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Numerical Study of Dust-Cloud Interaction over Egypt

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ABSTRACT

This article is addressing the interaction between cloud and dust from the numerical modeling perspective. Our focus will be on a distinct dust event followed by a rain event harnessing the WRF-CHEM model capability in simulating the dust phenomenon accurately throughout all of its stages: erosion, transport, and deposition (dry and wet removal). As well as leveraging the model high capability in predicting cloud and precipitation as well. In this study we utilize the WRF-CHEM scheme that counts for the interaction between dust and cloud. It was focused on the particulate matter PM10 in growth, development, evolution stages, in-cloud, and below-cloud.

Keywords: WRF-CHEM; particulate matter; wet scavenging; in-cloud; below-cloud.

Introduction

Dust aerosols have a principal role in the climate radiative forcing. They are the main constituent of global particulate matter budget. And consequently, this fraction of the budget represents a reasonable concern in a variety of research areas such as air quality; and atmospheric chemistry (Seinfeld and Pandis, 2016). Atmospheric chemistry is the core of this study. Dust aerosols alter the climate forcing through its impact on the microphysics of the atmosphere (Abdul-Razzak and Ghan, 2000). And also influence interaction with solar radiation (Zhang *et al*., 2002). Dust aerosols also host and provide the media for a variety of chemical reactions take place in the atmosphere; in the so-called atmospheric chemical aging; which controls the uptake of the gas phase organic and inorganic compounds (Gong *et al*., 2006). Furthermore; and which is important the most; is the impact of mineral dust aerosols in the cloud activation; nucleation; and in reciprocity the impact of cloud and rain in dust aerosol removal; wet deposition; the scope of this study. Handling dust aerosols-cloud interaction from the numerical modeling perspective is one of the most challenging issues facing the state-of-the-art models whether in the global and regional scale or the mesoscale models (Easter *et al*., 2004). In the global scale model, the difficulty lies in the difference between the spatial and temporal scale of the model and the scale of the real-world processes; and consequently, the parameterization of aerosol-cloud interaction relevant processes. In the mesoscale models; the sophistication arises mainly from the aerosol composition and size distribution representation in the model(Abdul-Razzak and Ghan, 2000). The diversity of aerosol model schemes varies between the sectional and modal approach of size distribution and the representation of aerosol composition within each type of size distribution. Furthermore, the aerosol activation approach itself varies from simple parameterization to mechanistic parameterization (Abdul-Razzak and Ghan, 2002). We adopted a mechanistic parameterization scheme in the WRF-CHEM model; namely; Abdul-Razzak and Ghan; which is multi-mode and sectional aerosols scheme; and this is the one we are to assess in this study.

Materials and methods:

It is very rare that the event of dust storm coincides with rain event, cause rainfall in Egypt is associated with atmospheric circumstances that usually occur in such one season (winter); whiles dust

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events are associated with other characteristics that often take place in other season (fall); but it can happen that those different circumstances intersect; will focus on event regarding following conditions:

- Distinct dust event.
- Distinct rain event.
- Dust occurs prior to rain.
- Separation of events not long.

Monitoring the two phenomena separately assuring model can capture each phenomenon accurately the two aspects dust event with rain event while dust rain interaction disabled; then dust event with rain event but with dust rain interaction enabled.

Monitoring the two phenomena separately

We monitored the two events throughout different observations datasets we used MODIS imagery for dust events and TRMM for rain; applying scrutiny in which the two events coincide according to the aforementioned criteria. Figure 1 and Figure 2 show visual depiction of the two data sets of the dust and rain phenomena.

