Numerical modeling and hazard analysis of Kuwait dust storm events using WRF Chemistry model

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Abstract: Dust storms have a negative impact on socio-economic events in Kuwait, including traffic accidents, seaport closures, airport shutdowns, and flight delays, and agriculture degradation. From the diurnal analysis of weather parameters, it was noticed that dust storms were more severe from noon to late evening hours and gradually slowed down during the night hours. Sometimes, these strong dust storms may last up to 2-3 days in a row. WRF-Chemistry (WRF-Chem) model has been implemented to analyze the genesis, intensification, and dissipation of the dust storm events. From the WRF-Chem model simulations, it was noted that the diurnal variations of the weather parameters such as relative humidity, temperature, and wind speed associated with the dust storms are realistically simulated over the State of Kuwait and significantly comparable with the station observations. It was also noted that there are a significant variation in the amount of dust deposition, dust concentration, and dust emission both spatially and temporally at district-levels all over Kuwait. From WRF-Chem model simulations, it was noted that during a strong event, the maximum daily-accumulated dust deposition could reach up to 140-160 g/m^2. However, during the moderate and low dust storm events, the values are up to 60-80 g/m^2 and 20-40 g/m^2 respectively. During a strong dust storm event, the daily accumulated dust concentrations could reach up to 0.18-0.2 g/m^3 and the dust particles can rise up to 3 km in the air from ground surface. However, the vertical extents of the dust particles in the air can rise up to 2.5 km and 1 km from ground surface during the moderate and low events respectively. Dust storms have no fixed season of occurrence in Kuwait, hence an early warning system for dust storms should be implemented and public awareness should be increased to mitigate the hazard's impacts.

Keywords: Dust storm, WRF-Chemistry, Dust storm hazard analysis

1. Introduction

Dust storms are common meteorological hazards in arid and semi-arid regions. Kuwait is one of the countries affected severely by dust storms. The dust storms affecting the State of Kuwait are mostly cross border phenomena primarily driven by large-scale circulations. From the ECMWF climatological data analysis, it was noted that the airstreams over the Arabian Peninsula were generally stronger during June, July, and August due to the high-pressure area that sits over this region and creates strong pressure gradients between the Arabian Peninsula and the Mediterranean region. At the same time of the year, during June, July, and August, the peninsular region also experiences low humidity, high temperature, and high evaporation, which helps to drive the cross-border dust storm events over Kuwait. The most important prerequisite is the establishment of a sufficiently large low-level pressure gradient to drive strong winds capable of dust emission and long-range transport. During the summer months, there are two main continental heat lows, the first low-pressure area established over the border of India and Pakistan and the second one over the Arabian Peninsula. The heat lows over the Arabian Peninsula start developing in May, rises to its peak during July, and then gradually slows down to its lowest point in October. However, the most prominent heat lows over the Arabian Peninsula are noticed during June, July, and August, from the ERA-Interim monthly mean analysis (Dee et. al., 2011). The areas with strong inflow into these Arabian Peninsula heat lows are located northwest of Kuwait. The strong airstreams pass over dust source regions leading towards the marked heat lows causing dust storms that are more frequent over Kuwait and adjacent regions during the months of June, July, and August as compared to the rest of the months. Al-Dousari and Al-Awadhi (2012) identified five major source areas of dust for Kuwait, which are the western desert of Iraq, the Mesopotamian flood plain in Iraq, the northern desert of Saudi Arabia, the drained marshes in southern Iraq, and the dry marshes and abandoned farms in Iran. It is widely accepted that the use of a dust source function improves the estimation of dust emission fluxes in global/regional models (Ginoux et al., 2001; Schepanski et al., 2009; Zender, Newman, & Torres, 2003). The major dust sources are located in north and northwest parts of Kuwait, and since the winds dominantly blow from north and northwesterly directions during the summer months (mostly dry conditions) starting from April to October, this leads to more frequent dust storms over Kuwait during the summer months as compared to rest of the year. The recent study conducted by Al-Hemoud et. al., (2019) discussed the socioeconomic impact and risk assessment of sand and dust storms in Kuwait and their mitigation strategies.

