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URBAN AIR QUALITY, CLIMATE AND POLLUTION: FROM MEASUREMENT TO MODELING APPLICATIONS

Validation of PM_{10} and $PM_{2.5}$ early alert in Bogotá, Colombia, through the modeling software WRF-CHEM

Alejandro Casallas[1] · Nathalia Celis[1] · Camilo Ferro[1] · Ellie López Barrera[2] · Carlos Peña[3] · John Corredor[4] · Miguel Ballen Segura[1]

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Abstract

Air quality data from Bogotá, Colombia, show high levels of *particulate matter* (PM), which often generate respiratory problems to the population and a high economic cost to the government. Since 2016, air quality in the city of Bogotá has been measured through the *Bogota Air Quality Index* (IBOCA) which works as an indicator of environmental risk due to air pollution. However, available technological tools in Bogotá are not enough to generate early alerts due to PM_{10} and $PM_{2.5}$. Currently, alerts are only announced once the measured PM values exceed a certain standard (e.g., 37 μ g/m^3), but not with enough anticipation to efficiently protect the population. It is necessary to develop an early air quality alert in Bogotá, in order to provide information that improves risk management protocols in the capital district. The purpose of this investigation is to validate the *corrective alert* presented on the 14th and 15th of February of 2019, through the WRF-Chem model under different weather conditions, using three different setups of the model to simulate PM_{10} and $PM_{2.5}$ concentrations during two different climatic seasons and different resolutions. The results of this article generate a validation of two configurations of the model that can be used for the Environmental Secretary of the District (SDA) forecasts in Bogotá, Colombia, in order to contribute to the prediction of pollution events produced by PM_{10} and $PM_{2.5}$ as a tool for an *early alert system* (EAS) at least 24 h in advance.

Keywords Air quality modeling · WRF-CHEM · PM_{10} · $PM_{2.5}$ · Early alert system (EAS)

Introduction

Latin American cities like Bogotá face environmental problems related to air quality, mainly due to *particulate matter (PM)*. Additionally, the Colombian capital does not have an air quality prediction system. Instead, it presents real-time PM readings. The above reflects the lack of an *early alert system (EAS)* for air quality. In Bogotá, the concern for air quality began in the 1960s when particulate matter and sulfur dioxide began to be monitored with five stations (SDA 2011). In the 1980s, efforts were focused on establishing the relationship between air pollution levels and cases of respiratory diseases through the Air Quality Information System (SICA) (SDA 2011). In the 1990s, the Japan International Cooperation Agency and the *Secretary of Environment of the District of Bogotá (SDA)* determined air quality, meteorology, and sources of pollution in Bogotá, to establish guidelines on the development of air pollution control policies (SA 1992).

These studies were initiated in 1997, with the creation of the *Air Quality Monitoring Network (RMCAB)*, initially with five fixed and two mobile stations, to monitor *total particulate matter (PST)*, particulate matter smaller than 10 microns (PM_{10}), particulate matter smaller than 2.5 microns ($PM_{2.5}$), ozone (O_3), nitrogen oxides (NOx), and carbon monoxide (CO). RMCAB was designed in three phases, with a total of 32 stations for monitoring air pollutants and meteorological variables in different strategic points of the city (ELIOVAC 1996). However, in 2019, the RMCAB only has 12 fixed stations and a mobile station that generates information in real time. The data are managed by the SDA and reviewed and validated by the *Institute of Hydrology,*

Responsible Editor: Gerhard Lammel

✉ Alejandro Casallas
alejandro.casallas@correo.usa.edu.co

Extended author information available on the last page of the article

Meteorology and Environmental Studies (IDEAM) (SDA 2019).

Since 2005, the academic sector has presented different air quality studies in Bogotá, reporting inventories of industrial and vehicular sources which generate atmospheric emissions (Behrentz et al. 2006), characterizing the particulate material chemically, modeling receptors of the Colombian capital (Behrentz et al. 2008), and analyzing the concentrations reported by the RMCAB (Gaitán et al. 2007). These studies show that pollution by particulate matter in the city has increased, due to the economic growth of the city and the lack of effective measures to control emissions caused by fixed and mobile sources (e.g., Rojas and Galvis 2005; Vargas and Rojas 2010; Méndez Espinosa et al.2017).