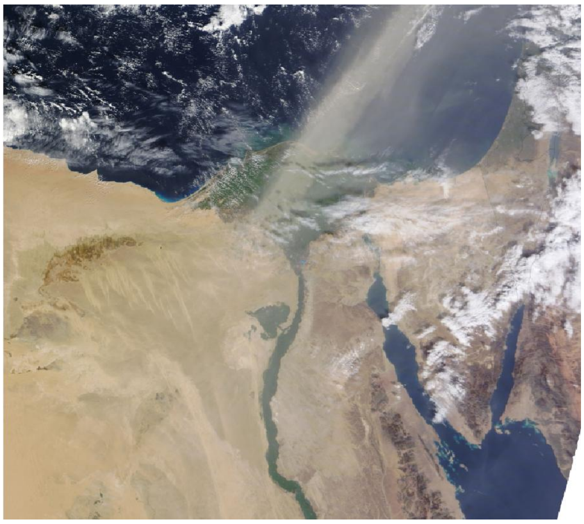

Fig 1: MODIS imagery for dust

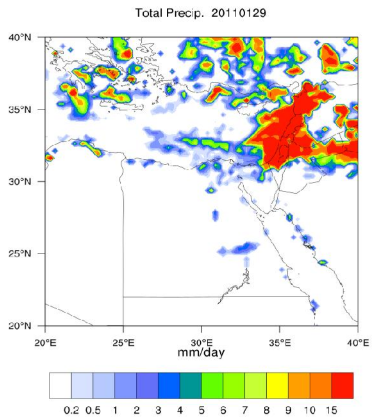

Fig 2: TRMM plot for rain

Selected Case Study

Egypt's rainfall characteristics are: seasonal; namely in wet season and it is of highest intensity in shoreline areas than inland areas. So, it was selected a distinct rain events, with records captured by observation means; WMO ground station; in shoreline areas. And dust events are often in fall and it is seldom that the two events coincide in such manner that dust outbreak occurs and a rain event catches up, using observation data for each of the two separate phenomena, we manage to select an event that fulfills the prescribed criteria, on 28-30 January 2011. So, for this study to attain the targeted objective, the modeling simulations are organized into two distinct types according to the purpose of simulation:

- WRF-CHEM runs but with no wet scavenging is enabled; to assess the model capability to predict both dust and rainfall severely. The visualization of the output of the simulation is shown in Figure 3.
- WRF-CHEM runs with wet scavenging is enabled; to assess the model capability to predict dust and rainfall interaction and feedback. The configuration for the simulation is encompassed in Table 1.

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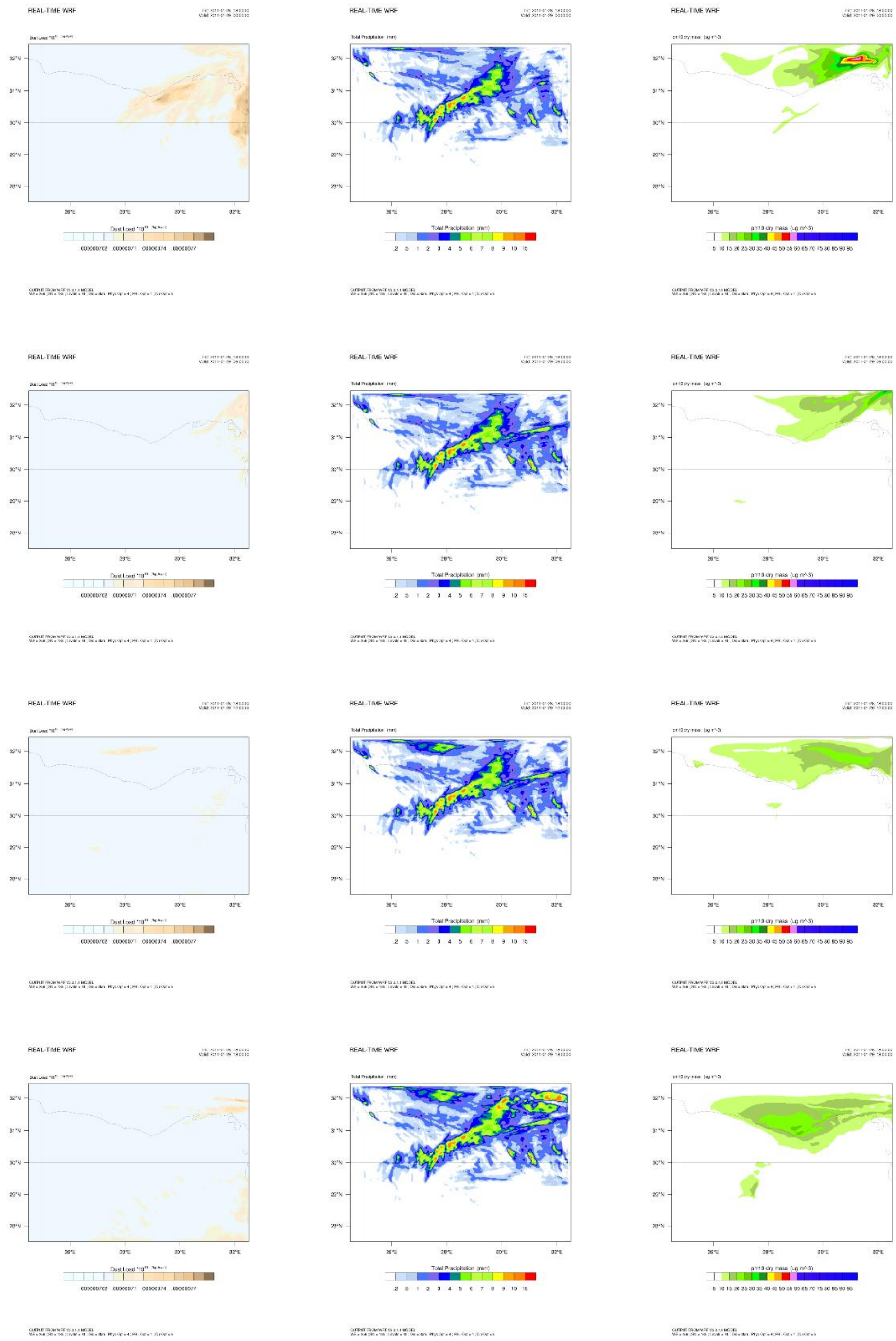