2. Methodology and Experimental design

2.1. Study area

A single domain was selected to simulate the dust storm events having horizontal resolution of 9 km and 51 vertical levels with 255 and 251 grid points, respectively along west to east and south to north directions. The model domain selected to simulate the dust storm events over Kuwait is shown in **Error! Reference source not found.**. The extent of the model domain was considered to cover the sources of dust emissions surrounding the State of Kuwait.

2.2. WRF-Chem model

The Weather Research and Forecasting model coupled with Chemistry module (WRF-Chem) version 3.9 is used to simulate dust storm events over the State of Kuwait. WRF-Chem is a coupled non-hydrostatic limited-area numerical model, able to simulate both meteorological fields and dust particle transport and their reciprocal feedbacks (Grell et al., 2012, Grell et al., 2005). It is both a research and operational model, which simulates and predicts the atmospheric concentrations of different gases and particles, taking into consideration natural mechanisms and human activities (pollutants) that affect dust particles of different sizes, considering the ways they are emitted and deposited.

Fig. 1: WRF-Chem model domain for the historical dust storm simulation

The initial and boundary conditions necessary to run the WRF model were obtained from the global model NCEP-NCAR Final Analysis (FNL) at 1º X 1º grid resolution . The FNL data can be further interpolated to model grid resolutions using the dynamical downscaling technique. The sources of these datasets are available every six hours and can be downloaded from the website. The vertical profile for each chemical species to start the model simulation was obtained from the climatology based upon results from a NOAA-Aeronomy Laboratory Regional Oxidation Model (NALROM). The physics parameterizations used in the model simulation are WSM-6 cloud microphysics (Hong et al, 2004), Grell cumulus parameterization (Grell et al, 1994), YSU planetary boundary layer scheme (Hong et al 2006), Unified Noah land surface model (Tewari et al, 2004), Monin-Obukhov surface layer option (Monin and Obukhov 1954), Goddard shortwave radiation, RRTM longwave radiation and GOCART simple aerosol scheme (Ginoux et. al., 2001) for chemistry option. The aerosol chemistry, vertical turbulent mixing option and dry deposition of aerosols are turned on in the model simulation. The model simulated dust storm events were validated with MODIS terra and aqua satellite imageries.

2.3 Classification of dust storm

The list of dust storm days and associated hourly weather parameters were received from Kuwait Institute for Scientific Research (KISR). Ten selected dust storm events were analyzed in terms of their associated weather parameters such as surface temperature, relative humidity, wind speed, and visibility to understand their genesis, diurnal variation, intensification, and impact assessment. These 10-selected dust storm events are given in Table 1. The dust storm events are categorized as strong, moderate and low, followed by Hoffmann et al., 2008. Event-wise maximum wind speed, maximum wind gust, minimum relative humidity, and minimum visibility presented in Table 1 were estimated from all the participating or available station observations.

Table 1: Selected dust storm events over Kuwait during 2007-2018

Events	Event date		Max Wind Speed (m/s)	Max Wind Gust (m/s)	Min RH (%)	Min Visibility (km)	Category
Event 1	26-06-2007	28-06-2007	13.6	22	4	0.8	Low
Event 2	05-06-2008	07-06-2008	18.9	25.3	4	0.3	Moderate
Event 3	30-06-2011	02-07-2011	20.4	27.7	3	0.2	Strong
Event 4	05-06-2012	07-06-2012	19.2	24.7	2	0.3	Moderate
Event 5	05-07-2012	07-07-2012	20	28	4	0.2	Strong
Event 6	02-06-2013	05-06-2013	16.6	24	2	0.6	Low
Event 7	07-06-2015	09-06-2015	18.1	23.2	2	0.4	Moderate
Event 8	13-03-2017	15-03-2017	16.7	22.2	5	0.5	Low
Event 9	27-06-2018	28-06-2018	17.2	23.2	5	0.4	Moderate
Event 10	27-07-2018	30-07-2018	20.7	28.8	3	0.2	Strong

2.4 Sensitivity study with dust emission schemes

Sensitivity tests were conducted to choose the best performing dust emission parameterization, which should be compatible with the GOCART simple chemistry parameterizations and other physics parameterizations used for these simulations. Two different dust emission parameterizations were analyzed, one is simple GOCART dust emissions (hereafter: dust1; (Ginoux et. al., 2001)) and the second one GOCART dust emissions with Air Force Weather Agency (AFWA scheme (LeGrand et. al., 2019)) modifications (hereafter: dust3).