The air quality reports generated by the SDA, based on the information reported in the *Air Quality Surveillance System*, determine that, for the city of Bogotá, the monitoring stations that report PM pollution above the maximum limits set by regulations are located in the southwest, which is explained by the topography and weather conditions of the region associated with the dry season (IDEAM 2018). This demonstrates the need to analyze, in urban areas of Bogotá, the $PM_{2.5}$ and PM_{10}, because it has been linked to harmful effects on public health (Ortíz Durán and Rojas Roa 2013; Park et al. 2012), as a result of the high content of toxic compounds (Gao and Ji 2018) and their easy entry into the respiratory system, interacting directly with the pulmonary alveoli (Franceschi et al. 2018). Likewise, multiple studies have reported that air pollution due to $PM_{2.5}$ can generate cardiovascular diseases (Maji et al. 2018) and neuro-degenerative diseases (Shou et al. 2019) which may imply a significant economic burden to public health systems.

In order to predict pollution events and design prevention strategies based on the behavior of the PM in Bogotá, some statistical and physical simulations have been developed based on the data reported by the RMCAB. For statistical simulations, forecast combination techniques with linear regression methods have been used, making combinations setups such as "smoothed" Bayesian information criterion (SBIC), "smoothed" Akaike information criterion (SAIC), and Granger and Ramanathan (1984, GR) (Westerlund et al. 2014). Physical simulations have been developed using the connection between a meteorological model (WRF) and a chemical model (chemistry transport model), and this coupling can generate inconsistencies in the results because of the way in which each model works (Longo et al. 2013). That is why in recent years, the WRF-CHEM model has been used, which numerically solves the equations of conservation of mass, energy, and momentum and also integrates the chemical component of the atmosphere. Therefore, the WRF-CHEM model has been used in Bogotá by Kumar et al. (2016) and González et al. (2018) and Powers et al. (2017), demonstrating that the model manages to predict the atmospheric and chemical conditions of Bogotá with good accuracy.

Since 2016, air quality in the city has been measured through IBOCA, which functions as an environmental risk indicator for air pollution connected to the *District Alert System* of the *District Risk Management System and Climate Change* and *The Comprehensive System of Air Quality Modeling of Bogotá*(SIMCAB) (SDA 2019). However, even with these technological tools, access to consultation is not possible, and early alerts of contamination risk due to PM_{10} and $PM_{2.5}$ are not generated in the city. This is shown by the corrective alert (*orange*) that was declared in the southwest of the city, on February 14th and 15th of 2019 for $PM_{2.5}$, in which measures were taken once the reported values exceeded the daily standards and mitigation strategies were set such as the license plate environmental restriction which limited the use of private vehicles in the city.

This problem indicates the need to develop EAS in Bogotá in order to provide information that improves risk management protocols in the capital district. The purpose of this manuscript is to validate the WRF-CHEM model on days where an orange air quality alert was present in Bogotá due to PM_{10} and $PM_{2.5}$. Additionally, during two climatic seasons (dry and wet) and with different resolutions, the model is validated. In order to develop a comprehensive analysis of the model under different weather conditions and identifying parameters to adjust the model. The contents of this paper are presented below. In the "Methodology" section, a general description of the proposed methodology is presented. In the "Results and discussions" section, the results and discussions are presented. In the "Conclusions" and "Future work" sections, the conclusions and the future work close the paper.

Methodology

WRF-CHEM

The WRF-CHEM model is based on WRF and has a chemical model of the atmosphere attached (Grell et al. 2005; Fast et al. 2006). The WRF-CHEM is a non-hydrostatic numerical prediction system widely used for atmospheric studies of climate and emissions prediction. It was developed by the NOAA/ESRL (National Oceanic and Atmospheric Administration/Earth System Research Laboratory) and allows modeling air pollutants considering the topography of the study area (González Duque 2017; Grell et al. 2004; Grell and Baklanov 2011; Baklanov et al. 2014; Skamarock et al.2008).

