, Oman Sea and the western part of the Indian Ocean was involved. To study this phenomenon from different perspectives, satellite products, visibility from synoptic stations and synoptic maps were analyzed and the output of two numerical dust models of United States National Aeronautics and Space Administration-Goddard Earth Observing System (NASA-GEOS) and Dust Regional Atmospheric Model with 8 categories-Monitoring Atmospheric Composition and Climate (DREAM8-MACC) were examined. To qualitative and quantitative evaluate of the model outputs, the Aerosol Optical Depth (AOD) of TERRA/MODIS was used.

Results: Satellite imagery shows that in this case study, parts of the Persian Gulf and the Sea of Oman were affected by dust, and on July 30, dust particles entered the western half of the Indian Ocean. Comparison of model outputs with satellite data resulted that both models underestimate the AOD values, especially over water, and do not show well the entrance of dust particles into the eastern part of the Persian Gulf, the Gulf of Oman and the western half of the Indian Ocean.

Conclusion: Qualitative and quantitative comparison of AOD output of the two models with satellite data showed that the NASA-GEOS model had better performance and its output correlation with observational data was higher.

Introduction

Today, the occurrence of dust storms is one of the most important natural hazards in many countries, especially countries that are in the dust belt [1]. Sometimes severe dust storms affect living conditions in many countries in arid and semi-arid regions of the world [2]. The Middle East has abundant sources of dust [3]. Every year, a large amount of dust particles

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arises from this region and are transferred to other areas [4]. The number of dust storms in the Middle East has increased over the past decades [5]. For example, in Iraq, Sudan, the Arabian Peninsula, and the Persian Gulf region, more dust events have been reported [6]. Occurrence of dust storm over water areas causes a lot of environmental damage and cause the death of marine [7]. On the other hand, dust particles affect the rate of water evaporation from the sea surface by changing the amount of input and output radiation budget. The Persian Gulf as a region in the Middle East every year Severely affected by the dust. Existence of vast deserts in Saudi Arabia located in the south of the Persian Gulf [8] and Iraq and Syria in the west [9] and also the transfer of African dust particles to this region [10] are some of the most important factors that cause the occurrence of dust over the Persian Gulf.

On the other hand, the synoptic patterns over the region and wind direction have caused many dust storms occurrence over the Persian Gulf region [11]. The dust over the Persian Gulf region has been studied from different perspectives. In a study four severe dust storms over the Persian Gulf were synoptically analyzed [12]. The result showed that in all the studied dust, a low-pressure system was developed over the Persian Gulf and the southern half of Saudi Arabia, so that the deserts in the United Arab Emirates (UAE) and the southern half of Saudi Arabia are in front of the low-pressure center and influenced by south and southwesterly currents. Therefore, dust particles are transported to the Persian Gulf, the Gulf of Oman and southern regions of Iran. Another study also stated that winds in this region are sometimes associated with frontal systems that lead to dust over the Persian Gulf [13]. Many studies have been done using remote sensing data in this area. The Aerosol Optical Depth (AOD) during a dust storm in March 2012 using MODIS and AERONET data was analyzed [14]. Examining the output of numerical dust forecasting models is one of the important ways to identify how dust is emitted in the region and its transfer to the Persian Gulf and Gulf of Oman [15]. They evaluated the output of 8 operational dust models during a severe dust storm on July 14, 2014 over the Persian Gulf region and concluded that the outputs of the models are very different from each other. The two dust phenomena of 22 to 25 May 2012 and April 2015 were simulated using the WRF-Chem model [16]. The result indicates that the model simulates the temporal and spatial pattern of dust well.

This study investigates a severe dust storm from 27 to 31 July 2018, which covers a large part of the Persian Gulf, the Gulf of Oman and surrounding countries. During this dust event, large amounts of dust particles even were transported over the Indian Ocean. In the first part of this study, data and methods are presented. The second part, entitled results and discussion, presents synoptic maps, diagrams, and model outputs. The conclusions are presented in the third section.

Materials and methods

Fig. 1 shows the study area, which includes Syria, Iraq, Iran, Saudi Arabia, the United Arab Emirates, Oman, Yemen and other countries on the southern shore of the Persian Gulf. Parts of the Persian Gulf, the Gulf of Oman and the western shores of the Indian Ocean that have been affected by dust in this case are also observed in the figure. The location of two synoptic stations on Kish and Qeshm islands is also shown.

