



## Application of WRF-Chem Model to Simulate PM<sub>10</sub> Concentration over Bogota

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### ABSTRACT

The online meteorological and chemical transport Weather Research and Forecasting with Chemistry (WRF-Chem) model is implemented over Bogota and validated against ground-based observations for meteorological variables and PM<sub>10</sub> concentrations. The simulated average temperature shows a very small positive bias. The relative humidity and wind speed are also overpredicted for the selected simulations. The 24-h average PM<sub>10</sub> concentration is underpredicted compared to the overall ground observations. Overall, the present case study shows that the WRF-Chem model has an acceptable performance for meteorological variables as well as PM<sub>10</sub> concentration over Bogota. This study provides a general overview of WRF-Chem simulations and can serve as a reference for future air quality modelling exercises for PM<sub>10</sub> over Bogota.

**Keywords:** WRF-Chem; PM<sub>10</sub>; Air quality modeling; Bogota.

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### INTRODUCTION

Air pollution has become one of the most important concerns of the local authorities of Latin American cities as poor air quality can have adverse effects on human health including asthma, impaired lung function, cardiorespiratory illnesses and increased mortality rates (Mindell and Joffe, 2004), as well as on the ecosystem (Serengil *et al.*, 2010) and on climate (Menon *et al.*, 2008). Hence, there is a need for further research to estimate the impact of anthropogenic emissions on air pollutant concentrations in urban areas, as the largest contribution to anthropogenic emissions comes from urban sources that emit a large variety of gaseous and particulate species (Seinfeld and Pandis, 1998). Therefore, characterizing the impacts of urban pollutants requires detailed modeling studies. The main pollutants emitted into the atmosphere in urban areas are sulfur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), volatile organic compounds (VOCs), metal oxides, and particulate matter (PM/aerosols), mostly consisting of black carbon, sulfates, nitrates, and organic matter. These chemical pollutants include primary PM, which is directly emitted in the atmosphere from various sources (e.g., road traffic, construction sites, soil dust, fires), and secondary PM, which is formed in the atmosphere via chemical reactions in gas and aqueous phases, leading to the oxidation of precursors such as sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and volatile organic compounds

(VOC) to nonvolatile and semivolatile species. The recent economic developments in South America are accelerated due to the rapid growth of heavy industrial operations. The increasing urbanization in these countries will potentially cause wide-ranging consequences in terms of environmental problems. These areas have been suffering from severe air pollution problems for the past decade, and as industrial activity and the number of automobiles increases, the emission of PM, SO<sub>2</sub>, VOCs and NO<sub>x</sub> will also significantly increase. PM pollution, particularly in the respirable, fine and ultrafine size ranges – PM<sub>10</sub>, PM<sub>2.5</sub> and UFP, respectively – has become a field of great interest to scientists in recent decades because of its impacts on human health, climate change, and atmospheric visibility (Lecoeur and Seigneur, 2013). Thus, simulation of PM over urban areas is necessary to develop effective PM control strategies.

There are three main approaches, namely empirical, statistical, and deterministic, for air quality modeling. However, empirical and statistical approaches need more detailed historical data, and these approaches are also unable to address the physical and chemical processes of pollutants. The deterministic “3-D” air quality models combine emissions with meteorological and chemical atmospheric processes, and have been shown to lead to accurate forecasts. This approach is more computationally expensive and requires a higher-speed computer system with a larger memory and disk storage than empirical and statistical. However, there have been significant advances in computational technologies and computer architectures in the last two decades and these Atmospheric Chemistry Transport Models (ACTMs) are used to better understand the formation of gas and aerosol in the atmosphere. The ACTMs have several advantages. First, these models are capable of simulating the temporal

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and spatial concentrations under both typical and atypical scenarios (Zhang *et al.*, 2012). Second, they can be used as tools to assess the effects of past and future changes in aerosol (+ precursor) emissions (Gsella *et al.*, 2014). Third, they assist in the development of effective emissions reduction strategies to improve air quality. Fourth, these models do not require a large quantity of measurement data.

In recent years, many Chemistry-Transport Models (CTM) namely EMEP (Simpson *et al.*, 2003), TM5 (Krol *et al.*, 2005), CHIMERE (Bessagnet *et al.*, 2008), LOTOS-EUROS (Schaap *et al.*, 2008) and REMOTE (Langmann *et al.*, 2008) have been developed to better understand the physical-chemical processes of gas-phase species and particulate matter and are being applied in different parts of the world. However, most of the PM studies have focused on cities in the United States and Europe. CTMs are typically implemented in “offline” configuration, i.e., meteorological input is provided by an independent model, and is thus unable to simulate the complex aerosol-cloud-radiation feedbacks. Moreover, the decoupling of the meteorological and chemical models leads to a loss of information, due to the physical and chemical processes occurring on a time scale smaller than the output time step of the meteorological model (typically 1 hour) (Zhang, 2008). In addition, Grell *et al.* (2004) showed that most of the model variability in vertical velocity is attributable to higher frequency motions (period less than 10 minutes), yielding to much larger errors in vertical mass distribution in offline models with respect to “online” models, where meteorological and chemical processes are solved together on the same grid and with the same physical parameterizations (Zhang, 2008).

The main goal of the present study is to simulate the meteorological variables as well as PM<sub>10</sub> concentration using “online” meteorological and chemical transport Weather Research and Forecasting with Chemistry (WRF-Chem) model over Bogota for high PM<sub>10</sub> episodes. The evaluation of modeled meteorological variables and PM<sub>10</sub> concentration is based on comparison to ground-based observations over the study region. There are many reasons for focusing on Bogota. First, Bogota is the capital city of Colombia and fifth most populated city in Latin America with around 8.5 million inhabitants. Second, the emissions from traffic are currently an increasing concern for the city. Third, the levels of air pollutant concentrations have been shown to be well above the national ambient air quality standard, especially for PM<sub>10</sub>. Fourth, at present there is no extensive study that uses the WRF-Chem model to simulate the PM<sub>10</sub> concentration over Bogota. However, some combined techniques to estimate and evaluate the emission inventories have been done for air quality modeling studies over this region (Zarate *et al.*, 2007).

## METHODOLOGY

### WRF-Chem Model

WRF-Chem was developed at NOAA/ESRL (National Oceanic and Atmospheric Administration/Earth System Research Laboratory). Detailed descriptions of the model were given in Grell *et al.* (2005). Fast *et al.* (2006) updated

WRF-Chem by incorporating complex gas-phase chemistry, aerosol treatments, and photolysis scheme. The air quality component of WRF-Chem is fully consistent with the meteorological component; both components use the same transport scheme (mass and scalar preserving), the same horizontal and vertical grids, the same physical schemes for subgrid-scale transport, and the same time step for transport and vertical mixing. There are several different chemistry, aerosol and photolysis schemes to choose from in WRF-Chem (Grell *et al.*, 2005; Fast *et al.*, 2006).

In this work, the Lin *et al.* microphysics scheme (Lin *et al.*, 1983), the YSU (Yonsei University) PBL scheme (Hong *et al.*, 2006), and the NOAA (National Centers for Environmental Prediction-NCEP, Oregon State University, Air Force, and Hydrologic Research Lab) land surface model (LSM) (Chen and Dudhia, 2001) were used. Atmospheric shortwave and longwave radiations were computed by the Dudhia scheme (Dudhia, 1989) and by the RRTM (Rapid Radiative Transfer Model) scheme (Mlawer *et al.*, 1997), respectively. Two different gas phase chemistry schemes were used in this objective. The RADM2 (Regional Acid Deposition Model version 2) chemical mechanism (Stockwell *et al.*, 1990) and the Carbon Bond Mechanism version Z (CBMZ) (Zaveri and Peters, 1999) were used as gas-phase chemistry scheme. The MADE (Modal Aerosol Dynamics Model for Europe) aerosol mechanism (Ackermann *et al.*, 1998) coupled with the SORGAM (Secondary Organic Aerosol Model) parameterization (Schell *et al.*, 2001), and the Fast-J photolysis scheme (Wild *et al.*, 2000) were used for PM<sub>10</sub> simulations.

### Emissions

We used the global anthropogenic emissions data for gaseous species (CO<sub>2</sub>, CO, NO<sub>x</sub> = NO + NO<sub>2</sub>, SO<sub>2</sub>, NH<sub>3</sub>, and total Volatile Organic Compounds - VOCs) compiled and distributed by the Emission Database for Global Atmospheric Research (EDGAR) system (<http://www.mnp.nl/edgar>) (Olivier *et al.*, 2005). These emissions data were based on the EDGAR estimates for 2005.

