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Sensitivity of the meteorological model WRF-ARW to planetary boundary layer schemes during fog conditions in a coastal arid region

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ABSTRACT

In this study, we intercompare seven different PBL schemes in WRF in the United Arab Emirates (UAE) and we assess their impact on the performance of the simulations. The study covered five fog events reported in 2014 at Abu Dhabi International Airport. The analysis of Synoptic conditions indicated that during all examined events, the UAE was under a high geopotential pressure and light wind that does not exceed 7 m/s at 850 hPa (~1.5 km). Seven PBL schemes, namely, Yonsei University (YSU), Mellor-Yamada-Janjic (MYJ), Moller-Yamada Nakanishi and Niino (MYNN) level 2.5, Quasi-Normal Scale Elimination (QNSE-EDMF), Asymmetric Convective Model (ACM2), Grenier-Bretherton-McCaa (GBM) and MYNN level 3 were tested. In situ observations used in the model's assessment included radiosonde data from the Abu Dhabi International Airport and surface measurements of relative humidity (RH), dew point temperature, wind speed, and temperature profiles. Overall, all the tested PBL schemes showed comparable skills with relatively higher performance with the QNSE scheme. The average RH Root Mean Square Error (RMSE) and BIAS for all PBLs were 15.75% and −9.07%, respectively, whereas the obtained RMSE and BIAS when QNSE was used were 14.65% and −6.3% respectively. Comparable skills were obtained for the rest of the variables. Local PBL schemes showed better performance than non-local schemes. Discrepancies between simulated and observed values were higher at the surface level compared to high altitude values. The sensitivity to lead time showed that best simulation performances were obtained when the lead time varies between 12 and 18 h. In addition, the results of the simulations show that better performance is obtained when the starting condition is dry.

1. Introduction

Monitoring and forecasting hazardous weather conditions have always been critical for, among others, air traffic controllers, ground transportation authorities, urban planners, and energy users and producers. It is critical to understand such processes and develop the capabilities to monitor and forecast their dynamics with good accuracy. To this end, different mesoscale numerical weather prediction models were used around the world for short and medium range weather prediction with fine spatial resolution that reaches few hundred of meters. Examples of these models include the US Rapid Update Cycle (RUC) model (Benjamin et al., 2004), the Weather Research and Forecasting (WRF) model (Huang et al., 2008), the Consortium for Small Scale Modeling (COSMO) (Rockel et al., 2008), the Japan Meteorological Agency Non-Hydrostatic Model (JMA-NHM) (Saito et al., 2006), and the Canadian Mesoscale Compressible Community (MC2) model (Benoit et al., 1997).

Among the above-mentioned models, WRF (Huang et al., 2008; Wang et al., 2009) is widely used to forecast regional and local weather conditions for both research and operational applications with its two main cores, the Advanced Research WRF (ARW) and the Nonhydrostatic Mesoscale Model (NMM) developed first at NCAR and NCEP, respectively. The model has a wide range of physical parameterizations representing the cumulus, microphysics, planetary boundary layer (PBL), atmospheric radiation, and land surface processes that account for the interaction between the atmosphere and the earth's surface. The proposed parameterization options in WRF range from simple to more sophisticated and computationally costly ones that are updated regularly with newly developed versions. Depending on the model domain, spatial resolution, location, and application, researchers are reporting different simulation performances using different combinations of physical schemes to simulate atmospheric processes.

The PBL schemes, in particular, play a critical role in controlling the exchanges of mass, energy, and moisture between land, ocean, and atmosphere and therefore impact the performance of the simulations differently. They particularly influence the simulation of low level winds, cloud and diffusion of the dynamic, and the thermodynamic parameters (Garratt, 1994). They have been thoroughly studied in the literature in

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simulating the meteorological parameters and their impacts on the prediction of various atmospheric conditions like precipitation (Jankov et al., 2005; Wang et al., 2014), thunderstorms (Madala et al., 2014), wind and atmospheric flow (Carvalho et al., 2014; Hariprasad et al., 2014; Marjanovic et al., 2014), and for air quality forecast purposes (Cuchiara et al., 2014; Hu et al., 2010).

This study places a particular interest in studying the impact of PBL parameterizations and the lead time on the simulations of the meteorological parameters during fog events in the UAE. The formation, dispersion, and decay of fog have previously been modeled using one dimensional (1D) or three dimensional (3D) models or a combination of both. Steeneveld et al. (2015) used WRF and HARMONIE models to study fog events over the Netherlands and showed that the former simulates radiation fog well. They reported that the choice of PBL parameterization is critical for forecasting fog onset while fog dispersal is more affected by the choice of the microphysics scheme. This is in line with previous studies that reported different performances using different PBL schemes. Román-Cascón et al. (2012) found better performance with the MYNN 2.5 than QNSE and MYJ when simulating fog in Spain. Payra and Mohan (2014) used the ACM2 PBL scheme in the simulation of the ambient temperature, relative humidity and wind speed for the determination of a multi-rule-based diagnostic approach for fog prediction in New Delhi. Wong and Lai (2010) found an improvement of the parameterization of turbulent mixing and condensation processes with the MYNN3 scheme using the Hong Kong Observatory's Non-Hydrostatic Model. Steeneveld et al. (2015) reported more widespread fog areas with higher liquid water content with the simulation using YSU than with the MYNN 2.5 PBL scheme for fog simulation over Europe. They also noticed that the boundary layer formulation is more critical for the prediction of the fog onset while the choice of the microphysics scheme is the key element for fog dissipation forecast. Shi et al. (2012) compared MM5 to the coupled PAFOG-MM5 model for fog predictions in eastern China. Better performance of the MM5 model for the simulation of the advection-radiation fog was reported. Recently, Milovac et al. (2016) analyzed the impact of combination of non-local and local PBL schemes with different land surface models and concluded that the non-local PBL schemes simulate a deeper and drier convective boundary layer than the local schemes. Overall, when the sensitivity to PBL schemes is studied, different and inconsistent performances were reported (Román-Cascón et al., 2012; Steeneveld et al., 2015; Wong and Lai, 2010) which suggests that conclusions are site specific and therefore studies should be carried out for different sites for an accurate assessment. A one year study over Europe conducted by García-Díez et al. (2013) showed that the performance of WRF model in simulating surface temperature, temperature profiles and specific humidity using YSU, MYJ and ACM2 PBL schemes depend on the different atmospheric conditions that prevail on the different times of the day and the seasons. Wyszogrodzki et al. (2013) analyzed the errors in simulating the 2 m temperature and 10 m wind over the United States using YSU PBL scheme and found a great seasonal and diurnal variability in the biases that depend on the forecast length, geographic location and meteorological conditions.