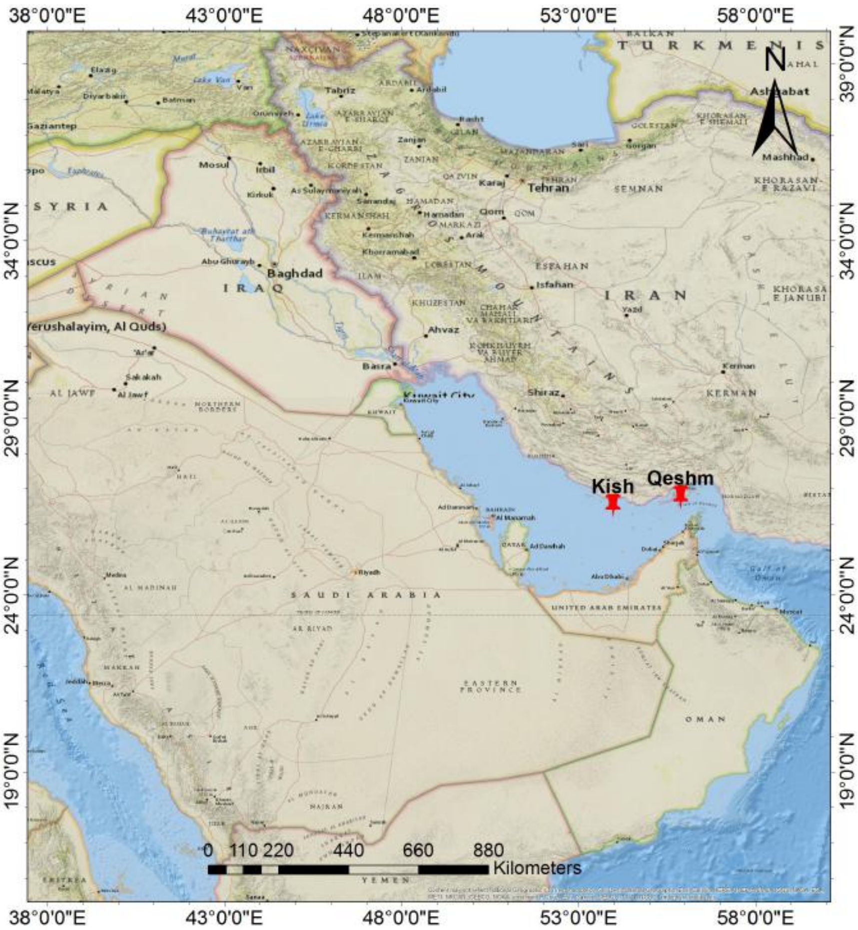


Fig. 1. The study area

In this study, the severe dust of July 27-31, 2018 has been investigated using satellite images and data, synoptic stations data in the region, synoptic maps and the outputs of operational dust forecasting models. First, to investigate the dust mass in the area, the MODIS true color images of Terra and Aqua satellites were examined. The time series of visibility in Kish and Qeshm islands synoptic stations as well as AOD from MODIS were presented to analyze the intensity of the phenomenon in the region and the trend of these quantities during the studied days. ERA5 re-analysis data with 0.25° resolution was used to Synoptic analysis and mean sea level pressure, wind speed at 10 m and temperature and geopotential height at 850 and 500 hPa maps were plotted. To determine the dust particle path and the atmospheric currents in the area, the HYSPLIT model was run backward from the Persian Gulf region at an altitude of 500 m using GDAS data with 0.5° resolution. Finally, the AOD output of United States National Aeronautics and Space Administration-Goddard Earth Observing System (NASA-GEOS) and Dust Regional Atmospheric Model with 8 categories-Monitoring Atmospheric Composition and Climate (DREAM8-MACC) operational dust forecasting models from https://sds-was.aemet.es were validated. The MODIS/TERRA AOD at 550 nm which is retrieved with combined Dark Target and Deep Blue algorithms was used to qualitatively and quantitatively evaluation of these dust model outputs.

Statistical analysis

In this study, in order to quantitatively evaluate the output of the NASA-GEOS and DREAM8-

MACC operational dust forecasting models, their values were compared with satellite data from July 27 to 30, 2018, and the statistical quantities of root mean square error, bias and correlation coefficient were used.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2} \quad (1)$$

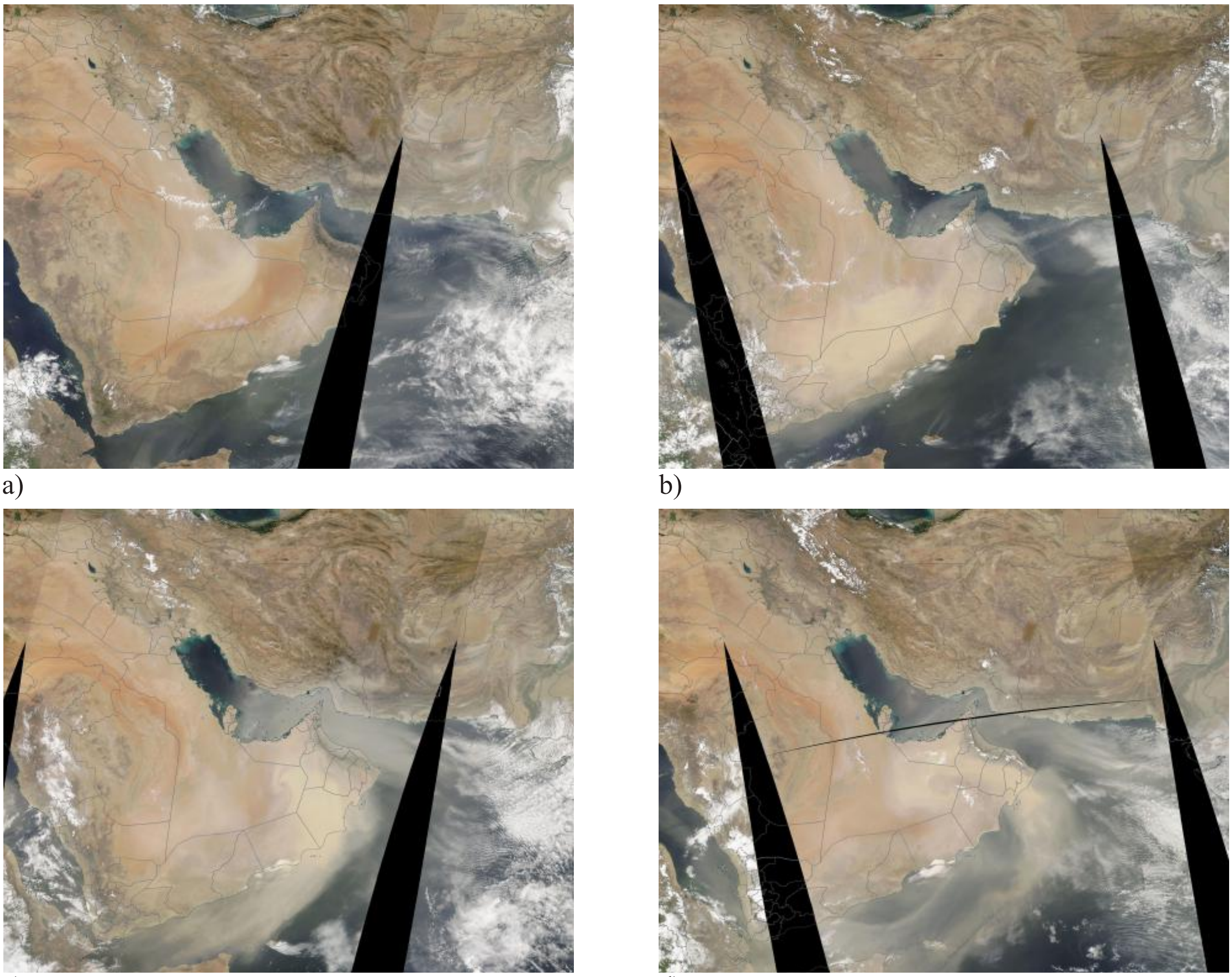
$$Bias = \frac{\sum F_i}{\sum O_i} \quad (2)$$

$$r = \frac{\sum(F_i-\bar{F})(O_i-\bar{O})}{\sqrt{\sum(F_i-\bar{F})^2}\sqrt{\sum(O_i-\bar{O})^2}}. \quad (3)$$

In all equations, F_i is the model output and O_i is the observational data at each grid point, N is the total number of grid points and overbar indicates the average value on all grid points.