### Experimental Design and Episode Selection

The modeling domains are presented in Fig. 1. The model was configured with three two-way nested domains with spatial resolution changing from 27 km to 3 km. The WRF-Chem version 3.5 model was built over a mother domain (D1) with a 27-km spatial resolution, 120 columns and 120 rows, centered at 4.61°N, 74.01°W. It covers Colombia, Ecuador, Venezuela, parts of the Pacific Ocean, the Atlantic Ocean and the Caribbean Sea. The first nested domain (D2) has a 9-km spatial resolution, 121 columns and 121 rows, and comprises the whole of Colombia. The innermost domain (D3) is centered over Cundinamarca area, which includes Bogota, with 121 columns and 121 rows of 3 km × 3 km grid cells. The vertical structure of the model includes 32 layers covering the whole troposphere. Topography, land use and land water datasets were interpolated from United States Geological Survey (USGS) with the appropriate spatial resolution of each domain (10', 2' and 30" for D1, D2 and D3 respectively). The model was

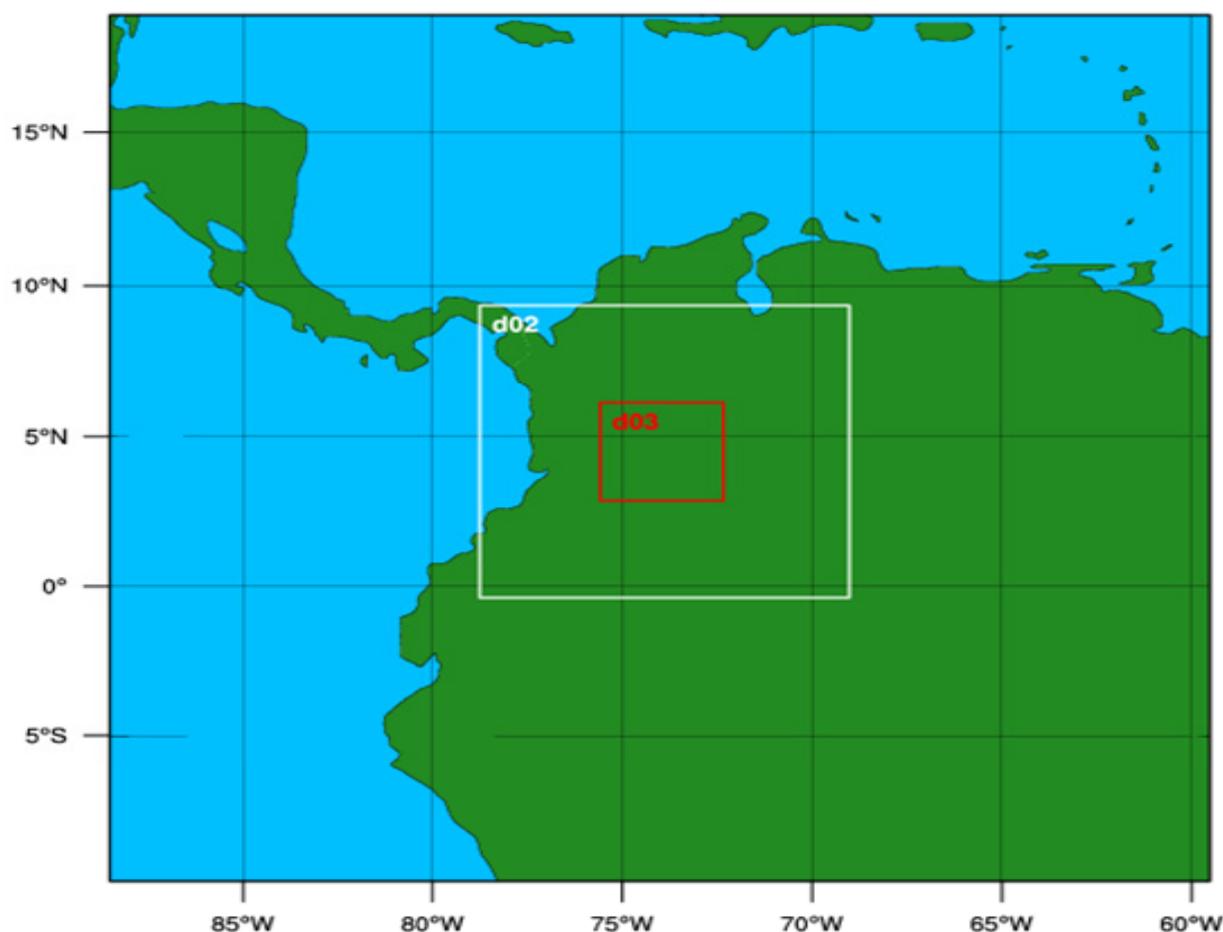


Fig. 1. Configuration of the WRF-Chem model domains.

initialized by real boundary conditions using NCAR-NCEP's Final Analysis (FNL) data (NCEP-DSSI, 2005) having a spatial resolution of  $1^\circ \times 1^\circ$  ( $\sim 111 \text{ km} \times 111 \text{ km}$ ) and a 6-h temporal resolution.

The simulation was conducted for six high particulate matter episodes; from 04 Jan 00 h to 06 Jan 06 h, 13 Jan 00 h to 15 Jan 06 h, 15 Feb 00 h to 19 Feb 06 h, 12 Mar 00 h to 14 Mar 06 h, 29 Jul 00 h to 31 Jul 06 h UTC of the year 2010 and 09 Feb 00 h to 11 Feb 06 UTC of the year 2012. The first 6 h of each period are considered spin-up time, while the remaining hours are used for analysis. The selection of temporal domain for particulate episodes is based on 24 h average  $\text{PM}_{10}$  concentration exceeding  $120 \mu\text{g m}^{-3}$  at a minimum of two monitoring stations for at least two consecutive days across the study area. This approach allows for the evaluation of the chemical transport model under different atmospheric conditions, which are relevant for air quality.

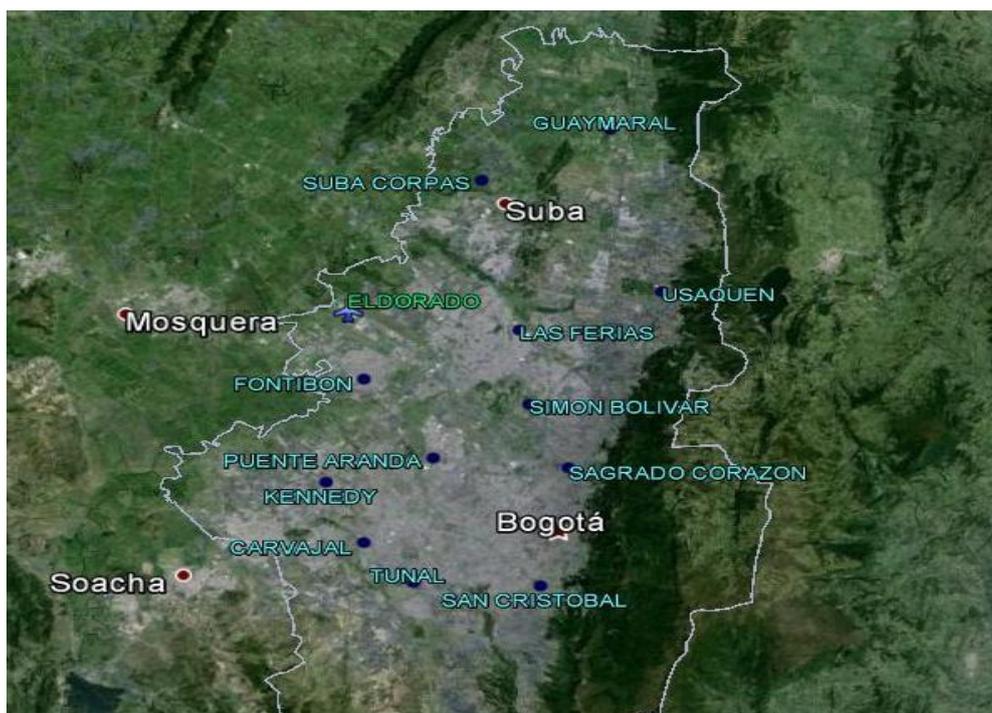
#### Observational Dataset and Evaluation Methodology

The evaluation of this study is carried out with the focus on the fine-grid domain (D3). There are 12 air quality stations, namely Carvajal, Fontibon, Guaymaral, Las Ferias, Simon Bolivar, Puente Aranda, Suba Corpas, Tunal, Usaquen, Kennedy, Simon Bolivar, Sagrado Corazon and San Cristobal, which were selected to provide the surface

meteorological and air pollutants observations on an hourly basis over Bogota. The locations of these stations are shown in Fig. 2.