3. Result and Discussion

3.1. Evaluation of meteorological parameters

The WRF-Chem model validations for both "dust1" and "dust3" were conducted for simulated weather parameters such as surface relative humidity (at 2m; Rh2m), surface wind speed (at 10m; ws10m), and surface temperature (at 2m; T2m) along with the available weather observations at various stations for the 12th to14th March 2017 dust storm events. For 12th to 14th March 2017 dust storm simulation, WRF-Chem model was initialized at 0000 UTC (0300 hr. Arabian Standard Time, AST) on 12th March 2017, and simulated for 72-hr up to 0000 UTC on 15th March 2017.

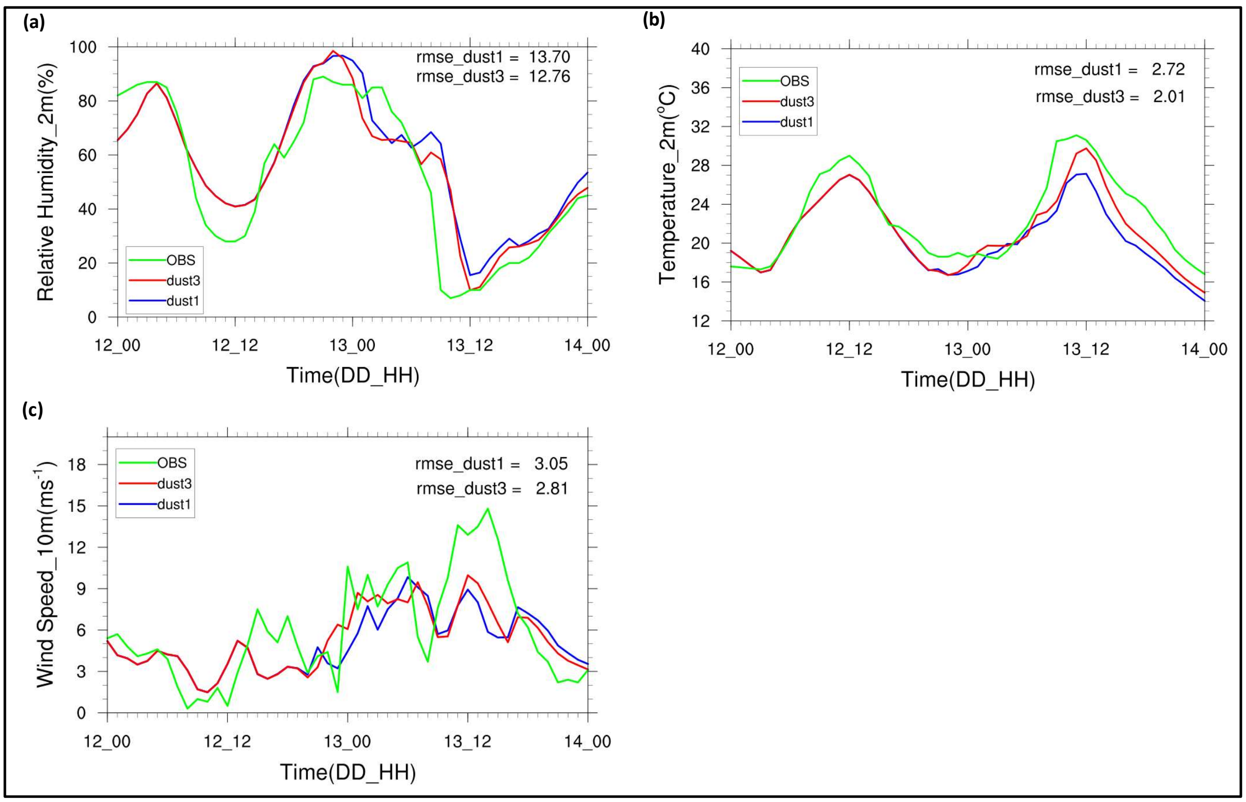


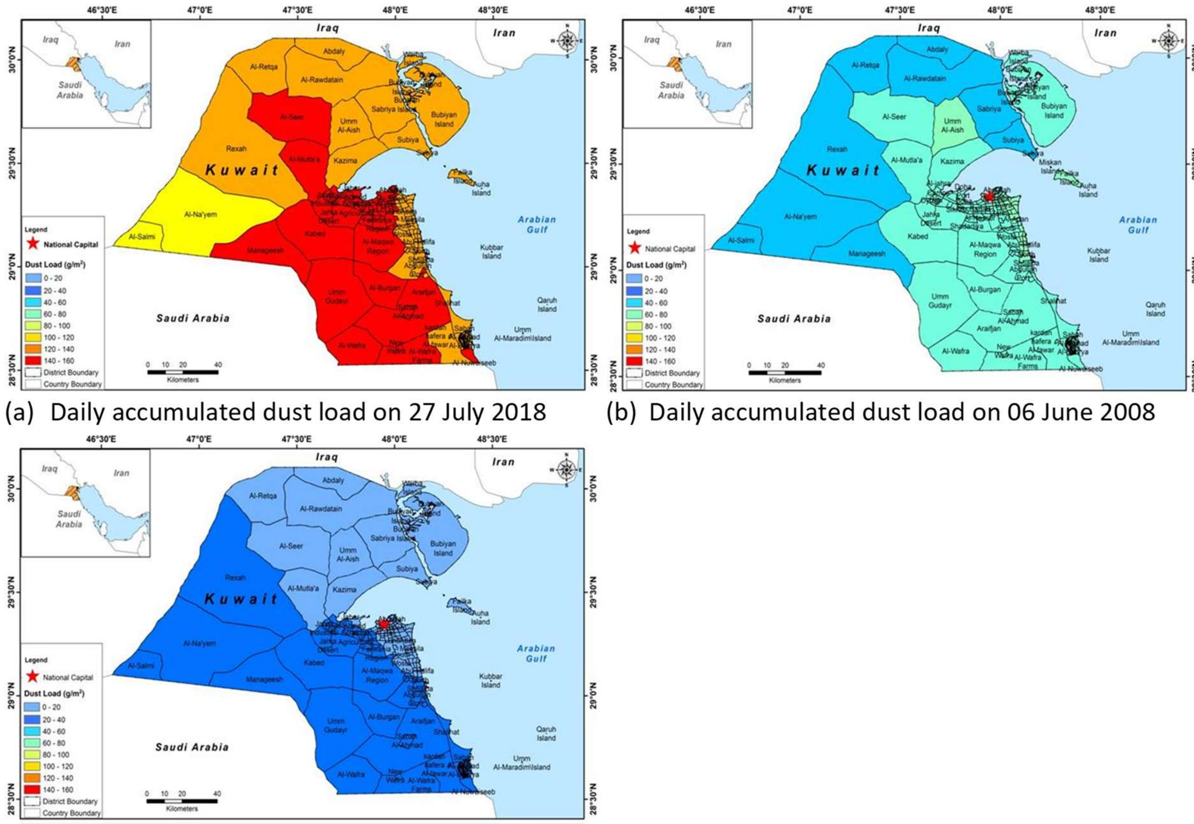
Fig. 1: Time-series analysis and comparison between WRF-Chem model simulated and station observations for (a) surface relative humidity, (b) surface temperature and (c) surface wind speed at Sabriya, Kuwait for 12th and 13th March 2017