Results and discussion

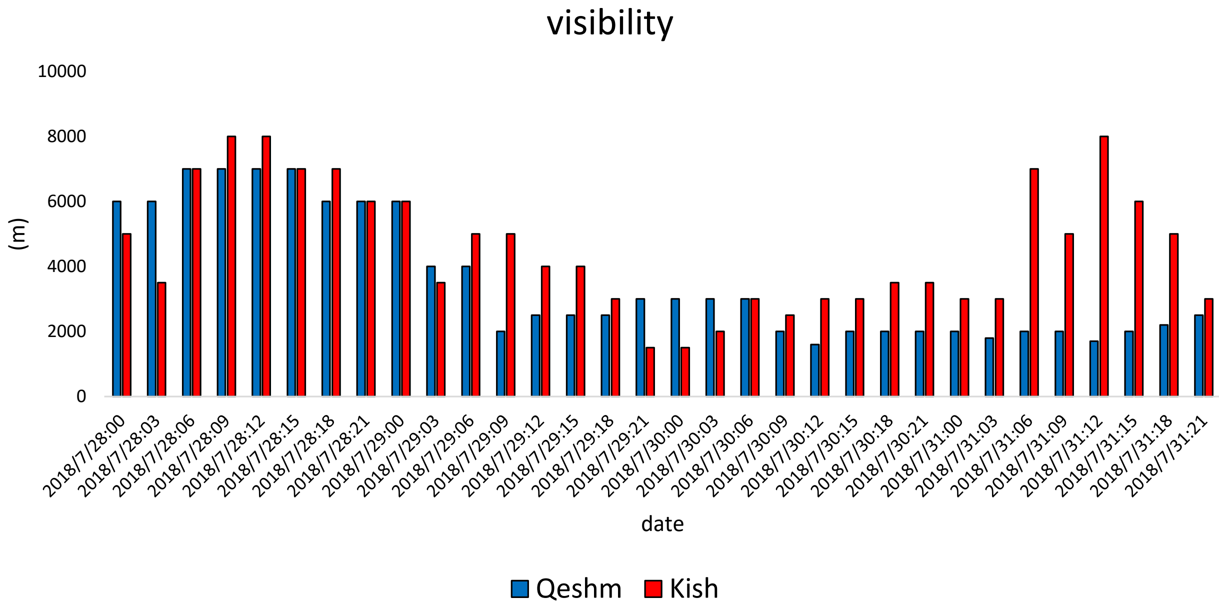
Fig. 2 shows the dust mass in the study area from 27 to 31 July 2018 using MODIS true color images. On July 27, dust is observed on the southern shores of the Persian Gulf, central Saudi Arabia and southeastern Iraq, and the western half of the Persian Gulf. On July 28, the southern half of Saudi Arabia, Oman and Yemen, as well as the eastern Persian Gulf, the Strait of Hormuz and the western regions of the Gulf of Oman, are affected by dust. On July 29, dust concentration in the region increased sharply, and dust particles entered large parts of the Persian Gulf and the Gulf of Oman. Heavy dust is also observed in the western parts of the Indian Ocean on this day. On July 30, as the dust mass transferred to the east, its concentration decreased slightly, but the dust affected a larger part of the Indian Ocean.



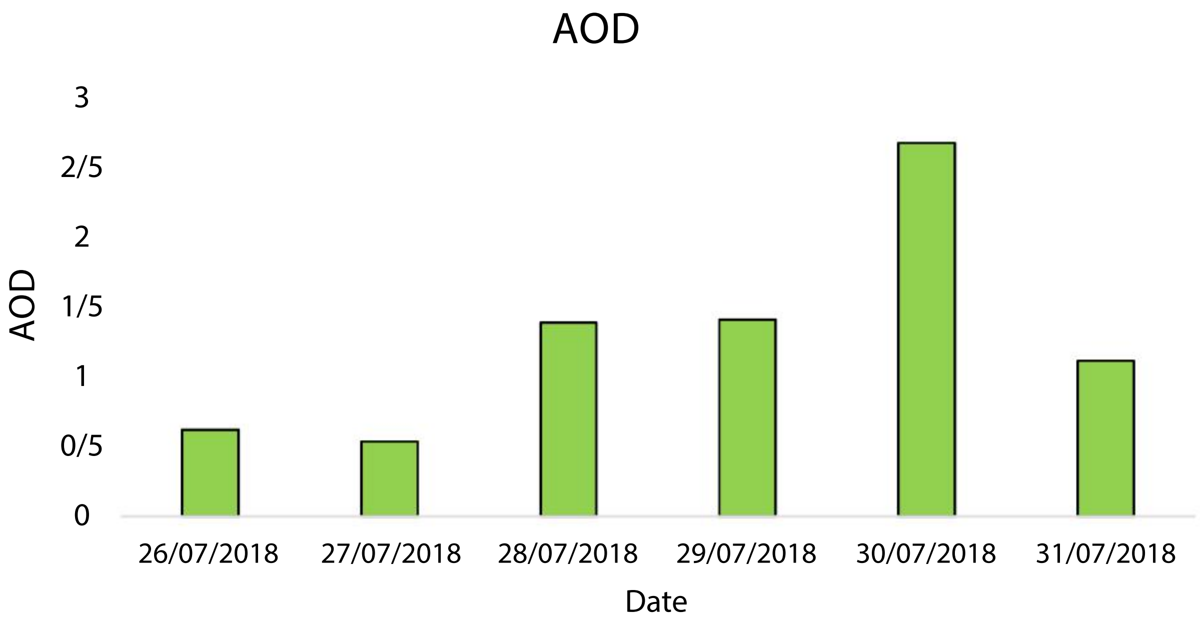
a) b) c) d)

Fig. 2. True color image of MODIS on a) 27th, b) 28th, c)29th, d)30th July 2018

The visibility at Kish and Qeshm synoptic stations on July 28-31, 2018 is observed at Fig. 3a. A sharp decrease in visibility is observed in both stations since July 29 and its value in both stations reached about 3000 m since the end of this day. The lowest value of visibility at Qeshm station was reported 1600 m at UTC12 on July 30 and at Kish station was 1500 m at UTC21 on July 29. Visibility data of two stations shows that the persistence of dust in Qeshm station is longer than Kish station and although the visibility in Kish station has gradually increased since July 31, but the values of visibility in Qeshm station on this day are still about 2000 m. The area average values of MODIS/TERRA AOD on the western regions of the Persian Gulf are shown in Fig. 3b The highest AOD values were observed in this region on July 30 and its value reached 2.67.



a)



b)

Fig. 3. a) The visibility (m) of Kish and Qeshm synoptic stations from 28 to 31 July 2018 with 3 h intervals, b) The area average AOD over eastern Persian Gulf from 26 to 31 July 2018