Fig. 3: Dust mass conc (left column), accumulated rainfall (middle column), and PM10 mass conc (right)

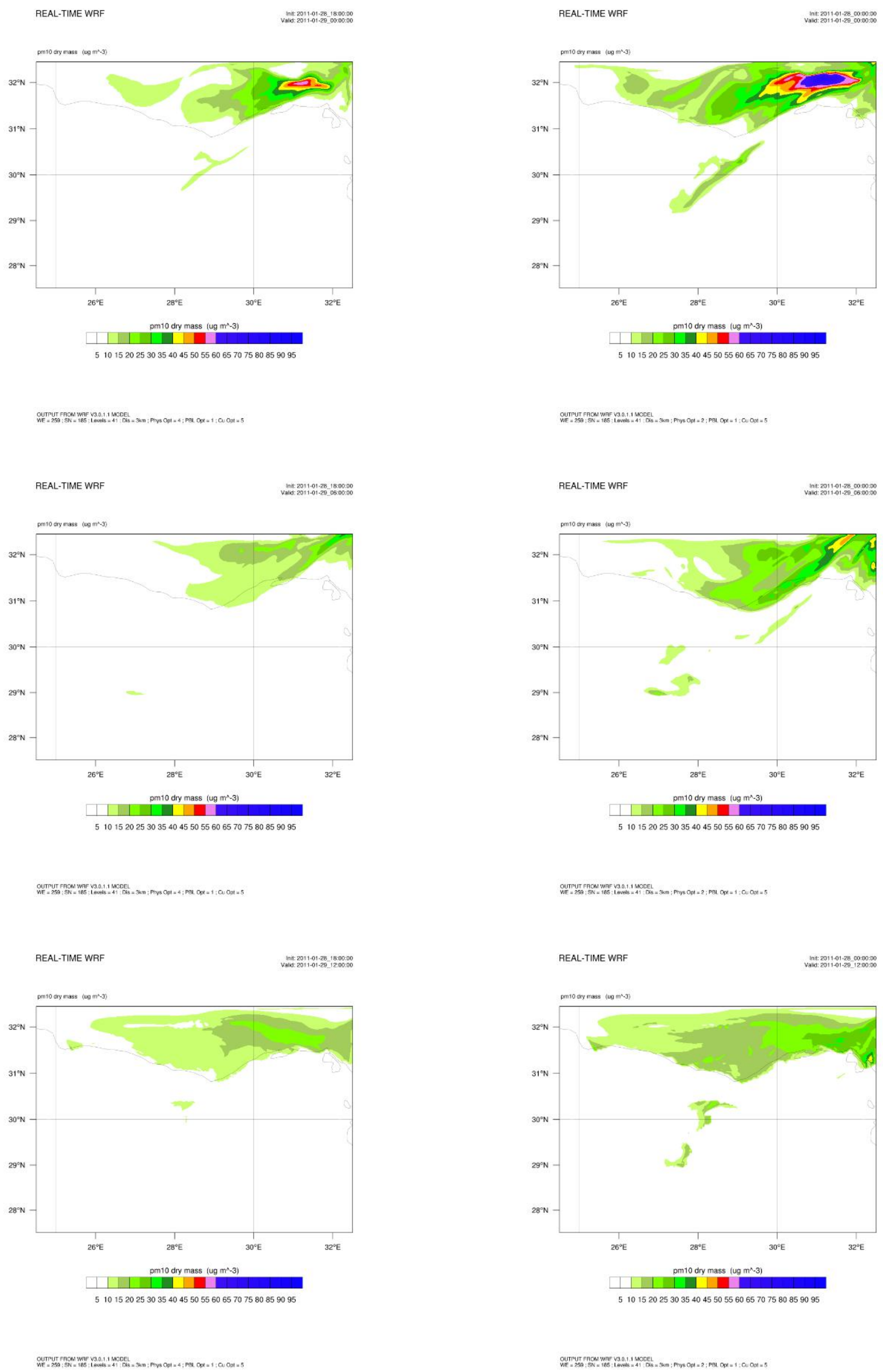
Table 1: WRF-CHEM physics/chem namelist options for wet scavenging runs.column)

physics/chem option	**Description**	**Value**
surface_input_source	If = 3 ; use dominant land and soil categories from WPS/geogrid If = 1 ; dominant categories recomputed in real.	3
ra_sw_physics	Goddard shortwave scheme.	2
mp_physics	microphysics option Lin *et al*. scheme.	2
chem_opt	CBMZ chemical mechanism and MOSAIC using 4 sectional aerosol bins including some aqueous reactions.	9
Progn	prognostic cloud droplet number included in the Lin *et al*. and Morrison microphysics scheme.	1
phot_opt	uses Fast-J photolysis.	2
aer_ra_feedback	feedback from the aerosols to the radiation schemes turned on, combined with the “chem_opt” parameter.	1
wetscav_onoff	wet scavenging turned on in the simulation, combined with the “chem_opt” parameter.	1
cldchem_onoff	cloud chemistry turned on in the simulation, combined with the “chem_opt” parameter.	1
dust_opt	MOSAIC and MADE/SORGAM dust emissions option (does not requires extra input data)	2
seas_opt	MOSAIC or MADE/SORGAM sea salt emissions.	2