Meteorological and chemical observational datasets from the aforementioned monitored stations are used for model evaluation. The meteorological variables evaluated include temperature at 2-m (T2), relative humidity at 2-m (RH2), wind speed at 10-m (WS10), and wind direction at 10-m (WD10). The chemical species evaluated is 24-h average  $\text{PM}_{10}$ .

The model is evaluated using discrete evaluation. Bias error (BE), gross error (GE), the root mean square error (RMSE) and index of agreement (IA) are calculated against all available meteorological observations. For meteorological parameters, according to a report for the MM5 Meteorological Model over the continental U.S. prepared for the U.S. EPA (Tesche and Tremback, 2002), bias should be  $\leq 0.5 \text{ m s}^{-1}$  for the wind speed;  $\leq 10^\circ$  for wind direction with a gross error of  $\leq 30^\circ$ ;  $\leq 0.5^\circ\text{C}$  for temperature with a gross error of  $\leq 2^\circ\text{C}$ ; and  $\leq 10\%$  for relative humidity with a gross error of  $\leq 20\%$ . However, BE can be  $30^\circ$  for wind direction in complex terrains. In addition, mean normalized bias (MNB) and mean normalized gross error (MNGE) are also calculated to check the performance of particulate matter. The mean fractional bias (MFB) criterion of 60% as suggested by Boylan and Russel (2006) is adopted for daily averaged



**Fig. 2.** The meteorological and air quality observations over the inner domain during the study period.

**Table 1.** Statistical evaluation of temperature, relative humidity, wind speed, and wind direction for different schemes for  $PM_{10}$  episodes.

Schemes	Error	T2	RH2	WS10	WD10
RADM2	BE	0.63	4.62	0.24	-6.51
	GE	1.91	11.56	1.21	102.83
	RMSE	2.42	14.30	1.64	133.73
CBMZ	IA	0.90	0.82	0.63	0.50
	BE	0.59	4.48	0.28	-9.08
	GE	1.91	11.64	1.22	103.11
	RMSE	2.40	14.35	1.67	134.43
	IA	0.90	0.82	0.63	0.51

$PM_{10}$  concentration in this study. The factor of two (FAC2) (0.50) and sigma ratio (0.5–1.5) are also considered to check the performance of a chemistry transport model for  $PM_{10}$  concentration. We have considered the same criteria for this study.

### Evaluation of Model Performance

#### Evaluation of Meteorological Variables

Table 1 summarizes the performance of WRF-Chem model for RADM2 and CBMZ gas phase chemistry for surface meteorological variables over  $PM_{10}$  episodes. This table shows that there are no significant differences between these two gas-phase chemistry schemes for meteorological variables. BE, GE and IOA with RADM2 are (0.63, 1.91, 0.90) and (4.62, 11.56, 0.82) for temperature and relative humidity respectively, and 0.24, 1.64 and 0.63 for wind speed. For the CMBZ scheme, BE, GE and IOA are (0.59, 1.91, 0.90) and (4.48, 11.64, 0.82) for temperature and relative humidity, respectively and 0.28, 1.67 and 0.63 for wind speed. The evaluation criteria of wind direction is not satisfied for

either scheme, and the BE, GE and MAE are (-6.51, 102.83, 78.65) and (-9.08, 103.11, 78.21) for RADM2 and CBMZ schemes, respectively. These statistics suggest that the model overpredicts surface temperature, relative humidity, and wind speed for these selected  $PM_{10}$  episodes. The slightly higher temperature may be due to the higher soil temperatures and higher sensible heat fluxes for these selected episodes. The overprediction of wind speed is consistent with other studies where WRF tends to overpredict WS10 due in part to unresolved topographical features by the default surface drag parameterization and in part to the use of coarse horizontal and vertical resolution of the domain (Cheng and Steenburgh, 2005; Mass and Ovens, 2010; Shimada *et al.*, 2011).

#### Evaluation of Chemical Prediction

The statistical evaluations for  $PM_{10}$  against the observations are shown in Table 2, which shows the performance of WRF-Chem model for RADM2 and CBMZ gas phase chemistry for 24-h average  $PM_{10}$  concentration over  $PM_{10}$  episodes. This table shows that BE, GE, RMSE, MNB,

**Table 2.** Statistical evaluation of 24-h average PM<sub>10</sub> for PM<sub>10</sub> episodes.

Schemes	BE	GE	RMSE	MNB	MNGE	MFB	$\sigma_m/\sigma_o$	FAC2
RADM2	-32.02	36.69	45.99	-37.52	42.99	-46.19	0.75	65%
CBMZ	-47.48	47.73	55.69	-55.64	55.93	-77.07	0.33	42.86%

**Table 3.** Statistical evaluation of hourly, daily maximum, day and night PM<sub>10</sub> with RADM2 scheme.

Evaluation	BE	GE	RMSE	MNB	MNGE	MFB	$\sigma_m/\sigma_o$
Hourly	-32.73	47.05	64.76	-38.07	54.73	-47.05	0.69
Daily Max	-73.32	88.05	106.33	-42.10	50.56	-53.32	0.84
Day	-27.13	39.06	47.87	-29.70	42.77	-34.88	0.89
Night	-37.81	40.85	51.65	-47.47	51.29	-62.24	0.54

MNGE, MFB and  $\sigma_m/\sigma_o$  are (-32.02, 36.69, 45.99, -37.52, 42.99, -46.19, 0.75) and (-47.48, 47.73, 55.69, -55.64, 55.93, -77.07, 0.33) for RADM2 and CBMZ schemes, respectively. It reveals that WRF-Chem model performs better with the RADM2 scheme than with the CBMZ scheme, with respect to all statistical errors for PM<sub>10</sub> episodes and, in addition, satisfies MFB criterion of 60% and sigma ratio (0.5–1.5) for PM<sub>10</sub> concentration. The model is underpredicting the 24-h average concentration of PM<sub>10</sub> against the observations for both the selected gas phase RADM2 and CBMZ schemes. This may result from the lack of exact emission rates of pollutants over the study domain. The statistical evaluations for hourly and daily maximum PM<sub>10</sub> predicted from RADM2 scheme against the observations are also shown in Table 3. This table shows that BE, GE, RMSE, MNB, MNGE, MFB and  $\sigma_m/\sigma_o$  are (-32.73, 47.05, 64.76, -38.07, 54.73, -47.05, 0.69) and (-73.32, 88.05, 106.33, -42.10, 50.56, -53.32, 0.84) for hourly and daily maximum, respectively. In addition, predicted concentration of PM<sub>10</sub> from RADM2 scheme is also statistically evaluated against the observations after dividing in two sub-categorizes (i) day time and (ii) night time in Table 3. This table reveals that BE, GE, RMSE, MNB, MNGE, MFB and  $\sigma_m/\sigma_o$  are (-27.13, 39.06, 47.87, -29.70, 42.77, -34.88, 0.89) and (-37.81, 40.85, 51.65, -47.47, 51.29, -62.24, 0.54) for day and night, respectively. It suggests that model is able to perform better for day time in comparison to night. So it concludes that WRF-CHEM is simulating the concentration of PM<sub>10</sub> better in unstable condition in comparison to stable condition over the study area.