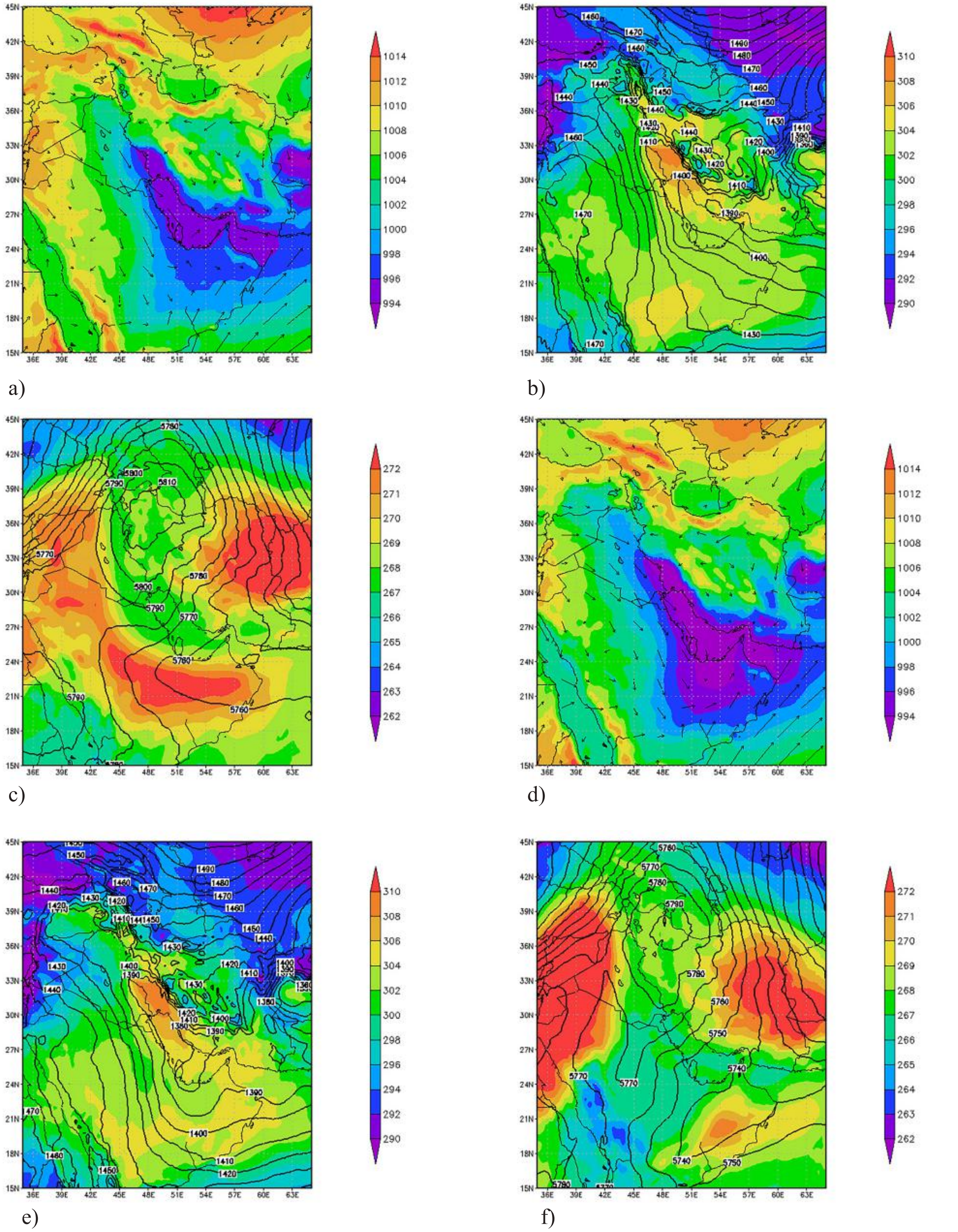


Fig. 4. The mean sea level pressure and 10 m wind vectors, temperature and geopotential height at 850 and 500 hPa levels at 00UTC on a), b), c) 27th and d), e), f) 28th July 2018

Synoptic analysis

Fig. 4 shows the mean sea level pressure, 10 m wind velocity, temperature and geopotential height at 850 and 500 hPa levels at UTC00 on July 27 and 28, 2018. On July 27, a low-pressure system is observed on the Persian Gulf and the Gulf of Oman in surface map. The change in wind direction from northwesterly to southwesterly is shown in southern Saudi Arabia. In the satellite image of this day (Fig. 1a), a mass of dust can be seen in this area. At 850 hPa level, a small low-altitude closed center can be seen on the northern shores of the Persian Gulf, whose tongues penetrated as far as southern Saudi Arabia. At the 500 hPa level, the center of a low-altitude closed area in the south of the Gulf of Oman, whose trough extends from the west to the central regions of Saudi Arabia is shown. On July 28, in the surface map, the low pressure located over the Persian Gulf was strengthened and a decrease in pressure is observed in this area. Strong southwesterly winds in southern Saudi Arabia and Oman caused the dust particle transfer to the Gulf of Oman and the Indian Ocean. At the 850 hPa level, the low-altitude closed center covered a larger area and its trough became deeper. At 500 hPa level, the decrease in altitude in the south and west of the Persian Gulf was significant compared to the previous day, so that the 5740 m contour is observed on the strait of Hormuz.

The HYSPLIT model output at UTC12 on July 29, 2018, can be seen in Fig. 5. The backward trajectories show that the predominant atmospheric currents were southwesterly over the western half of the Persian Gulf and the Strait of Hormuz and dust particles were transferred to the Persian Gulf from countries in the southern shores, including the UAE, Saudi Arabia and Oman.

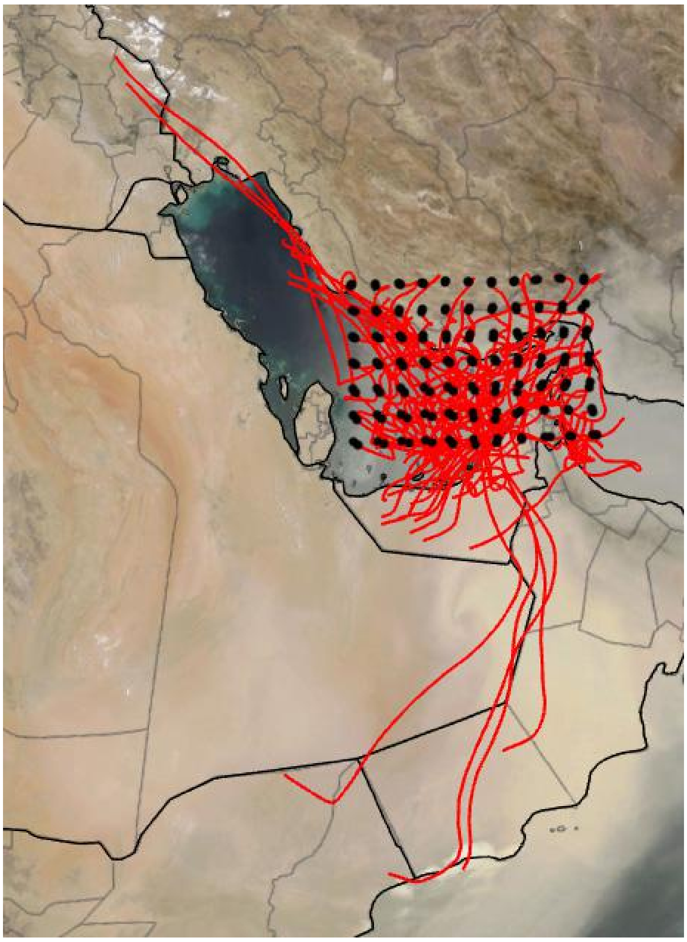
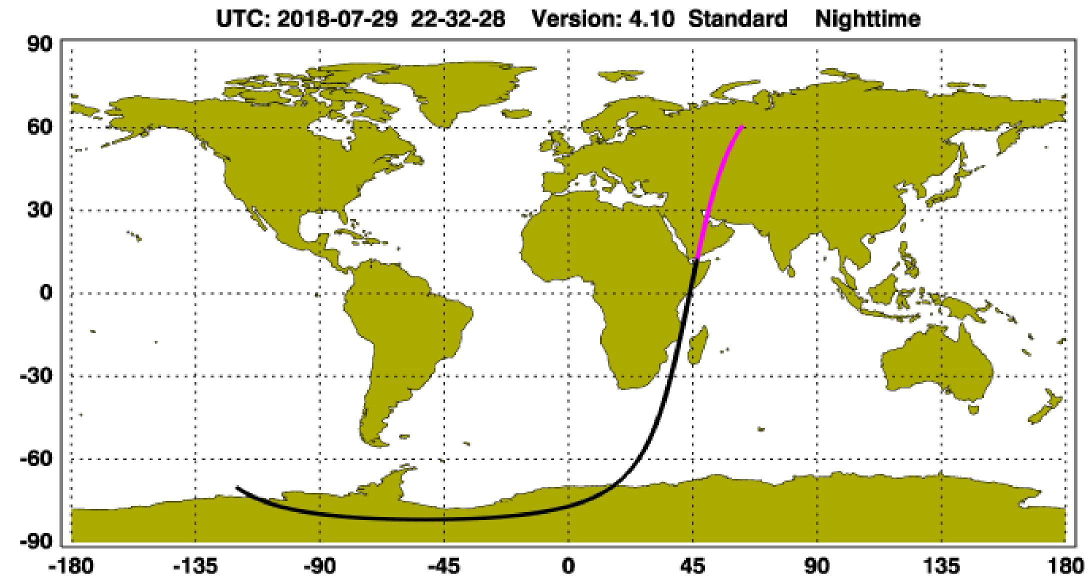