The time-series analysis for Rh2m, ws10m and T2m at Sabriya station for 12th and 13th March 2017 is shown in Fig. *1*. Similar time-series analyses have been conducted for all available station observations. It was noticed that both the experiments, dust1 and dust3 simulated exactly similar values for Rh2m, ws10m, and T2m on 12th March 2017 (prior to dust storm); however, there are significant variations between both the model simulations during the dust storm day (after 24-hr simulation). Fig. *1* shows that both the model simulations realistically captured the diurnal variations of surface relative humidity, wind speed, and temperature observations at Sabriya, Kuwait. It was also noticed that, “dust3” parameterization simulated lower relative humidity, higher temperature and higher wind speed during the dust storm day as compared to “dust1” parameterization and closer to observations (Fig. 1). The root mean squared error (RMSE) was estimated for all three weather parameters to quantify the best-performing dust parameterization and to implement for the dust storm simulation within the WRF-Chem model. It was noticed that the RMSE values of “dust3” parameterization are consistently less as compared to “dust1” parameterization in Rh2m, ws10m, and T2m simulations at Sabriya, Kuwait. Similar, results also obtained from the majority of the dust storm events. These weather parameters are mostly responsible for the genesis and intensification of dust storm events. Hence, “dust3” parameterization was selected for the historical dust storm simulations. WRF-Chem model simulations could not be validated for dust parameters such as dust concentration and dust deposition, due to the unavailability of such observations.

3.2 Spatiotemporal analysis of dust parameters

The WRF-Chem model simulated dust parameters such as dust loading, dust concentration and dust emission are inter-compared between strong, moderate and low dust storm events. The daily-accumulated dust load maps at district-level for the State of Kuwait during strong, moderate, and low dust storm events are depicted in Fig. 2. The WRF-Chem model simulated dust load was computed from the sum of five bin sizes of dust particles used in the model simulations: 0–2 μm, 2–3.6 μm, 3.6–6 μm, 6–12 μm, and 12–20 μm. The dust load maps generally describe the amount of dust deposition over a particular place or district within a certain period of time. It was noticed that almost all districts of the State of Kuwait are vulnerable to dust deposition during strong to moderate dust storm events. It shows that during the strong dust storm event, the maximum daily accumulated dust deposition could reach up to 140-160 g/m^2 (Fig. 2). However, during the moderate dust storm event, the values could rise up to 60-80 g/m^2 (Fig. 2). The daily-accumulated dust deposition at district-level are comparatively less during the low dust storm events and the values could rise up to 20-40 g/m^2 (Fig. 2). Similar analysis has also been conducted for dust emission and dust concentration. It has been noticed that the western and northwestern districts are more susceptible to dust emissions during cross border dust storm events. It depicts that the daily-accumulated dust emissions over the highly susceptible districts are up to 16-20 g/m^2 during the strong and moderate dust storm events.

However, it is very low, i.e. up to 0-4 g/m^2, during the low dust storm events. The district-level dust concentration values near the surface could reach up to 0.12-0.15 g/m^3 during strong dust storm events. However, the near-surface dust concentration values are up to 0.03-0.06 g/m^3 during moderate to low dust storm events.



(a) Daily accumulated dust load on 27 July 2018 (b) Daily accumulated dust load on 06 June 2008

(c) Daily accumulated dust load on 13 March 2017

Fig. 2: WRF-Chem model simulated daily accumulated dust load (g/m^2) from (a) strong dust storm event 27-30 July 2018, (b) moderate dust storm event 05-07 June 2008 and (c) low dust storm event 13-15 March 2017

Fig. 3 depicts the time-height analysis of dust concentration during the strong, moderate, and low dust storm events at Kuwait City. It shows that dust particles can rise in the air up to a height of 3km from the surface during the strong event. Whereas, during moderate and low dust storm events, it can rise up to 2.5 km and 1 km respectively above the ground surface. The magnitudes of dust concentration are comparatively higher near the surface. It was also noted that, dust concentrations are comparatively higher at stations located in the western part of Kuwait, which are more exposed to dust emission as compared to the Kuwait City Station.