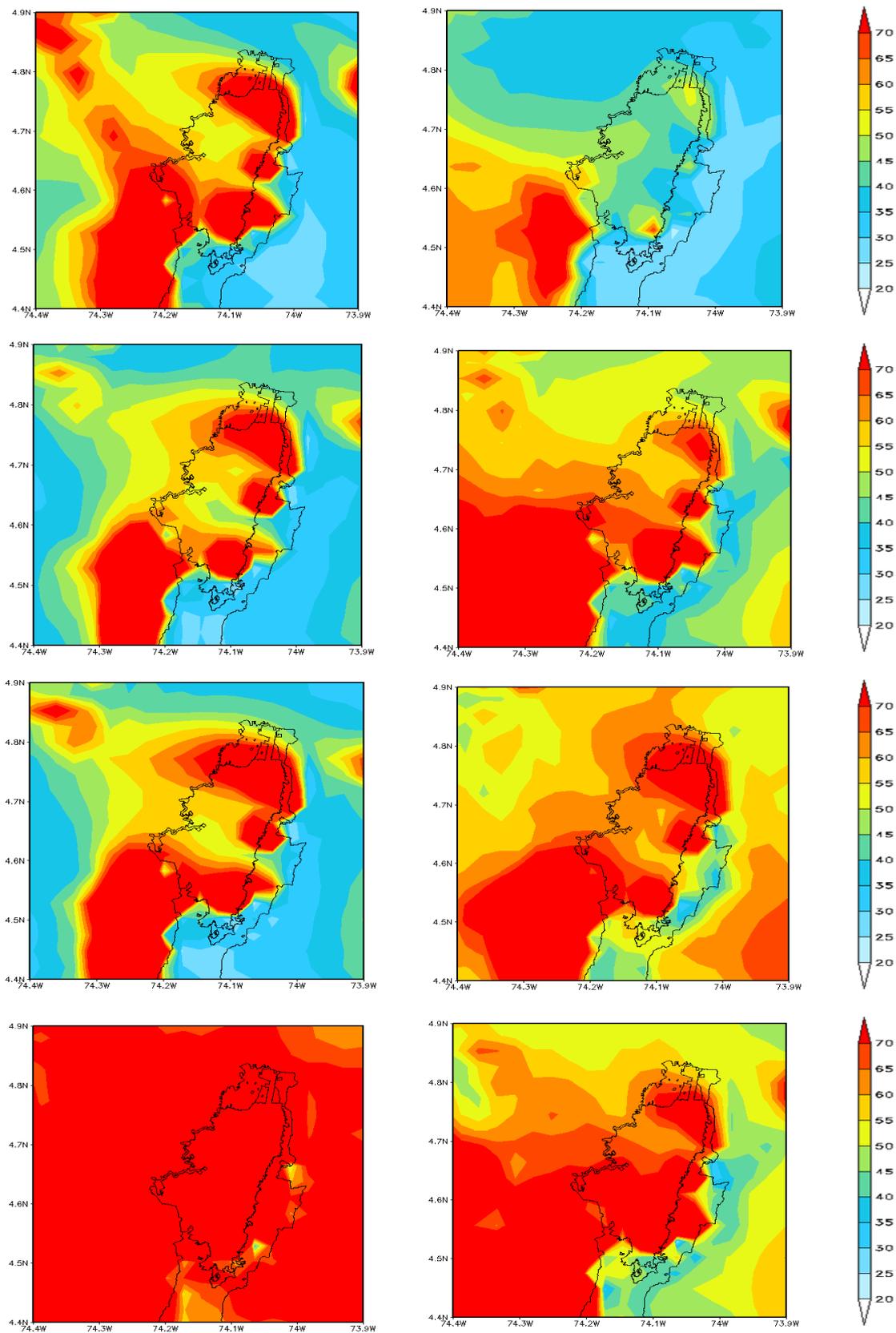
#### Spatial Evaluation

Figs. SM1–SM3 show the spatial distribution of 24-h average T2, wind field at 10m and RH2, respectively, over Bogota, with the RADM2 gas phase chemistry scheme for all 14 days of PM<sub>10</sub> episodes. Fig. SM1 shows that surface temperature is lower in the middle of the study domain, which may be because of the slightly higher altitude of this region. However, Fig. SM2 shows that wind speed over the Andes Mountains is higher than observations, probably because of the down-draft of wind over the mountain region. Fig. SM3 suggests that relative humidity at 2 m is mostly higher than observations in all selected episodes. Figs. 3 and 4 show the spatial distribution of 24 h average PM<sub>10</sub> for RADM2 and CBMZ gas phase chemistry schemes,

respectively, over Bogota for PM<sub>10</sub> episodes. Both figures show that the WRF-Chem model is able to show the spatially distributed PM<sub>10</sub> very well for all days of selected PM<sub>10</sub> episodes, and that the WRF-Chem model with the RADM2 scheme shows a higher 24-h average PM<sub>10</sub> concentration than the CBMZ scheme over the study domain.

#### Temporal Evaluation

The diurnal variations in observed and simulated surface temperature, wind speed, and relative humidity for RADM2 gas phase chemistry option averaged over each monitoring station for all 6 episodes are presented in Figs. 5, 6 and 7 respectively. These figures suggest that the model is able to capture the diurnal variation of these selected meteorological variables very well. The wind direction, being an angular quantity, is compared with wind roses. The hourly average angular distribution of WRF-chem model with RADM2 scheme simulated, and observed wind directions at 10 m is shown in the form of wind roses in Figs. 8(a) and 8(b), respectively. Both of these figures also show that simulated and observed prevailing winds are mostly from the southeast and southwest directions. Fig. 9 shows a comparison of 24-h average PM<sub>10</sub> concentration in the form of scatter plot for RADM2 and CBMZ schemes for all monitored stations. These figures show that the WRF-Chem model with RADM2 scheme is able to capture 65% of the 24-h average observed PM<sub>10</sub> within the FAC2. With the CMBZ scheme, the WRF-Chem model is able to capture only 42.86% of 24-h average observed PM10 within the FAC2, meaning that WRF-Chem performs better with the RADM2 scheme than with the CBMZ scheme for PM<sub>10</sub> simulations. Fig. 10 shows the hourly PM<sub>10</sub> concentration with RADM2 and CBMZ schemes average over all monitored station in Bogota. This figure is also showing that RADM2 scheme is performing better than CBMZ scheme for hourly PM<sub>10</sub>. In addition, this figure also suggests that peak concentrations are partially shifting from the time from the observations. It may be due to the biasness in simulated wind direction by the model and the selected pattern of hourly emissions. However, underestimation or overestimation may also be due to the other meteorological variables like wind speed and temperature as model is not able to simulate exact meteorological variables. Therefore, the inclusion of data assimilation techniques may improve the overestimation or underestimation.



**Fig. 3.** Spatial distribution of 24-h averaged WRF-Chem model (RADM2 scheme) simulated  $\text{PM}_{10}$  concentration ( $\mu\text{g m}^{-3}$ ) over Bogota for selected  $\text{PM}_{10}$  episodes. The left panel represents 04–05 Jan, 13–14 Jan, 15–16 Feb, 17–18 Feb, 12–13 Mar, 29–30 Jul of year 2010 and 09–10 Feb of year 2012 from the top down. Similarly, the right panel represents 05–06 Jan, 14–15 Jan, 16–17 Feb, 18–19 Feb, 13–14 Mar, 30–31 Jul of year 2010 and 10–11 Feb of year 2012 from the top down.