Fig. 5. the backward trajectories of HYSPLIT model at 500 m height at 12 UTC on July 29, 2018

The line shown in Fig. 6a shows part of the the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite path on July 29, 2018. The colored part is related to some parts of study area which is shown in panels b to d. Attenuated backscatter (Fig. 6b), whose small values indicate clear air. Large amounts of this quantity are related to the ice crystals in the cloud. Because airborne particles also increase reflection, this quantity also increases if there are aerosols in the atmosphere. The amount of attenuated backscatter on parts of the satellite path over Saudi Arabia and the Persian Gulf is significant. Fig. 6c shows the level 2 Vertical Feature Mask (VFM) data. According to the VFM values, in a large part of the path specified in Fig. 6d. Aerosols can be seen that they have reached an altitude of more than 6 km. The aerosol type in the fig. 6d indicates that at lower latitudes up to about 30 N which is related to the northern coast of the Persian Gulf, the type of aerosol is dust and up to latitude 45 N located in central regions of Iran is polluted dust.

a)



b)

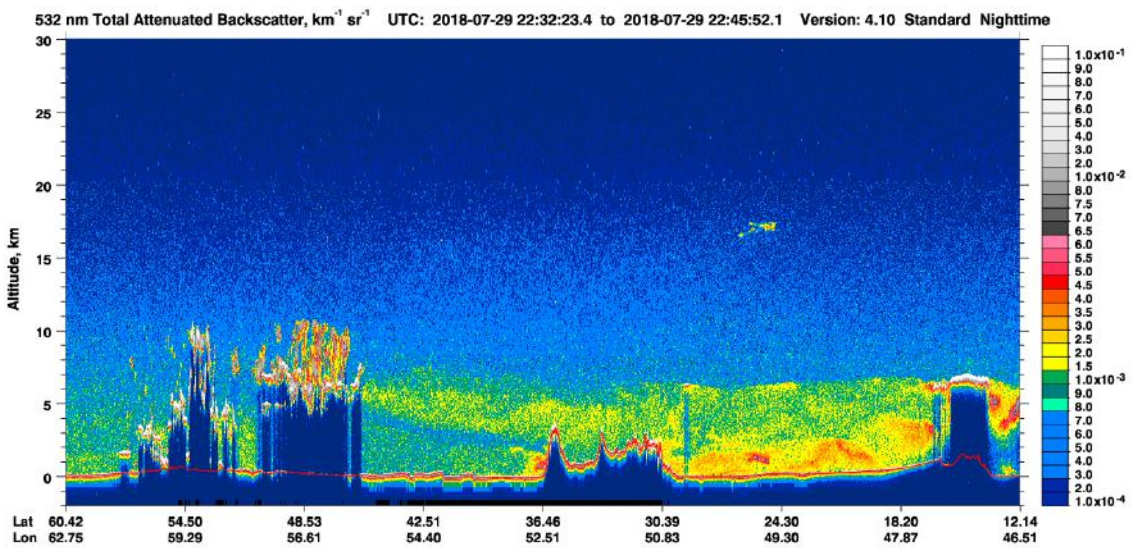
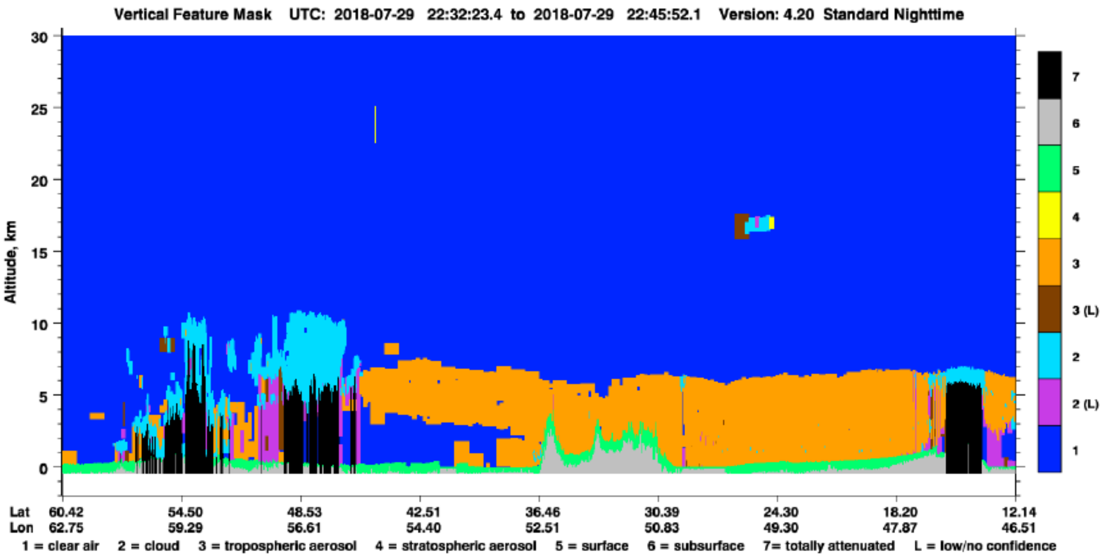


Fig. 6. a) The CALIPSO satellite path, b) total attenuated backscatter, c) vertical feature mask, d) aerosol type at 22:32 to 22:45 UTC on July 29, 2018

c)



d)