Results and Discussion

Comparison between interaction disabled and interaction enabled

Applying the configuration described in the previous table we got WRF-CHEM output in which wet scavenging is enabled which means event if particulate matter is well parametrized in ordinary WRF-CHEM model run; we will get a more accurate model solution for Particulate matter; when we enable wet scavenging. A comparison between results from the two different configurations is illustrated in Figure 4:


REAL-TIME WRF
pm10 dry mass (ug m^-3)
32°N
31°N
30°N
29°N
28°N
26°E
28°E
30°E
32°E
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95

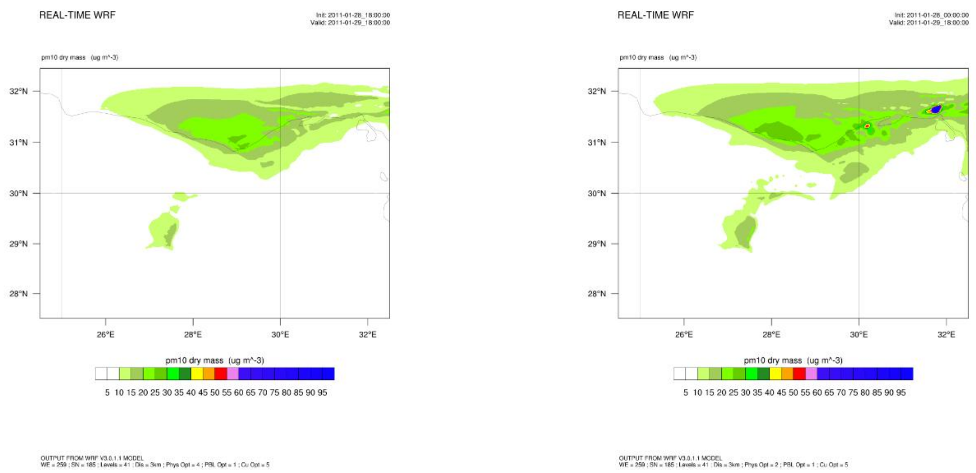


Fig 4: Comparison between wet scavenging disabled (left column) and wet scavenging enabled (right column)

Cloud aerosol interaction details

There are two distinct types of cloud-aerosol interaction; in-cloud and below-cloud. Aerosol particles are the core of cloud droplet formation (nucleation). The aerosols properties control the cloud aerosols interaction process. It is a two-way interaction; i.e., its composition (the content of water soluble materials) influences cloud droplet formation in the activation stage (nucleation). On the other hand, its physical/chemical properties alter the climate radiation forcing as a feedback in the development stage. The development of aerosol as cloud condensation nuclei CCN is governed by many factors, such as the aerosol size distribution, aerosol physical/chemical properties, and the humidity conditions throughout the cloud formation. As a matter of fact, not all clouds result in precipitation; consequently, the destination of the very first activation nuclei is eventually residing in the atmosphere due to the evaporation of the containing cloud droplet. The development of the cloud droplet into the rain droplet plays the main role in wet removal (deposition) of aerosols whether the in-cloud aerosols (via in cloud scavenging) or below-cloud aerosols (through below cloud scavenging). The two types of scavenging are well parameterized in WRF-CHEM. We carried out model simulations to monitor the development aerosol-cloud interaction process in the formation and growth stage of cloud droplet (nucleation). It was observed an increase in the mass concentration of particulate matter; and in the mean time we monitor the auto conversion stage that yields precipitation; rain in our case; resulting in the removal of particulate matter. The cloud distribution has a wider range than precipitation; So, to spot the cloud-aerosol in the activation stage will rely on spatial visualization that depicts dust, and water vapor interaction affecting PM10 mass concentration Whereas in the scavenging stage point time series is more effective in the representation of the interaction.

Dust rain interaction validation

WRF-CHEM model validation is carried out using MODIS imagery using two satellite image retrievals from two types of imagers; AQUA and TERRA; at two different overpass times; the AERONET synergy tool display for the dust event is illustrated in Figure 5, then to get the corresponding WRF-CHEM simulation times as shown in Figure 6.