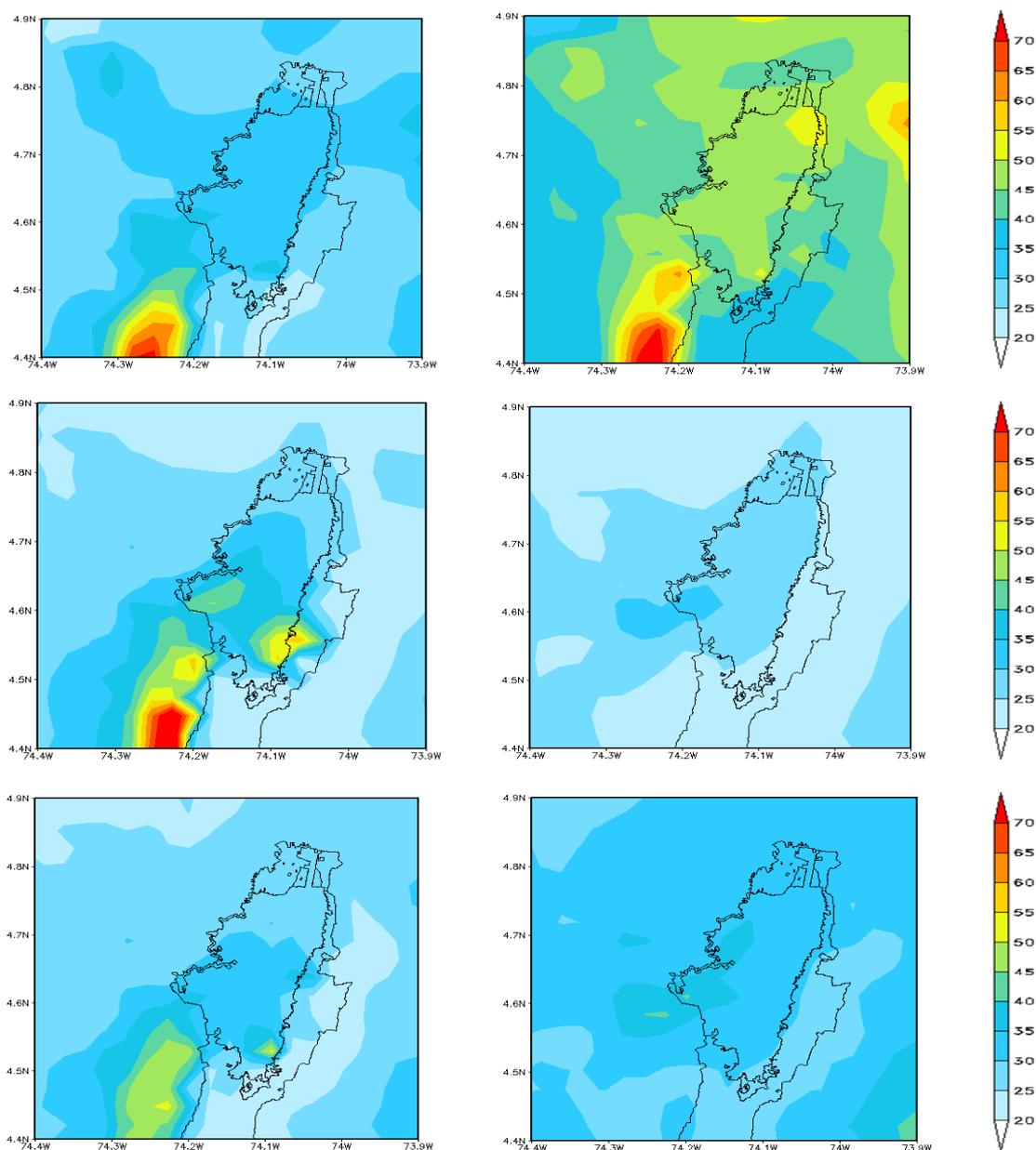


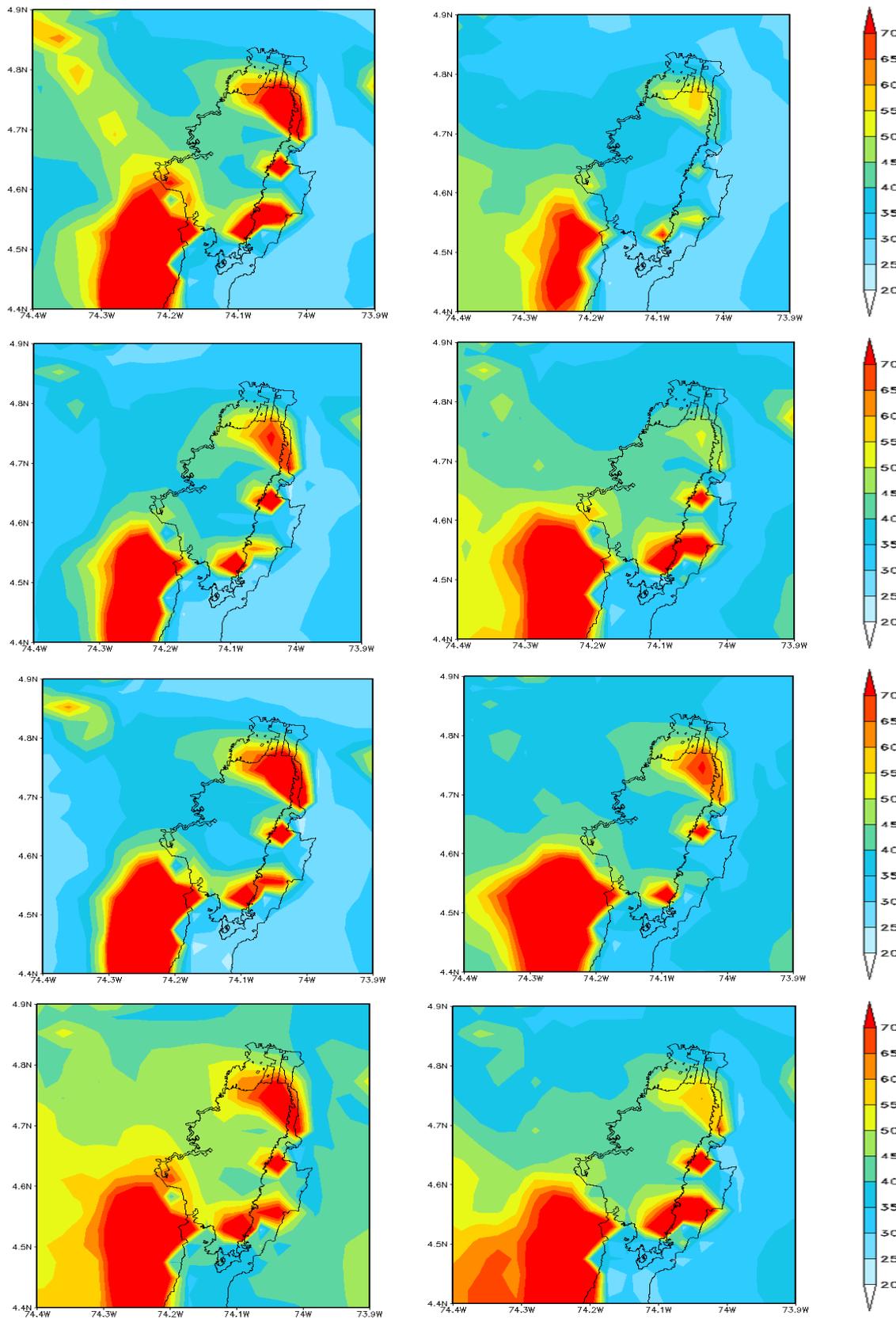
Fig. 3. (continued).

Fig. 10 also reveals that the WRF-Chem model is simulating higher 1-h  $PM_{10}$  concentrations for the first three episodes, namely 04–06 Jan, 13–15 Jan and 15–19 Feb, and lower 1-h  $PM_{10}$  concentrations for other three episodes, namely 12–14 Mar, 29–31 Jul of year 2010 and 09–11 Feb of the year 2012. This may be because WRF-Chem model has been simulated high wind speed for the first three episodes, as shown in Fig. SM2, thus particles are transported over Bogota from the Andes Mountains or outside Bogota.

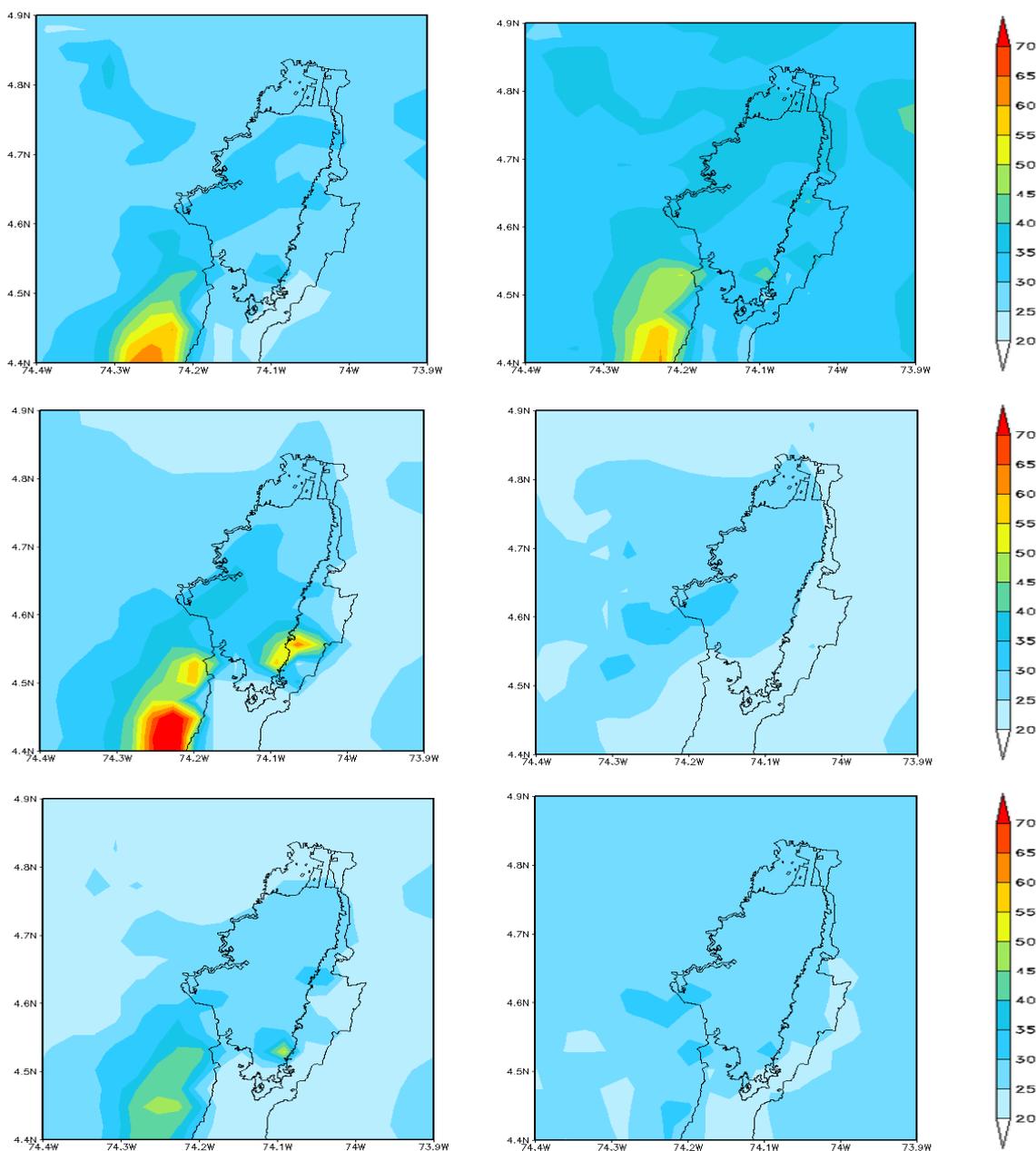
## CONCLUSIONS

In this study, WRF-Chem was used to simulate  $PM_{10}$  concentrations over Bogota. The simulations were evaluated in terms of domain-wide discrete evaluation, as well as