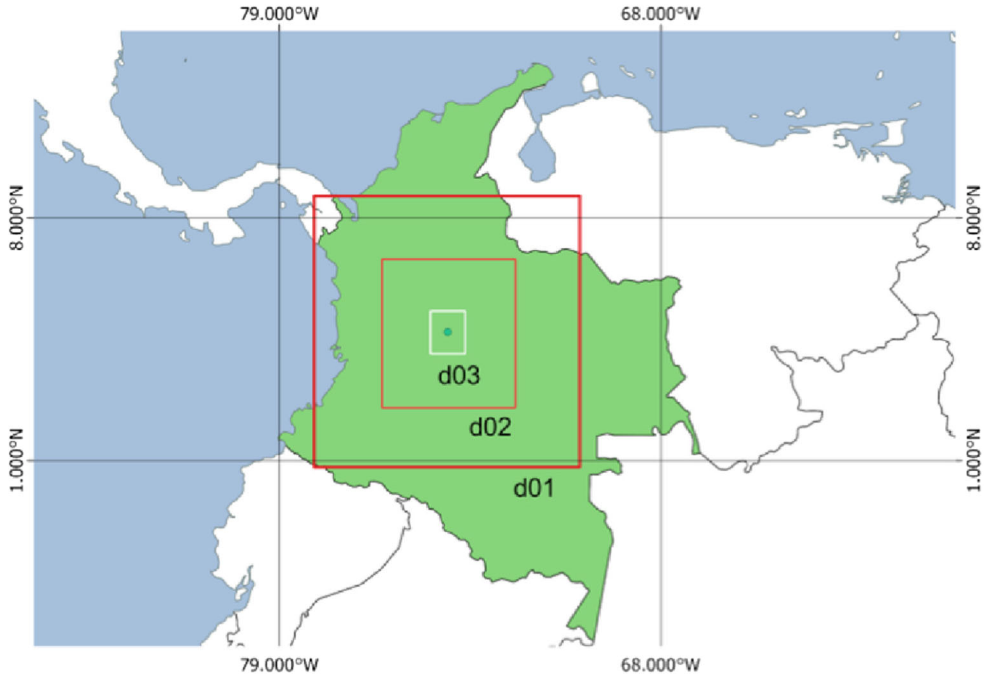


Fig. 1 Configuration of the WRF-Chem model domains

Initial conditions

In this article, the emission data reported by Emission Database for Global Atmospheric Research (EDGAR-HTAP) are used and, therefore, the EDGAR estimations are considered with the chemical reactions that the database offers (Olivier et al. 2005). The input data are from RMCAB along with the data from EDGAR-HTAP global inventory (due to the low number of monitoring stations available for the study). The meteorological entry data are from GFS (Global Forecast System) with the resolution of 1° (National Oceanic and Atmospheric Administration 2018). For the above, a downscaling is made, in which the resolution of the global model is incremented, the chemical part is integrated, and the topographical data is improved. The topography is improved using the data base created by IDEAM and the Instituto Geográfico Agustín Codazzi (IGAC)[1].

Episode selection and experimental design

The simulation is presented in 3 nested domains (Fig. 1) centered in El Dorado airport (4.705° and -74.150°). The first domain uses a grid of 15 km × 15 km for low resolution, and a grid of 4.5 km × 4.5 km for high resolution; the domain spans all of Colombia and a part of Venezuela and Panama. The second domain has a grid of 5 km × 5 km for low resolution, and a grid of 1.5 km × 1.5 km for high resolution: this domain spans over Cundinamarca and therefore, Bogotá. The third domain covers all of Bogotá, has a grid of 1.67 km × 1.67 km for the low-resolution model, and a grid of 0.5 km × 0.5 km for high resolution. It is important to emphasize that to select the domains, the specifications of Skamarock et al. (2008) are taken into account.