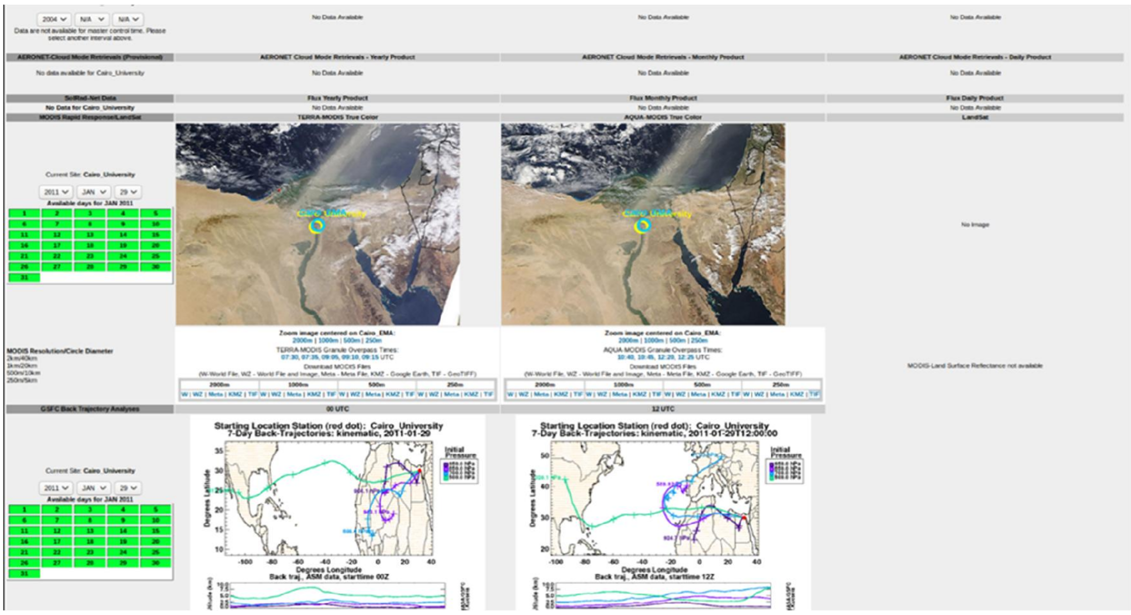


Fig 5: AERONET synergy tool display for the dust event

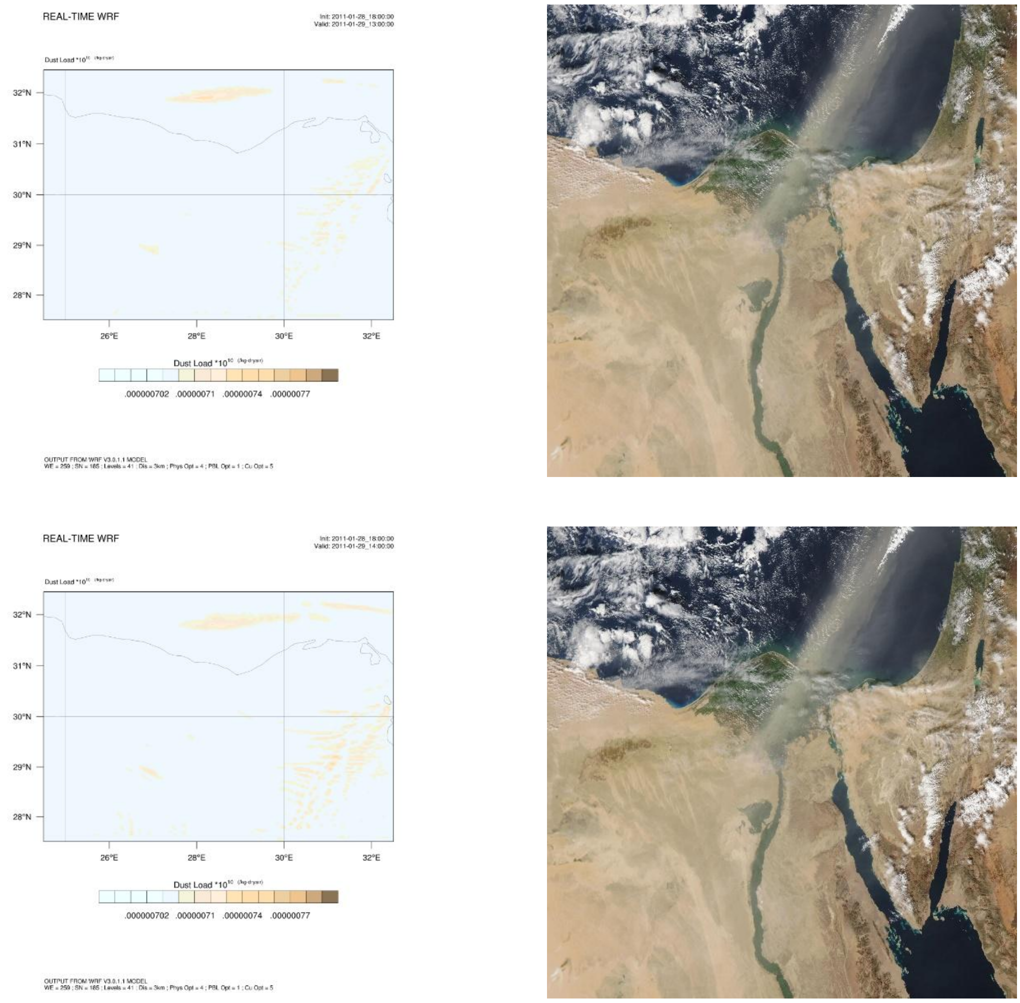


Fig 6: WRF-CHEM simulation times

In-cloud interaction

The growth and development of particulate matter which reflect the interaction between cloud and dust is captured in WRF-CHEM simulation the