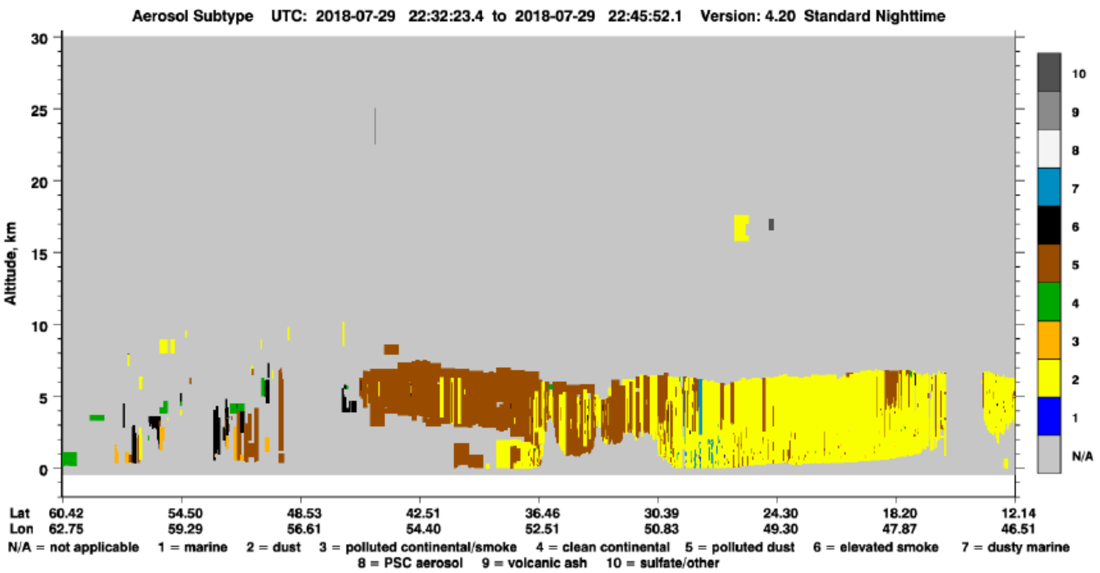


Fig. 6. a) The CALIPSO satellite path, b) total attenuated backscatter, c) vertical feature mask, d) aerosol type at 22:32 to 22:45 UTC on July 29, 2018

The dust concentration output of NASA-GEOS and DREAM-MACC dust models (Fig. 7) results that both models show the dust emission from eastern Syria and then the central and southeastern regions of Iraq to the western Persian Gulf because of blowing northwesterly (Shamal) winds. Therefor at UTC9 on the 27th July, they show the maximum dust concentrations over the southeastern Iraq, the western half of the Persian Gulf and the northeast of Saudi Arabia. However, the DREAM8-MACC model has shown higher dust concentrations in eastern Syria and the northern half of Iraq. According to satellite images and surface wind maps, on the 28th, due to the southwesterly winds, the transfer of dust from Saudi Arabia to the UAE and the western half of the Persian Gulf began, NASA-GEOS model shows it correctly, But the DREAM model shows the transfer of dust to central Saudi Arabia and near the coasts of the Red Sea. On day 29, both models show high dust concentrations on the southern shores of the Persian Gulf and Oman but underestimated the values in the eastern half of the Persian Gulf and the Gulf of Oman. They also could not show the heavy dust transfer to the Indian Ocean on this day.

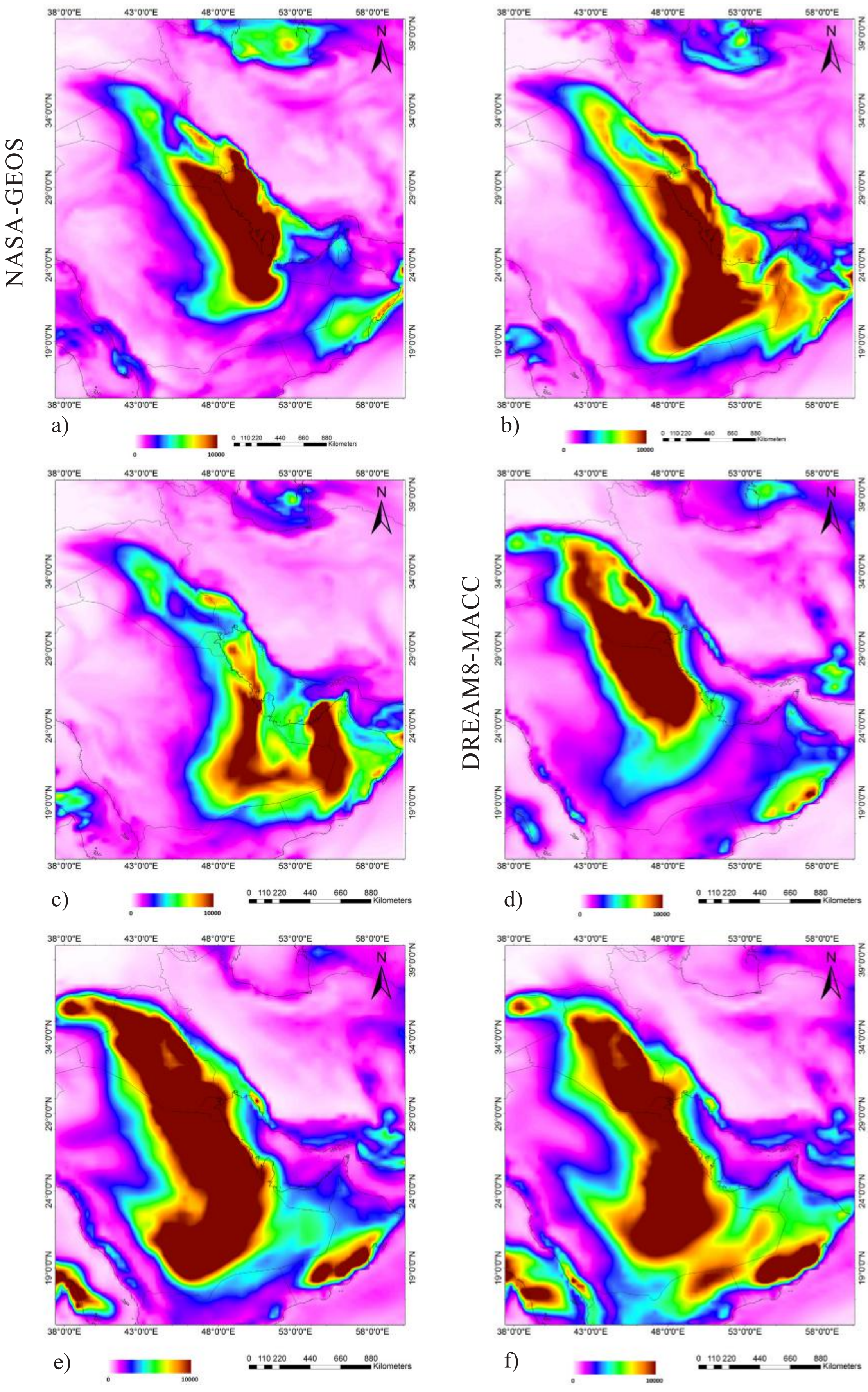


Fig. 7. Dust concentration of NASA-GEOS and DREAM8-MACC dust models outputs at 9UTC on a, d): 27th; b, e) 28th; c, f) 29th July 2018