For the data of *land water and land*, the US Geological Survey (USGS) (NCEP-DSSI, 2005) is used. In addition to this, the GFS model has 35 vertical layers, which comprise the entirety of the troposphere. The initial and boundary data are taken from the GFS with 1° a temporal resolution of 6 h (National Oceanic and Atmospheric Administration 2018). The simulations with 1.67 km are run with a time frame of 90 s and the simulations of 0.5 km are run with a time frame of 20 s.

The simulations were made for 2 days (from February 14th 00:00:00 UTZ to February 16th 00:00:00 UTZ, 2019), dates in which there are contamination incidents in dry season, and 2 days in wet season (from November 22nd 00:00:00 UTZ to November 24th 00:00:00 UTZ, 2018) in which there were not any contamination incidents, in order to prove if the model works in different climate seasons and for days with high and low PM concentrations. The dry season days are chosen because there was an orange alert in the southwest of Bogotá, and the environmental and public health authorities took prevention and correction measures, while the days in November are chosen because it was wet season and there were not any alerts.

[1] IGAC: Entity in charge of producing the official map and basic cartography of Colombia; one of its roles is to produce, research, regulate, make available, and publish the geographic, cartographic, agrological, cadastral, geodesic, and geospatial technological information

Model setups

Three different setups of the WRF-CHEM model are used in this work:

Model A: (Kumar et al. 2016) Physics parametrizations have been used. Resolution of 1.67 km (see Fig. 1 d03). In microphysics, the moment schemes 3-class and 5-class are used (Hong et al. 2004). The *Kain − FRITSCH* scheme is used to parametrize the cumuli (Kain 2004). The planetary boundary layer (PBL) is resolved through YSU scheme (Hong et al. 2006). For shortwave radiation the Dudhia Shortwave Scheme is used Dudhia (1989) and, for longwave radiation the Rapid Radiative Transfer Model (RRTM) (Mlawer et al. 1997) is used.

Model B: Executed with a resolution of 0.5 km (see Fig. 1 d03) using Ferrier microphysics because it improve the representation of distribution of raindrops in the tropics (Schoenberg Ferrier 1994). A different scheme is used to test its performance; for this, the cumuli are resolved by the Grell 3D Ensemble Scheme (Grell and Devenyi 2002) (used in Gilliland and Rowe 2007). Radiation schemes are the same used by Kumar et al. (2016): Dudhia Shortwave Scheme is used Dudhia (1989) for shortwave radiation, and RRTM is used Mlawer et al. (1997) for the longwave radiation. Finally, the model is allowed to explicitly solve the PBL equations given by the high resolution of the third domain (see Fig. 1 d03).

Model C: The resolution of the simulation is 1.67 km (domain 3) with Thompson's microphysics (Thompson et al. 2008) because it was tested for the tropics by Hernandez-Deckers and Sherwood (2016) obtaining satisfactory results. From the behavior of cumuli in Model A, the *Kain − FRITSCH* scheme is used Kain (2004). For complex topographies, the BouLac scheme for PBL parametrization is used (Bougeault and Lacarrere 1989). Dudhia Shortwave Scheme is used Dudhia (1989) for shortwave and RRTM (Mlawer et al. 1997) for long wave as explained in previous model.

For the three setups, the same initial conditions are used (see the section above). Different climatic seasons are compared: dry season (February 14 to 15, 2019) and wet season (November 22 to 23, 2018), and additionally the chemical settings proposed by Kumar et al. (2016) are used.

Air quality stations used to validate the models

Bogotá, the capital of Colombia, is the area where it is required to validate the models. Figure 2 shows the geographical location of the 6 stations analyzed.