phenomenon is monitored through visualization of model output for the distribution of water vapor mixing ratio, dust concentration, and PM10 mass concentration as shown in Figure 7.

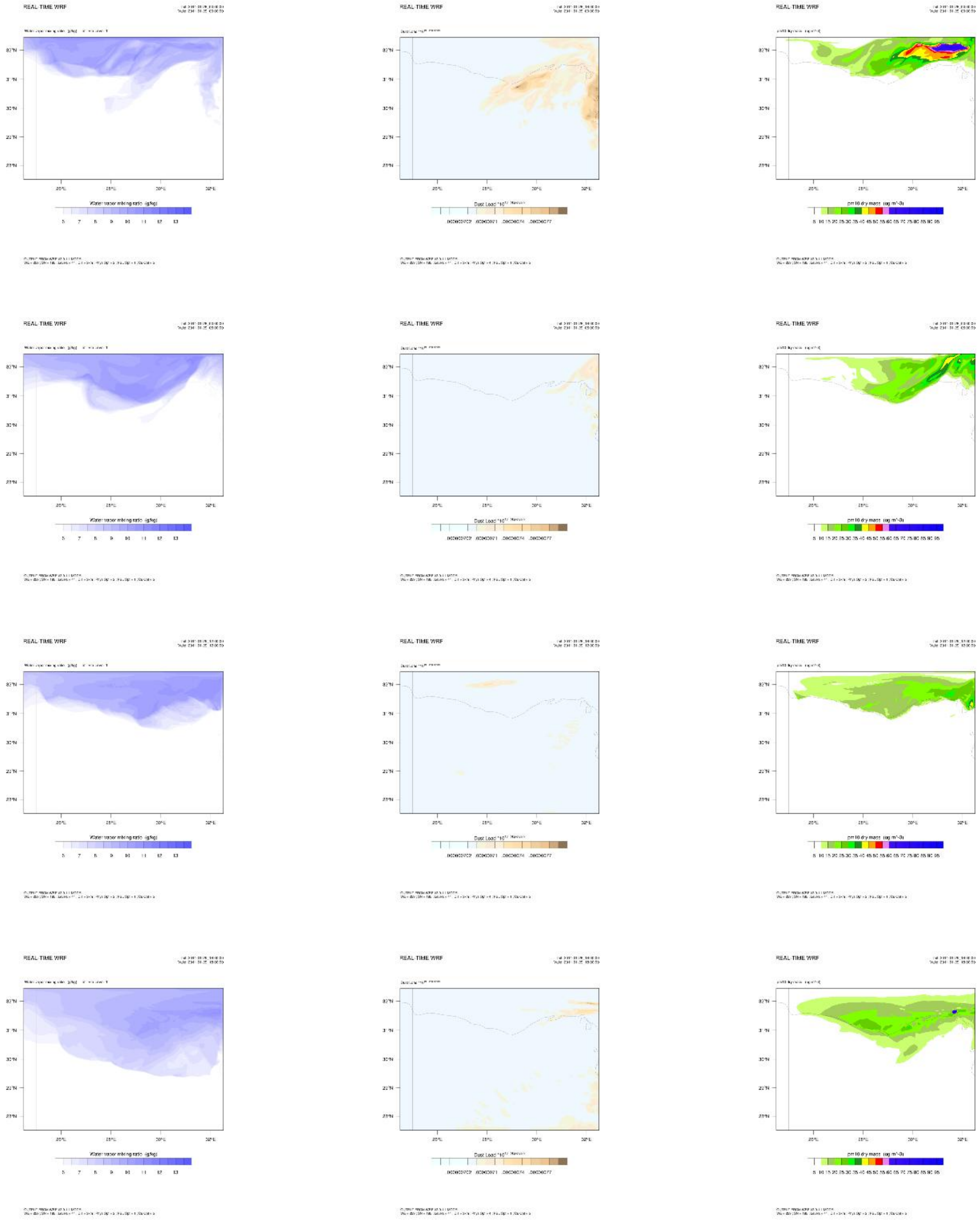


Fig 7: Water vapor mixing ratio (left column), dust concentration (middle column), and PM10 concentration (right column)