site-specific spatial and temporal evaluation. Sensitivity simulations using two different gas phase chemistry schemes, namely RADM2 and CBMZ. Discrete evaluation results show that the model underpredicts the 24-h average  $PM_{10}$  concentration. The WRF-Chem model performs better with the RADM2 scheme than with the CBMZ scheme with respect to all statistical errors, and it also satisfies the MFB criterion of 60% and the sigma ratio criterion (0.5–1.5) for  $PM_{10}$  concentration. Errors in simulating  $PM_{10}$  can be attributed to errors in simulating the  $PM_{10}$  components. Improving the simulations for  $PM_{10}$  species can help improve  $PM_{10}$  simulation overall. Bias in the simulations of  $PM_{10}$  species may compensate, leading to seemingly good  $PM_{10}$  simulations. The likely sources of errors in forecasted  $PM_{10}$  components include uncertainties in both



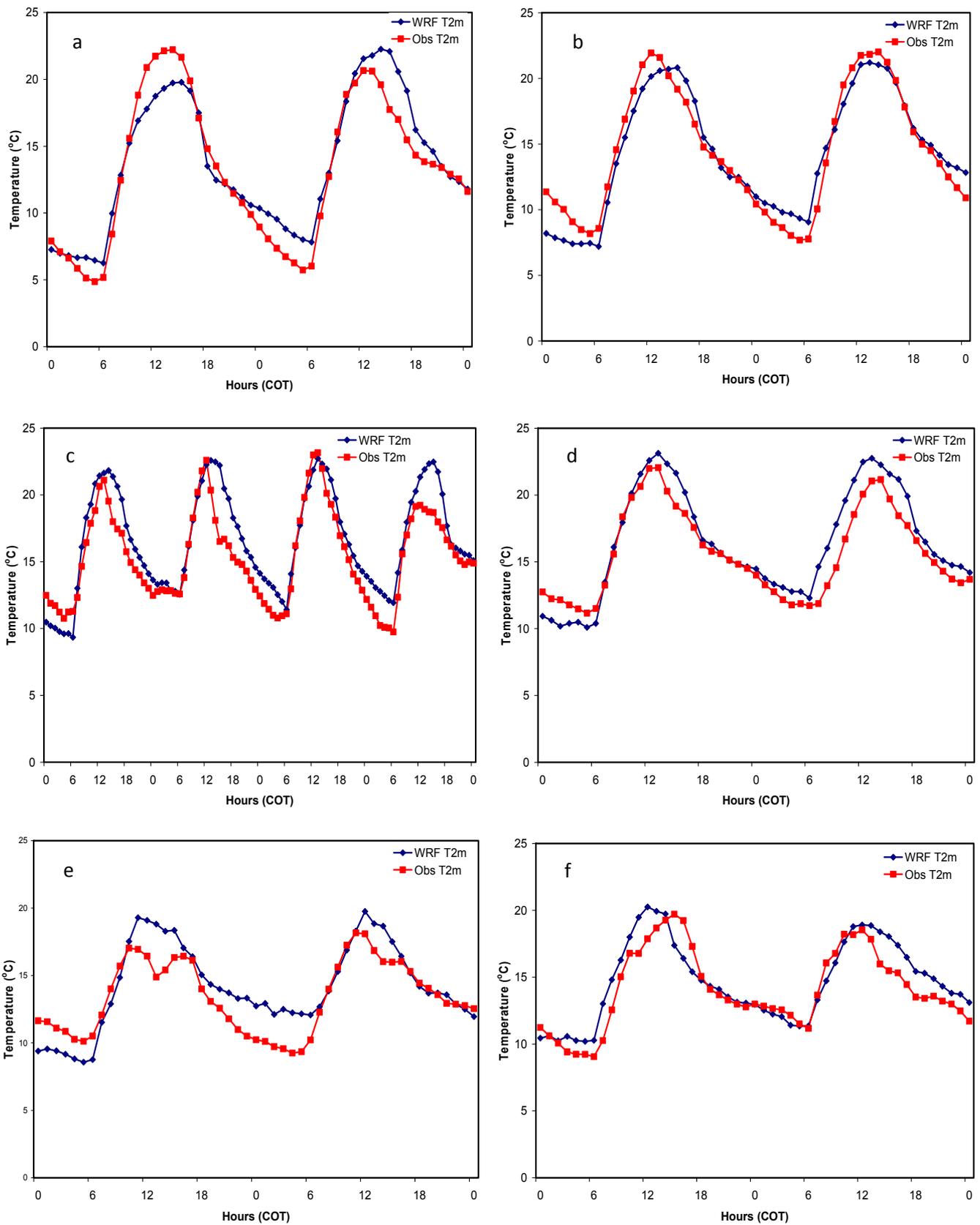
**Fig. 4.** Spatial distribution of 24-h averaged WRF-Chem model (CBMZ scheme) simulated  $PM_{10}$  concentration ( $\mu g m^{-3}$ ) over Bogota for selected  $PM_{10}$  episodes. The left panel represents 04–05 Jan, 13–14 Jan, 15–16 Feb, 17–18 Feb, 12–13 Mar, 29–30 Jul of year 2010 and 09–10 Feb of year 2012 from the top down. Similarly, the right panel represents 05–06 Jan, 14–15 Jan, 16–17 Feb, 18–19 Feb, 13–14 Mar, 30–31 Jul of year 2010 and 10–11 Feb of year 2012 from the top down.



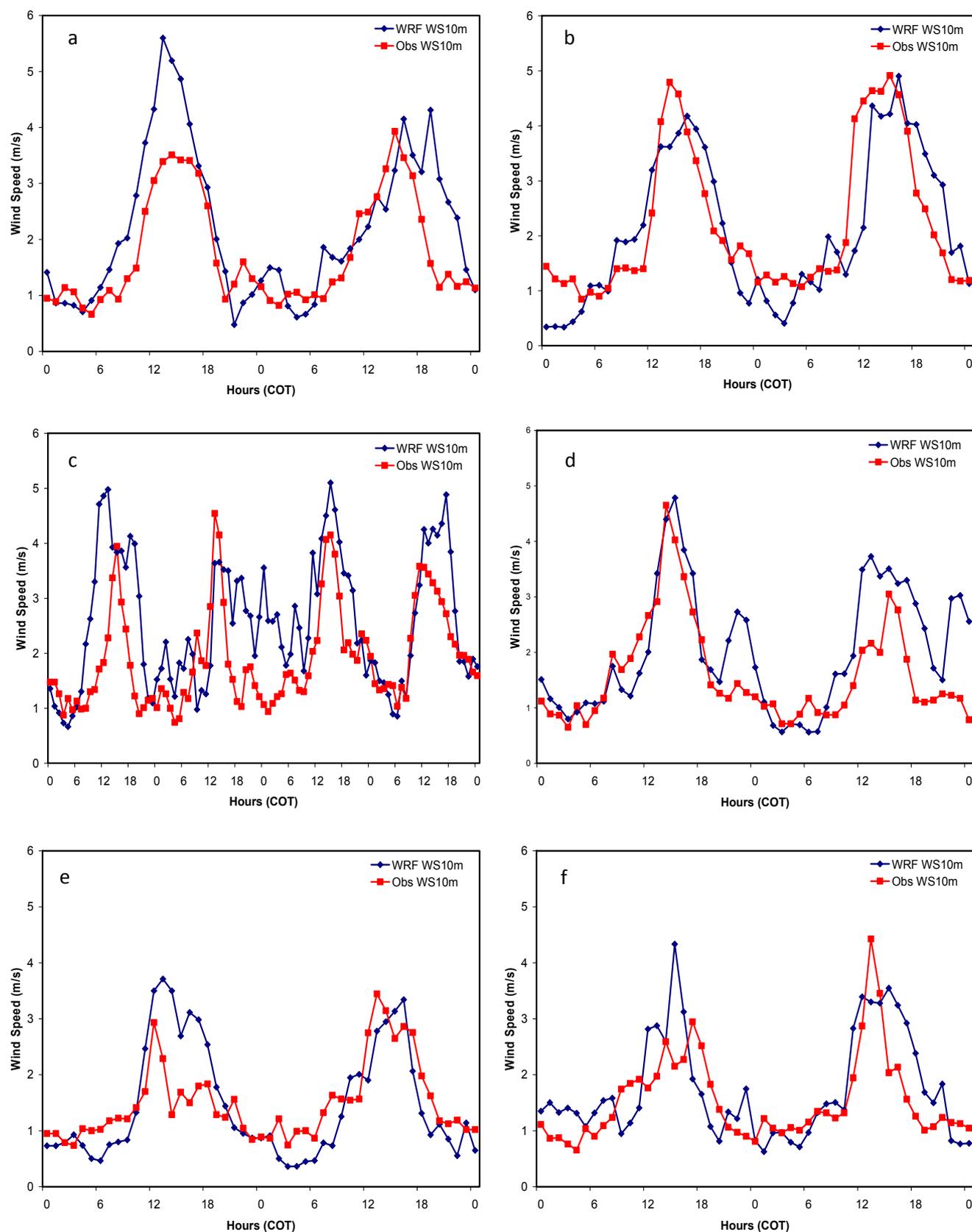
**Fig. 4.** (continued).