Validation of the alert and the AQI

To validate the early alert, two articles of the Resolution 2254 of 2017 are mentioned. The first one consists in defining the alert according to a concentration range, and the second one uses the Air Quality Index (AQI). AQI has a dimensionless value and it is used to report the state of the air quality depending on a color code linked to health effects (SDA 2019). Equation 1 is used in order to obtain the AQI values, which utilizes the cut points and indices established by the Resolution 2254 of 2017.

$$\frac{\mathbf{AQI} = \mathbf{I}_{High} - \mathbf{I}_{Low}}{\mathbf{C}_{High} - \mathbf{C}_{Low} * (\mathbf{C} - \mathbf{C}_{low}) + \mathbf{I}_{Low}} \quad (1)$$

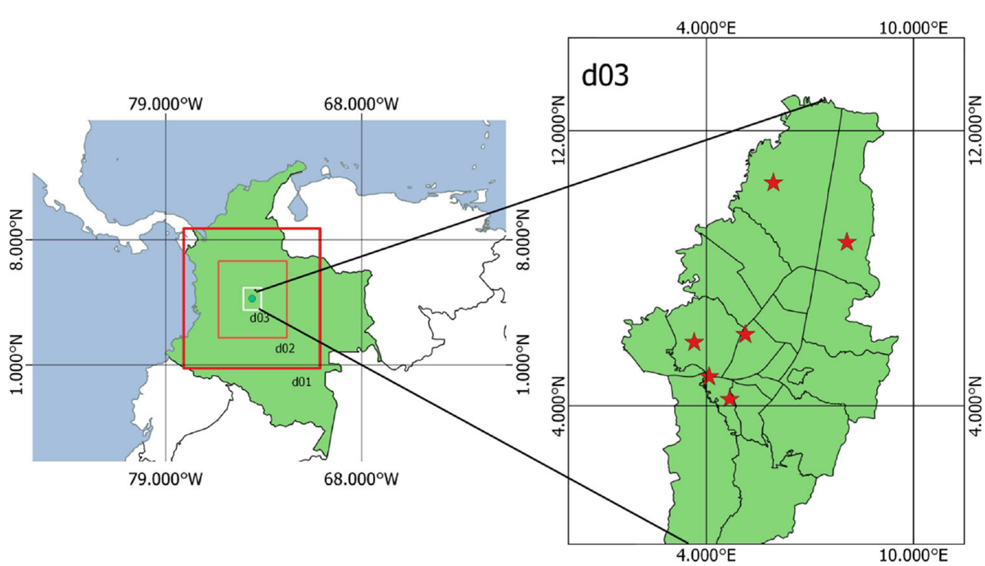


Fig. 2 Geographical location of the 6 stations analyzed in Bogotá, Colombia, Southwest: Carvajal, Kennedy, Tunal; Downtown: Puente Aranda; Northwest: Usaquén; Northwest: Suba. Stations selected for being operational and cover the analysis area appropriately

Equation 1. Calculation of **AQI**, where **C** is the concentration measured for the pollutant. **C** High is the cut point greater than or equal to **C** and **C** Low is the cut point less than or equal to **C**. **I** High is the **AQI** value corresponding to **C** High, and **I** Low to **C** Low.

In order to validate the model throughout the city and with higher precision in the southwest (zone that presents the higher pollutant concentration), the **AQI** values for six (6) stations in Bogotá are calculated. Figure 2 shows the geographical location of the six air quality stations in Bogotá. Three in the southwest (Carvajal, Kennedy, Tunal), one in downtown (Puente Aranda), one in the northeast (Usaquen), and one in the northwest (Suba). The Carvajal station presented orange alert due to $PM_{2.5}$ on February 14th and 15th, and, in general is the station that has had more alerts (IDEAM 2018).

Likewise, **AQI** values were calculated for the model's outputs in the coordinates of each station, to compare **AQI** calculated with the observations versus the one calculated with the different outputs of the model. With the objective of having several criteria to define the validity of the simulations, the following are taken into account: **correlation**, **root-mean-square error (RMSE)**, and **Bias**.

Results and discussions

Model evaluation

In Table 1, model **A** presents better results in dry season (February) in both days for PM_{10}, given by higher correlation and smaller RMSE and Bias. Additionally, in the physical settings the planetary boundary layer may represents a significant role in model **A**, using a non-local closure parameterization, according to González et al. (2018) is better than local closure parameterizations (model **C**). Values on February 14th are verified, in which the correlation is 0.53, and the lowest errors are presented (32.3 and 31.6) for RMSE and Bias. This result is significant to the research, because in that day there was an alert due to $PM_{2.5}$ (the model is adjusted to the alert values) and the model shows that for PM_{10} the observations and the model match (Figs. 5 and 6).