In the UAE, fog is one of the most hazardous weather processes with an adverse impact on road and aviation traffic and requires particular attention to understand its precursors and triggers. In fact, the region faces different challenging weather conditions that include low-level wind shear, strong temperature inversions due to the daily sea breeze formation, low-level jet formation, dust storms, fog events, and the large diurnal temperature variations related to the desert surface. The influence of the Arabian Gulf and the Sea of Oman on the western and eastern side of the country where fog events are frequently reported is strong. This is augmented by the large difference between inland and open sea temperatures which fosters condensation in land overnight especially during the months of October, December, and January (De Villiers and Van Heerden, 2007). Fog formation occurs usually in the western desert of the UAE towards the Empty Quarter borders with Saudi Arabia. Fog in Abu Dhabi usually forms overnight as a result of strong temperature inversion that is characteristic to arid regions and directly related to changes in the PBL. Fog then expands towards coastal regions as daytime approaches and dissipates as surface temperature rises right after sunrise. In the UAE, like elsewhere in the world, proper modeling of these processes and particularly those related to PBL dynamics is required to accurately predict fog formation and dissipation.

The ability of different numerical weather models to simulate fog conditions was addressed in different parts of the world (Bartok et al., 2012; Gultepe and Milbrandt, 2007; Payra and Mohan, 2014; Shi et al., 2012; Zhou et al., 2009). In the UAE region, only a limited number of studies addressing this issue exist. Bartok et al. (2012) evaluated the use of the WRF-ARW model with the one-dimensional PAFOG model for simulating the thermodynamics variables during fog events and highlighted the important role of land-see breeze on fog formation in the coastal desert UAE cities. Bartoková et al. (2015) introduced a decision tree-based model that is coupled with WRF for fog nowcasting in the region of Dubai, in the UAE. In another attempt, Ajjaji et al. (2008) examined the use of WRF to simulated fog conditions recorded on March 11, 2008 in the UAE with a qualitative assessment of the impact of a limited number of PBL, radiation, and microphysics parameterization. Despite these previous attempts, the sensitivity of WRF to different PBL parameterization schemes has not been thoroughly addressed in the particular arid environment of the UAE. This study constitutes to our knowledge the first attempt to thoroughly and quantitatively assess and intercompare PBL schemes in WRF in the UAE during different fog events. The implementation of WRF for weather forecasts in an arid region like the UAE which is the focus of this study requires a particular analysis of the sensitivity to different PBL schemes. The goal is to depict differences between local and non-local schemes and possibly recommend the optimum scheme for the region that could outperform the other schemes in WRF. Five fog events were selected to verify the different schemes. The model was verified using in situ and profile observations at Abu Dhabi airport. The study also put the focus on the analysis of the sensitivity of the model to the simulation lead time.

2. Study area

This study focuses on the United Arab Emirates (UAE) that is located to the east side of the Arabian Peninsula (Fig. 1). It is surrounded by the Arabian Gulf from the north and the west, the Gulf of Oman from the east, and the Empty Quarter desert from the south. Al Hajar Mountains dominate the east side of the country along the coasts of the Gulf of

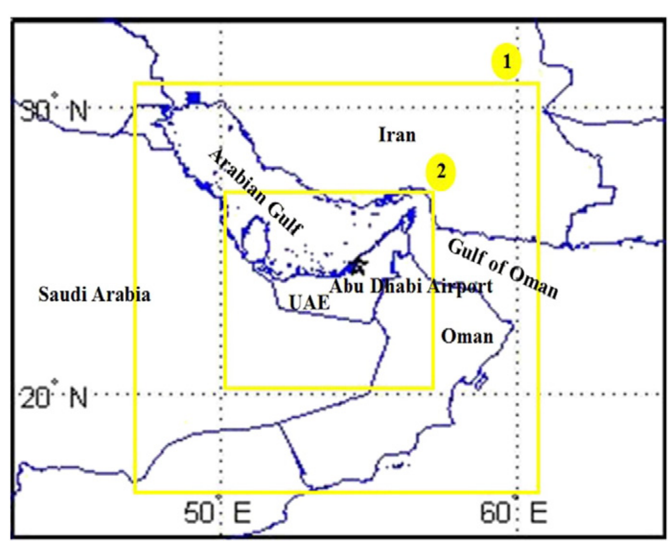

Fig. 1. Study area illustrated by WRF domain's setting, (1) parent domain and (2) nested domain.