Below-cloud scavenging

As alluded earlier we adopted point time series analysis to spot below-cloud scavenging. We carried out point validation in two different points in the course of dust storm movement:

- Coastal (Alexandria City): According to AERONET synergy tool when Dust storm was passing over Alexandria it was capture by Terra MODIS satellite whose satellite overpass time in between 7:30 and 9:15 UTC, as seen from Terra image and its WRF corresponding time; Figure 8. Then, we extracted both PM10 and Rain for Alexandria and plotted PM10 time series all together with rainfall time series to study the interaction (washout). The time series analysis is shown in Figure 9. The plot shows two rain peaks (the right axis) the first was at time 2011-01-28:15 (16 hours from initial time); was less than 0.3 mm and was prior to the dust plum peak between times 2011-01-29:06 and 2011-01-29:07 (30 hours from initial time) as seen both from MODIS Terra image and from WRF model plot and chart. So the dust missed rain and no interaction took place; in other words, wet deposition occurred and the decrease in PM10 may be due dry deposition by wind removal. The second (relatively larger) rain peak between times 2011-01-30:02 and 2011-01-30:03 (51 hours from initial time) did not miss the aerosols existing and a washout (wet deposition) was responsible for the sharp decrease in PM10 concentration in the successive hours, as shown in Figure 10.

- Inland (Cairo City): According to AERONET synergy tool when Dust storm was passing over Cairo city it was capture by Aqua MODIS satellite whose satellite overpass time in between 10:40 and 12:25 UTC as seen from Aqua image and its WRF corresponding time; Figure 11. Then, we extracted both PM10 and Rain for Cairo and plotted PM10 time series all together with rainfall time series to study the interaction (washout). The time series analysis is shown in Figure 12.

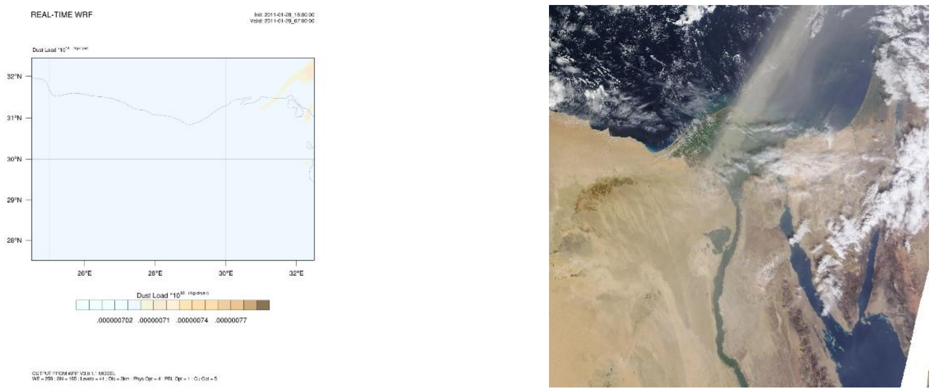


Fig 9: Terra image and its WRF corresponding time.

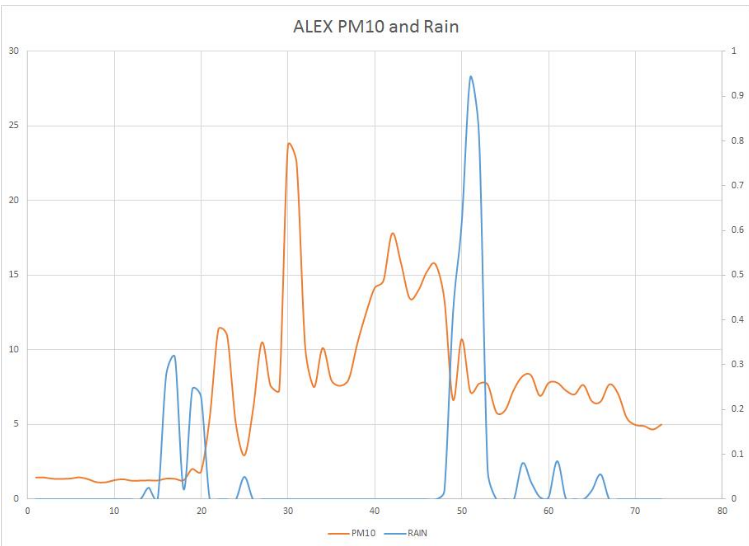


Fig 10: PM10 and Rain time series analysis for Alexandria.