When the results of the models assessed are analyzed, it is evident that model **B** is not very precise in any of the two pollutants modeled (Table 1), because the Grell 3D scheme is used and the convection was explicitly solved, fact that generates an overestimation of the pollutant concentrations due to the values produced by parametrization and to the explicit resolution of convection. It is possible that the cause of the imprecision was also a result of the mentioned condition, along with the static control and the better operation of Grell's scheme for mesoscale (Grell and Devenyi 2002).

On the other hand, when the model **C** results are analyzed, it shows better results of PM_{10} for the wet season, taking into account a 0.65 correlation, while it had a 14.14 RMSE and a Bias of 12.12 for November 22nd (Table 1), while in November 23rd the correlation was better (0.69), but the RMSE (22.72) and the Bias (22.14) were also the smallest (Table 1). The high correlation can be attributed to the more specific microphysics parametrization; the Thompson Scheme contemplates the proportions of the mix of five liquid and ice types (Thompson et al. 2008). In addition to this, the Boulac Scheme recreates accurately the turbulence behavior and as a result, the energy transport in the vertical for areas with complex topography (Bougeault and Lacarrere 1989); therefore, the predictions may have better precision.

In the same way used to determine the PM_{10}, model **A** is also precise to predict the behavior of the $PM_{2.5}$ in the two seasons, having a significant correlation in February 14th (0.58), errors of 43.23 for RMSE and of 35.82 for Bias (Table 1), simulating correctly the alert presented in the southwest of the city for the pollutants during the dry season. However, model **C** has a considerable precision having a significant correlation of 0.83 for February 15th, with a RMSE of

Table 1 Correlation, RMSE, bias for PM_{10} and $PM_{2.5}$ values of models **A, B**, and **C** for February 14th and 15th (2019) and November 22nd and 23rd (2018)

AQI	Dates	Parameter	Model **A**	Model **B**	Model **C**
PM_{10}	February 14th	Correlation	0.53	0.73	0.05
		RMSE	32.3	88.99	43.22
		Bias	31.6	88.69	42.91
	February 15th	Correlation	0.64	0.18	0.66
		RMSE	50.72	89.71	55.86
		Bias	46.87	89.38	53.91
	November	Correlation	0.38	0.64	0.65
		RMSE	29.54	69.01	14.15
		Bias	28.34	68.55	12.12
	November 23rd	Correlation	0.60	0.67	0.69
		RMSE	22.98	179.62	22.71
		Bias	21.65	178.65	22.14
$PM_{2.5}$	February 14th	Correlation	0.58	0.37	0.22
		RMSE	42.23	64.89	46.91
		Bias	35.82	61.39	42.16
	February 15th	Correlation	0.64	0.71	0.83
		RMSE	67.46	69.65	67.44
		Bias	61.67	64.93	61.79
	November 22nd	Correlation	0.34	0.09	0.26
		RMSE	57.44	91.84	27.83
		Bias	54.18	89.92	21.16
	November 23rd	Correlation	0.71	0.68	0.71
		RMSE	34.41	137.83	110.29
		Bias	33.29	137.05	110.06

64.44 and a Bias of 61.79. Therefore, it may be concluded that in the same season, both models (**A** and **C**) validate satisfactorily both PM concentrations. The aftermentioned is possible given that the models (**A** and **C**) use Kain-FRITSCH parametrization, unlike model **B** that uses Grell 3D scheme, suggesting that the convection is possibly determining to simulate the particulate concentrations.

The WRF-CHEM have better results when the resolution is 1.67 km for the two pollutants analyzed. This is illustrated in Figs. 3 and 4, where the PM_{10} and $PM_{2.5}$ emissions during the wet and the dry period are presented. However, there are some differences between the precision of the models analyzed for each pollutant for the periods assessment.