anthropogenic and biogenic emissions of PM precursors, which depend on meteorological predictions; uncertainties in emissions and chemistry over different locations (e.g., rural, urban, suburban), meteorological factors which can influence concentrations (e.g., T<sub>2</sub>, radiation for photochemistry and PBL height), biases in cloud properties and precipitation which influence formation of PM components and their wet deposition, as well as the different properties of the sites from different sampling and measurement networks. There is also a need to improve meteorological forecasts, especially large errors in the predictions of wind speeds. Wind is an important factor in driving the transport of pollutants and also affects other processes such as dry deposition. Errors in wind speeds and wind directions can

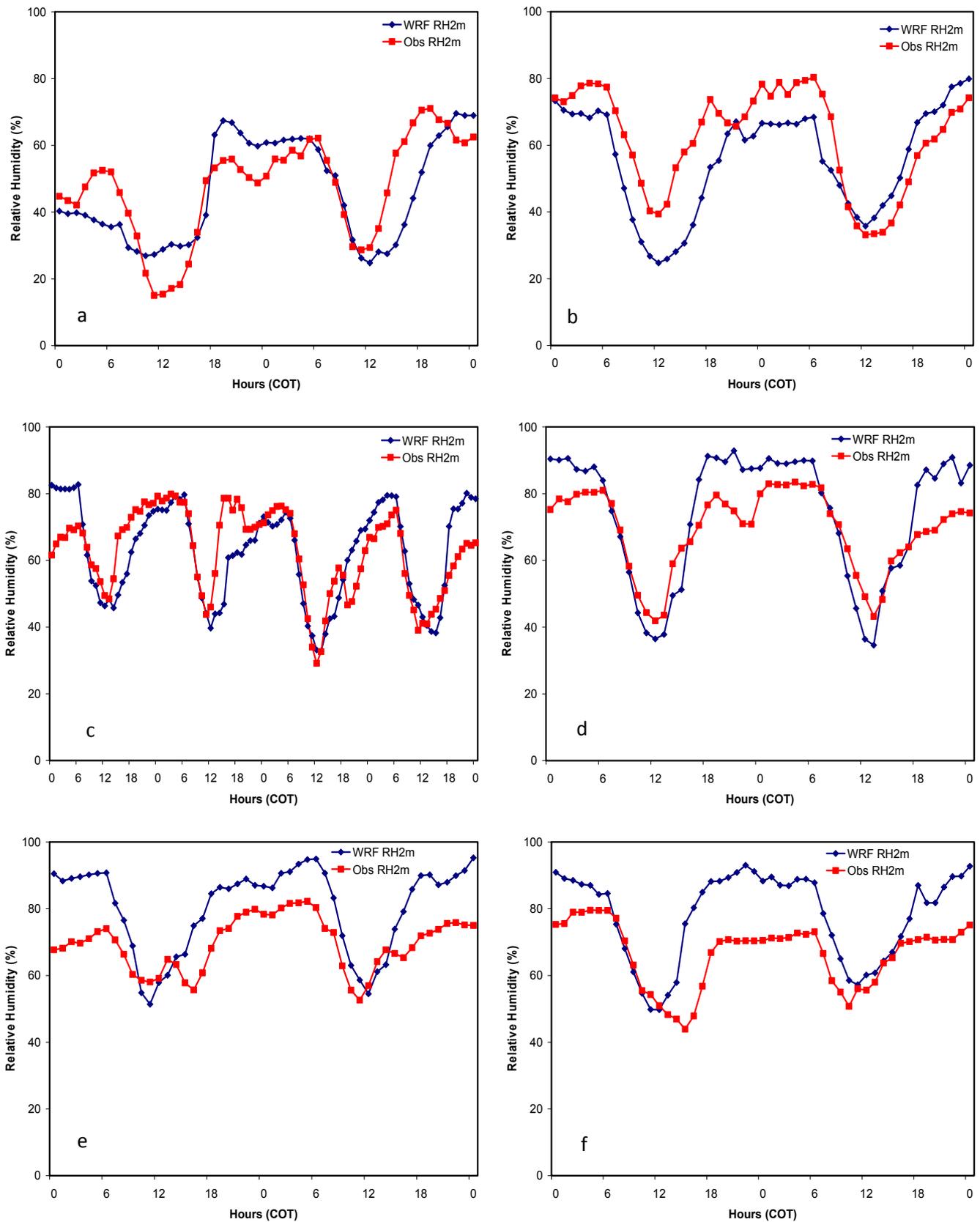
lead to poor representations of transport and mixing. The formation of clouds affects precipitation, which directly affects the wet scavenging of pollutants by cloud/rain drops and subsequent wet deposition. The changes in meteorology could in turn feed into the photolytic reactions. One way to improve such simulations would be to use the inclusion of better emission rates of primary PM and precursors of secondary PM, as well as the inclusion of data assimilation techniques. Accurate emissions are also essential to improve air quality simulations. Continuous real-time emissions that feed into the models are ideal; however, this may not be feasible. Errors may arise in the estimates of anthropogenic and biogenic emissions, which should be minimized.



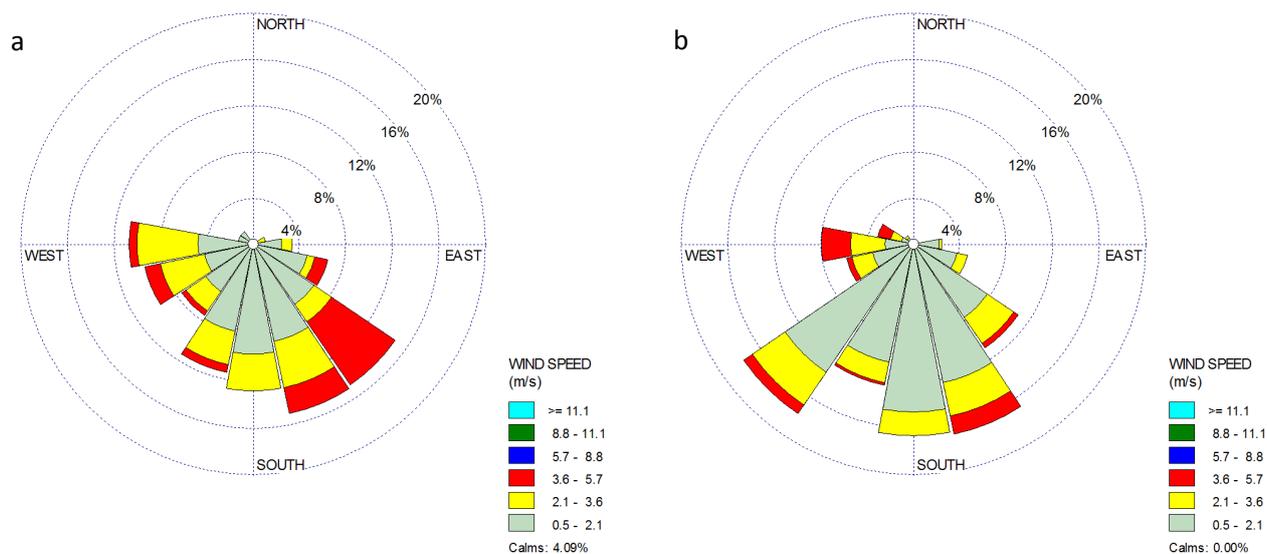
**Fig. 5.** Comparison of hourly time series between WRF-Chem model (RADM2 scheme) and observed temperature (°C) averaged over all the monitoring stations from 00 COT of (a) 04–06 Jan (b) 13–15 Jan (c) 15–19 Feb (d) 12–14 Mar (e) 29–31 Jul of year 2010 and (f) 09–11 Feb of year 2012.