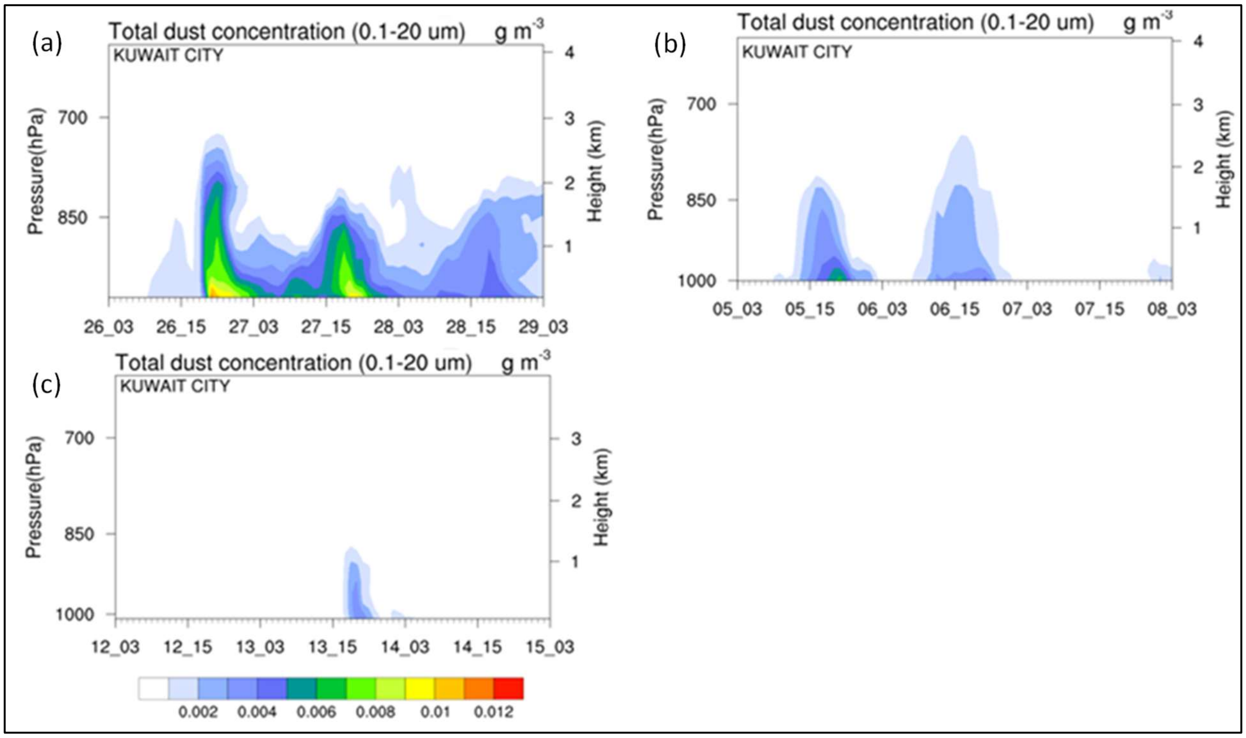


Fig. 3: Diurnal variations of WRF-Chem model simulated vertical profiles of the total dust concentration (g/m^3) at Kuwait City (a) strong dust storm event (26-28 July 2018), (b) moderate dust storm event (05-08 June 2008) and (c) low dust storm event (13-15 March 2017). X-axis shows Date and Hour (DD_HH) in AST

4. Conclusion

From the diurnal analysis of weather parameters, it was noticed that dust storms were more severe during noon to late evening hours and gradually slowed down during the night hours. Sometimes, these strong dust storms may last up to 2-3 days in a row. From the WRF-Chem modeling study, it was noticed that there were significant variations in the amount of dust deposition, dust concentration, and dust emission spatially at district-levels and temporally at 3-hourly and hourly time scales. Similarly, there are also significant variations in the dust parameters during strong, moderate and low dust storm events. From the weather parameter validation, it was noted that the GOCART dust emissions with AFWA scheme was outperformed the simple GOCART dust emission scheme. The WRF-Chem modeling system realistically captured the diurnal variations of the weather parameters such as relative humidity, temperature, and wind speed associated with the dust storms over the State of Kuwait. However, there were some differences in the magnitudes, which could be improved through the parameterization sensitivity and data assimilation research in the WRF-Chem model. This study inferred that

WRF-Chem model can be recommended for the dust storm hazard analysis at district level and at hourly or sub-hourly time scale. The model can be further validated for the dust parameters with ground observations and remote sensing products. The WRF-Chem modeling system can also be used as a real-time forecasting tool for dust storm forecasting and early warning system in the State of Kuwait and the Arabian Peninsula.

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