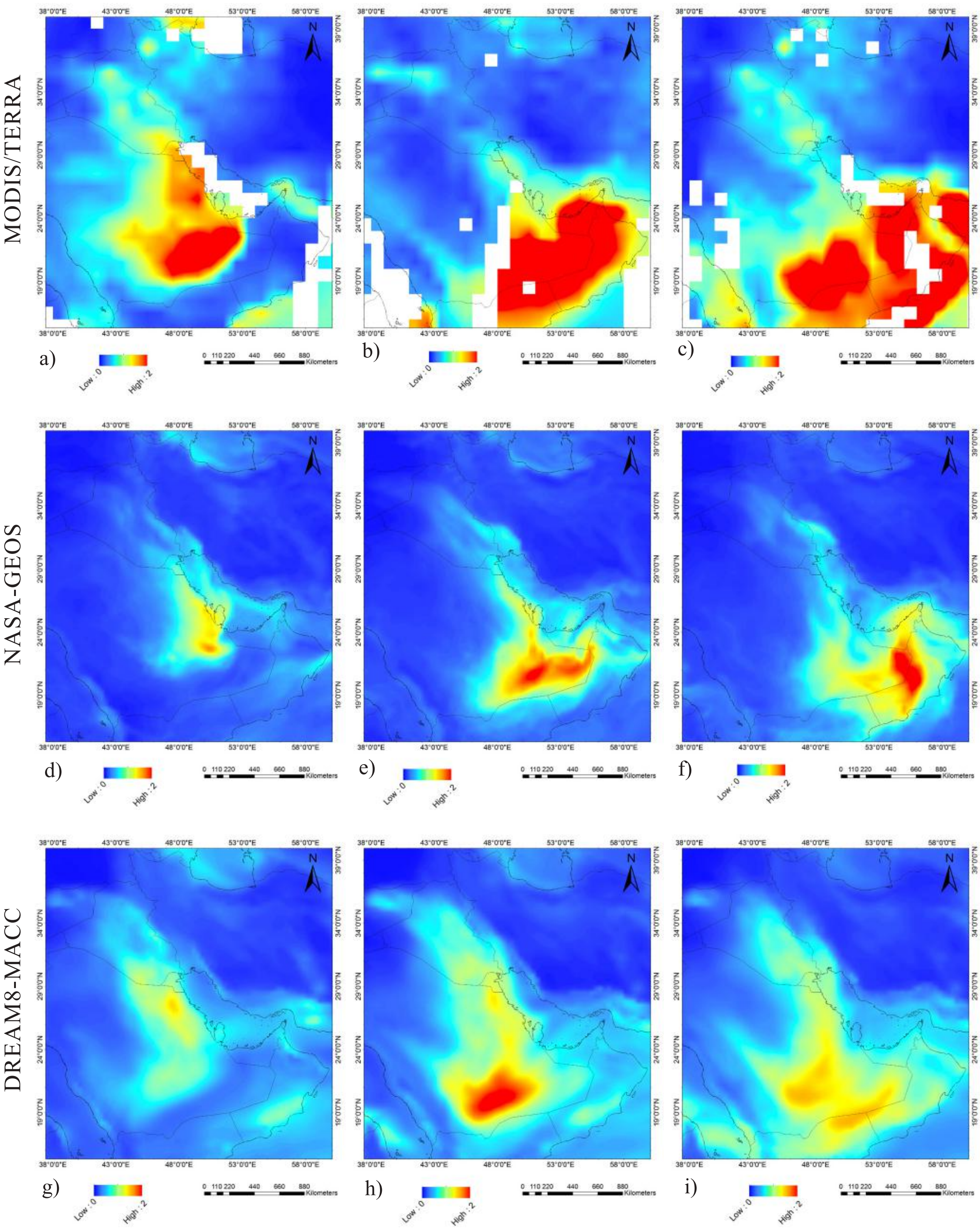
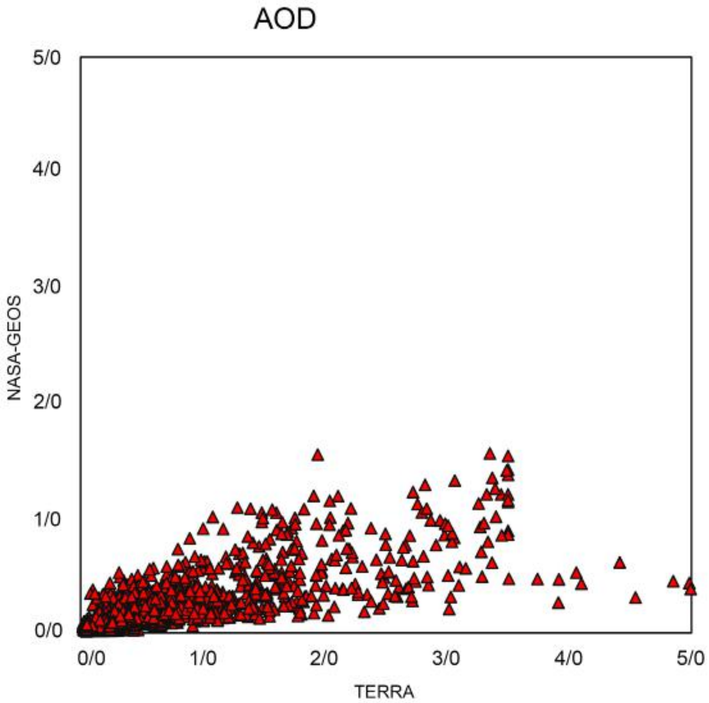


Fig. 8. AOD of MODIS/TERRA retrieved with combination of Dark target and Deep blue algorithms, NASA-GEOS and DREAM8-MACC models outputs in a), d) and g) July 27; b), e) and h) on July 28; c), f) and i) on July 29, 2018

a)



b)

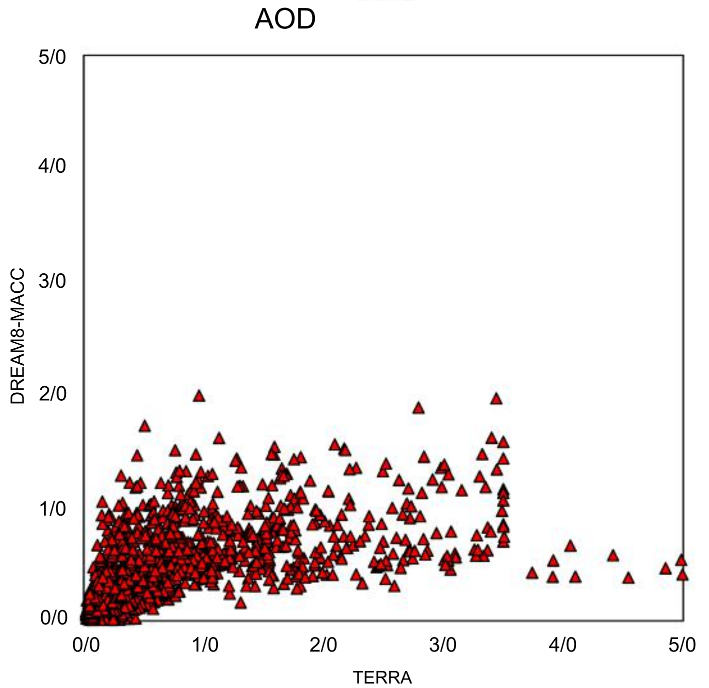


Fig. 9. AOD scatter diagram of MODIS/TERRA and a) NASA-GEOS and b) DREAM8-MACC model outputs on July 27-29, 2018

Fig. 8 Shows the AOD of MODIS/TERRA and the outputs of NASA-GEOS and DREAM8-MACC operational dust forecasting models on July 27, 28 and 29, 2018. On July 27, satellite data showed large AODs over the eastern half of Saudi Arabia and the southern shores of the Persian Gulf, as well as significant amounts of AOD over the large parts of Iraq. The outputs of the models on this day show that both models under-estimated the AOD. However, the DREAM8-MACC model output is more similar to the satellite product and has calculated AOD values in the southern half of Saudi Arabia and parts of Iraq more than the NASA-GEOS model in this day. On July 28, AOD in southern Saudi Arabia and a large part of Oman and Yemen countries, as well as the eastern half of the Persian Gulf and the Gulf of Oman, increased sharply compared to the previous day. On this day, both models underestimated AOD and could not show its increase over the region well. On July 29, AOD values in the eastern half of the Persian Gulf, the Gulf of Oman and parts of the Indian Ocean increased significantly, indicating the entry of dust particles over the waters, but on this day neither model was able to show AOD increase and under-estimated AOD values, especially on water.