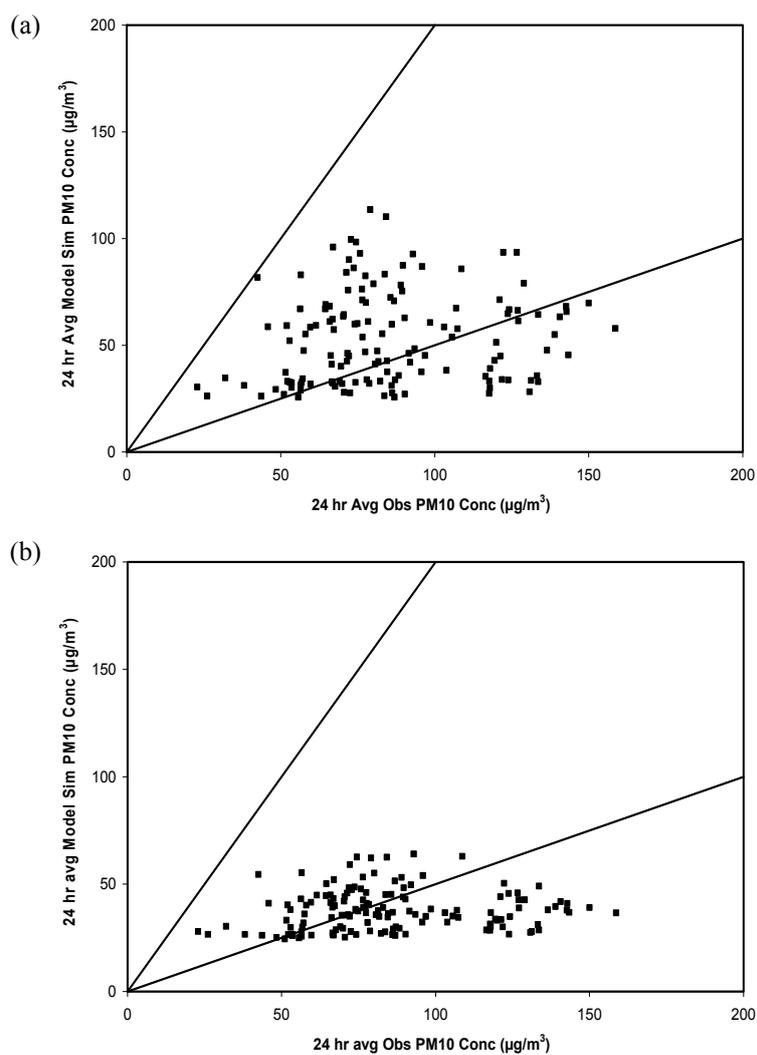
**Fig. 6.** Comparison of hourly time series between WRF-Chem model (RADM2 scheme) and observed wind speed ( $\text{m s}^{-1}$ ) averaged over all the monitoring stations from 00 COT of (a) 04–06 Jan (b) 13–15 Jan (c) 15–19 Feb (d) 12–14 Mar (e) 29–31 Jul of year 2010 and (f) 09–11 Feb of year 2012.



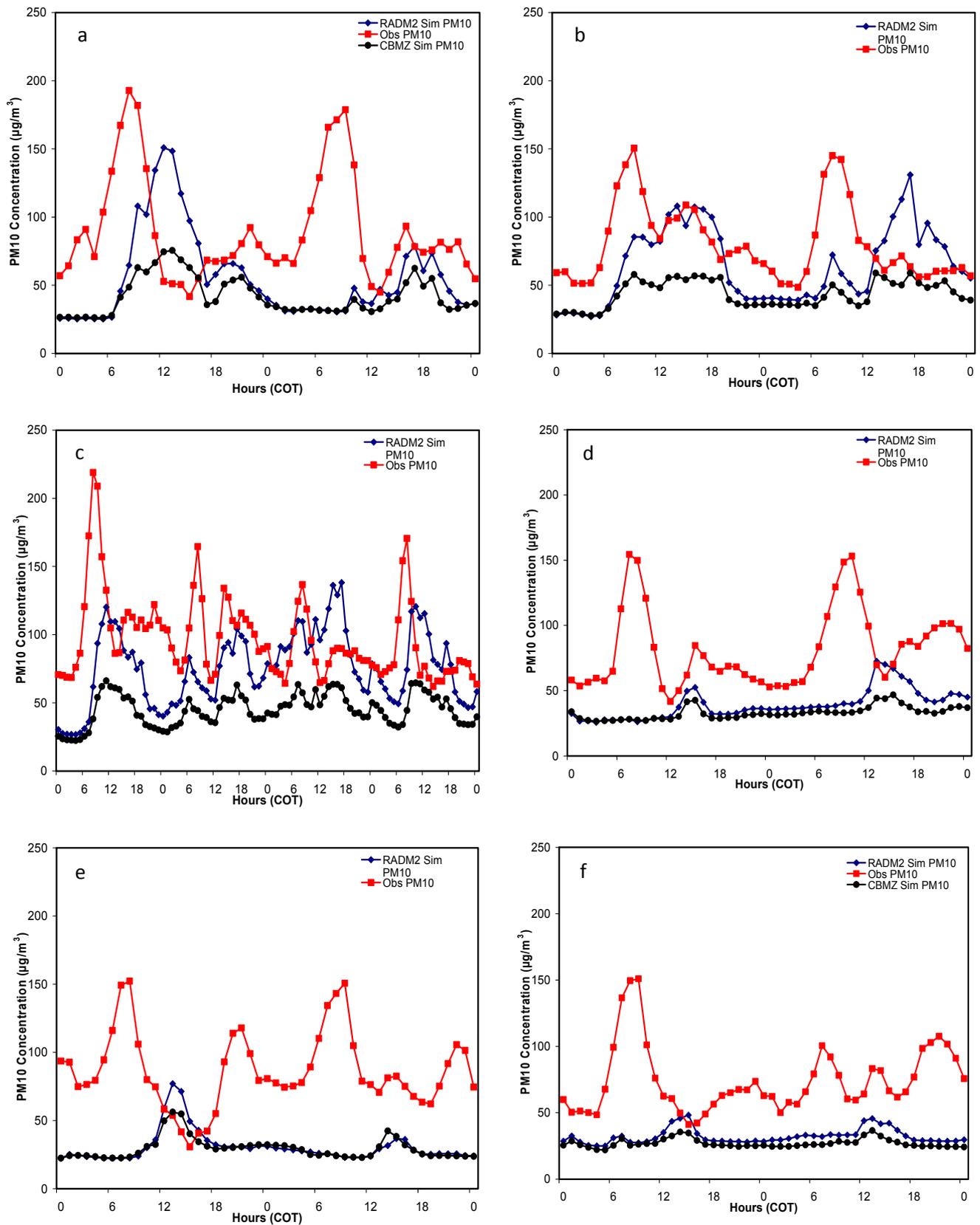
**Fig. 7.** Comparison of hourly time series between WRF-Chem (RADM2) and observed relative humidity (%) averaged over all the monitoring stations from 00 COT of (a) 04–06 Jan (b) 13–15 Jan (c) 15–19 Feb (d) 12–14 Mar (e) 29–31 Jul of year 2010 and (f) 09–11 Feb of year 2012.



**Fig. 8.** Comparison of wind rose plots of (a) WRF-Chem model (RADM2) and (b) observation over all the monitoring stations during the study episodes



**Fig. 9.** Scatter plot between 24-h average model simulated and observed  $PM_{10}$  concentration for (a) RADM2 and (b) CBMZ gas phase chemistry for all monitored stations during selected  $PM_{10}$  episodes



**Fig. 10.** Comparison of hourly time series between WRF-Chem (RADM2 and CBMZ schemes) and observed PM<sub>10</sub> concentration averaged over all the monitoring stations from 00 COT of (a) 04–06 Jan (b) 13–15 Jan (c) 15–19 Feb (d) 12–14 Mar (e) 29–31 Jul of year 2010 and (f) 09–11 Feb of year 2012.

## ACKNOWLEDGEMENTS

The present study is a part of research project “Adaptation of an Eulerian mesoscale weather and air quality modeling system to the CAR jurisdiction” funded by Regional Environmental Agency of Cundinamarca (CAR, Spanish acronym), Government of Colombia. The authors also acknowledge *Secretaría Distrital de Ambiente*, the Environmental agency of Bogota, for providing the observed meteorological parameters. We thank WRF-Chem developers for making the model available to the scientific community.

## SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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*Received for review, May 14, 2015*

*Revised, September 3, 2015*

*Accepted, October 12, 2015*