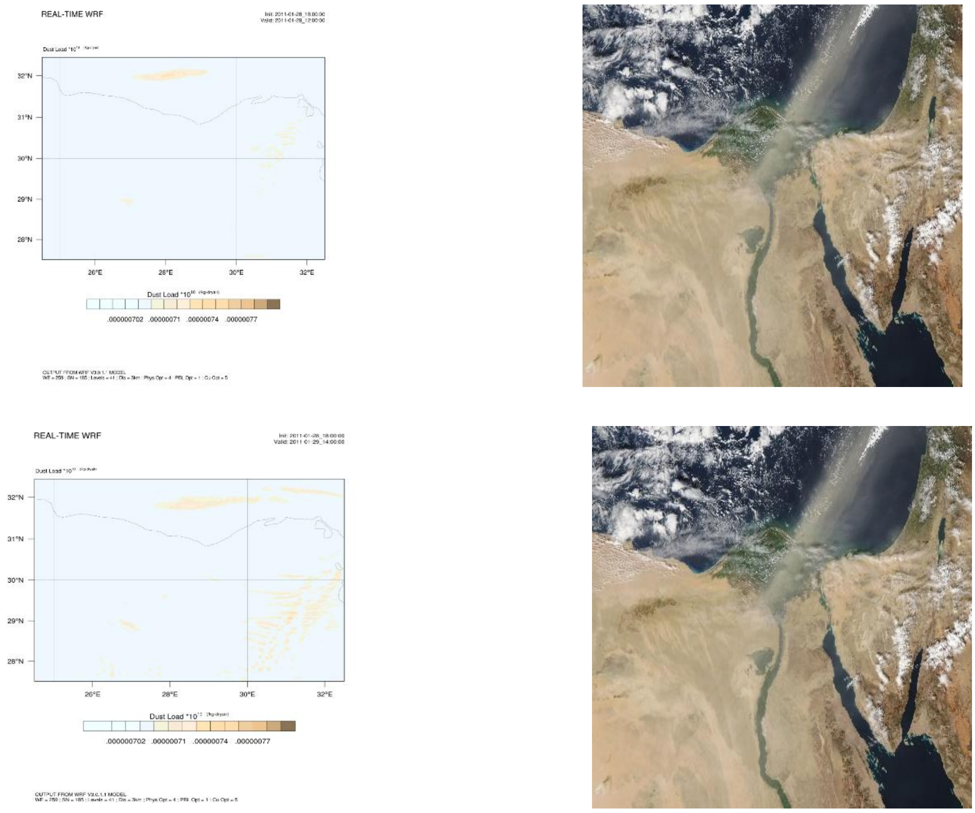


Fig 11: Aqua image and its WRF corresponding time

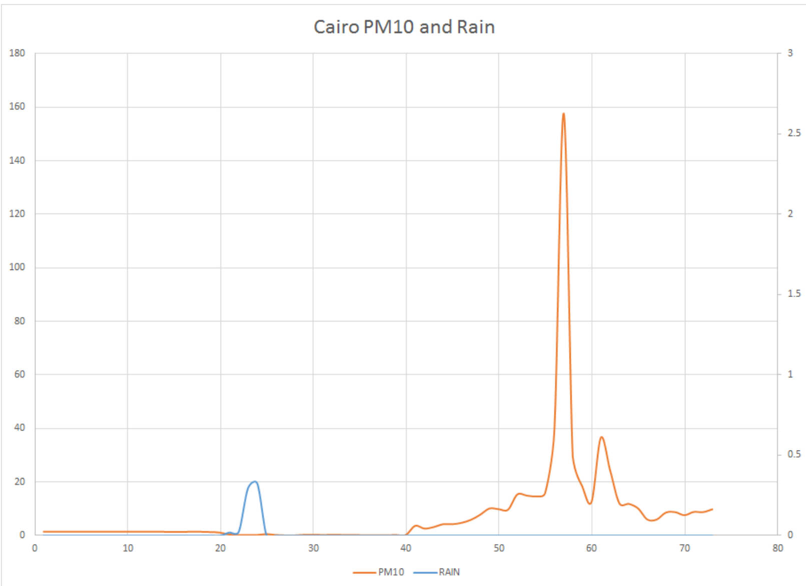


Fig 12: PM10 and Rain time series analysis for Cairo.

Conclusion

In this article we assessed the WRF-CHEM model capability in predicting dust and rain individually; each in turn, and the model option to account for the interaction between dust and rain, in the cloud formation stage and in wet deposition stage, the model could capture accurately the spatial distribution as well as analyze the temporal variation of dust and rain separately, furthermore the model managed to reveal in depth the nature of aerosol-cloud interaction from the very beginning at cloud activation process, through growth and development in cloud droplet formation, up to autoconversion process in which the cloud droplet converts to rain droplet causing the two types of aerosol removal in-cloud scavenging and below-cloud scavenging. We experienced the impact of the in-cloud nucleation via growth of PM10 mass concentration, and inspect below-cloud scavenging through the sharp decrease in PM10 mass concentration, in time series, shortly after a rain event in the so-called washout.

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