AOD scatter diagram of MODIS/TERRA and NASA-GEOS model and DREAM8-MACC model outputs can be observed at Fig. 9. The closer point to the diameter, indicates that the model output is more similar to the observation at that point. The diagrams show that both models underestimate the values, especially at higher AOD values.

The values of correlation coefficient, determination coefficient, root mean square error and bias of the two model outputs on July 27-29, 2018 are shown in Fig. 10. The RMSE values of the two models are very close together and the value is slightly lower for the DREAM8-MACC model, but the correlation and determination coefficient between NASA-GEOS model and satellite data is higher and this data has less bias. The correlation coefficient for NASA-GEOS model is 0.76 and for DREAM8-MACC model is 0.58.

	NASA_GEOS	DREAM8_MACC
mean error	-0/396039881	-0/263881617
RMSE	0/684907274	0/670515728
R	0/756191405	0/588368435
R2	0/571825441	0/346177415
bias	0/41930547	0/613082876

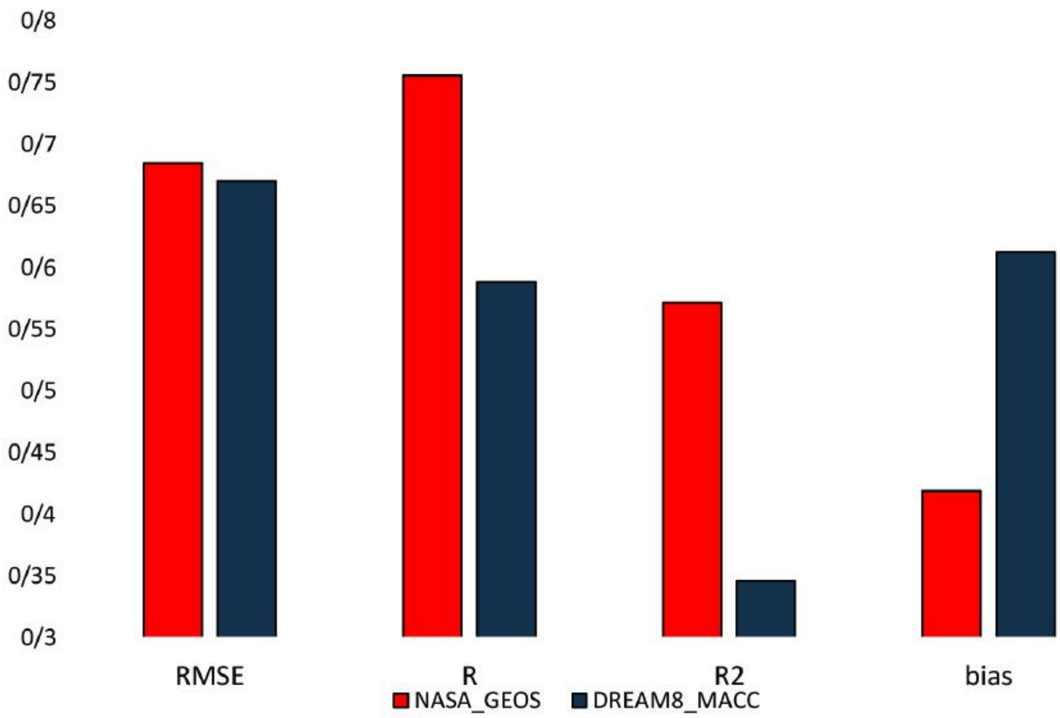


Fig. 10. Correlation coefficient, determination coefficient, root mean square error and bias of NASA-GEOS and DREAM8-MACC models outputs

Conclusion

A severe dust storm occurred over the Persian Gulf and the Gulf of Oman From July 27 to 31, 2018. Dust particles were first emitted from eastern Syria and central Iraq and entered the western half of the Persian Gulf. Over time, heavy dust masses from the southern coasts of the Persian Gulf, especially Saudi Arabia and the UAE, entered the eastern half of the Persian Gulf, as well as the Strait of Hormuz and a large part of Gulf of Oman, so that dust concentration increases over these areas Is. In the following hours, strong winds blew over the southern regions of Saudi Arabia as well as Oman, caused dust transfer to the Indian Ocean. Satellite images show that dust over the Indian Ocean was very severe. The study of visibility reported from Kish and Qeshm meteorological stations on July 28-31, 2018 resulted that a sharp decrease in visibility was happened in both stations from July 29, and at the end of this day, the visibility in both stations reached to values less than 3000 m. The maximum AOD values over the study area is observed on July 30. The synoptic analysis in this case study shows that a low-pressure system developed over the Persian Gulf and the Gulf of Oman and a decrease in pressure is observed over this region. Strong southwesterly winds in southern Saud i Arabia and Oman caused dust transfer to the Gulf of Oman and the Indian Ocean. At 850 hPa level, a low-altitude closed center can be seen in the region, whose tabs penetrated as far as southern Saudi Arabia. At the level of 500 hPa, the center of a low-altitude in the south of the Gulf of Oman is shown, whose trough extended from the west to the central regions of Saudi Arabia, and the decrease in altitude in the south and west of the Persian Gulf is relatively significant. The backward trajectories of HYSPLIT model shows that the predominant atmospheric currents over the eastern half of the Persian Gulf and the Strait of Hormuz, were southerly and southwesterly, and dust particles emitted from countries located in the south of the Persian Gulf, including the UAE, Saudi Arabia and Oman. According to the products of CALIPSO satellite, the type of Aerosols over the region was dust and dust particles penetrated to a height of about 6 m in the atmosphere. Dust concentration output of NASA-GEOS and DREAM-MACC models showed that both models calculated high dust concentration in the southern coasts of the Persian Gulf and the Gul of Oman but under-estimated the concentration over the eastern half of the Persian Gulf and the Gulf of Oman. The two models have not shown the transfer of dust particles to the Indian Ocean well. Comparing the AOD output of the two models with Terra satellite product results that neither of the two models could show an increase in AOD and underestimated the values, especially over water. The AOD scatter diagrams of the satellite data and the output of the two models also show that the models underestimated the AOD values. A comparison of the AOD output values of the models with the Terra satellite product results that NASA-GEOS model output was more accurate during this dust event the correlation coefficient between its output and the observational data was higher.

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Competing interests

The author declares that there are not any actual or potential competing interests.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely considered by the author.

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