During dry period, model **A** for PM_{10} has high accuracy on February 14th and 15th, but for $PM_{2.5}$ this model is accurate only on February 14th. Model **C** is more precise for February 15th (Fig. 3), and in wet period model **C** is accurate in simulations of PM_{10} on November 22nd and 23rd. Also, model **C** has the best results for $PM_{2.5}$ in November 22nd, but in November 23rd model **A** is more accurate (Fig. 4).

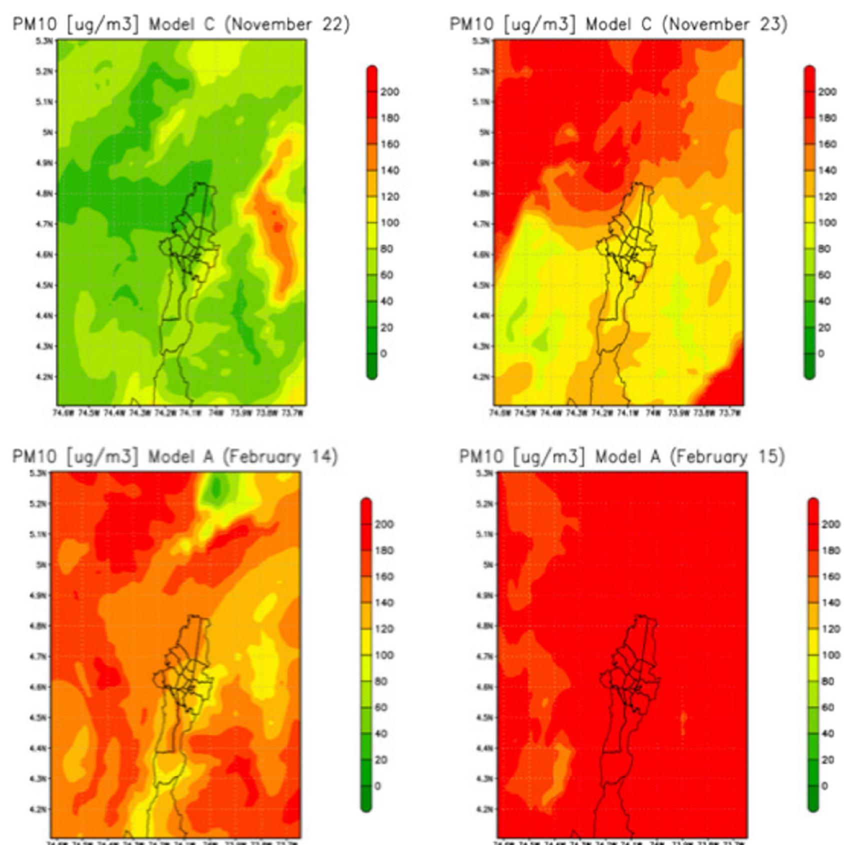
Alert evaluation

AQI is calculated from the model results. The purpose is to evaluate the simulations efficiency to predict alerts due to PM_{10} and $PM_{2.5}$ in the six selected monitoring stations (Figs. 5 and 6). For the PM_{10} during the dry season, model **A** manages to predict the index levels, establishing most of its values in the same range as the observed data (Fig. 5). However, during the wet season, even though models **A** and **C** report very close values, model **C** is more precise. The observed values are recorded at the limit of the first **AQI** range (green), and the simulations are at the beginning of the next range (yellow) (Fig. 5). These results show that, although the observations and simulation have close values of PM_{10}, they are not in the same alert range, since model **C** overestimates the values of **AQI**.

For $PM_{2.5}$ models, **A** and **C** have results of similar concentrations in dry season. The index values calculated with the simulation are not within the alert range in which the index is calculated with the observations found (Fig. 6). The tendency of data in all the stations is maintained; however, the determination of the alert was only possible in the Carvajal station, because the values are overestimated in one or two levels of the alert for the other stations. The former could be explained by the low resolution of the models. That is, the change in concentrations of $PM_{2.5}$ from one station to another is not significant.

During the wet season, there is no trend in which one model performs better than the others in determining the index (Fig. 6). For example, on November 22nd, the most accurate

Fig. 3 Output of third domain for PM_{10}



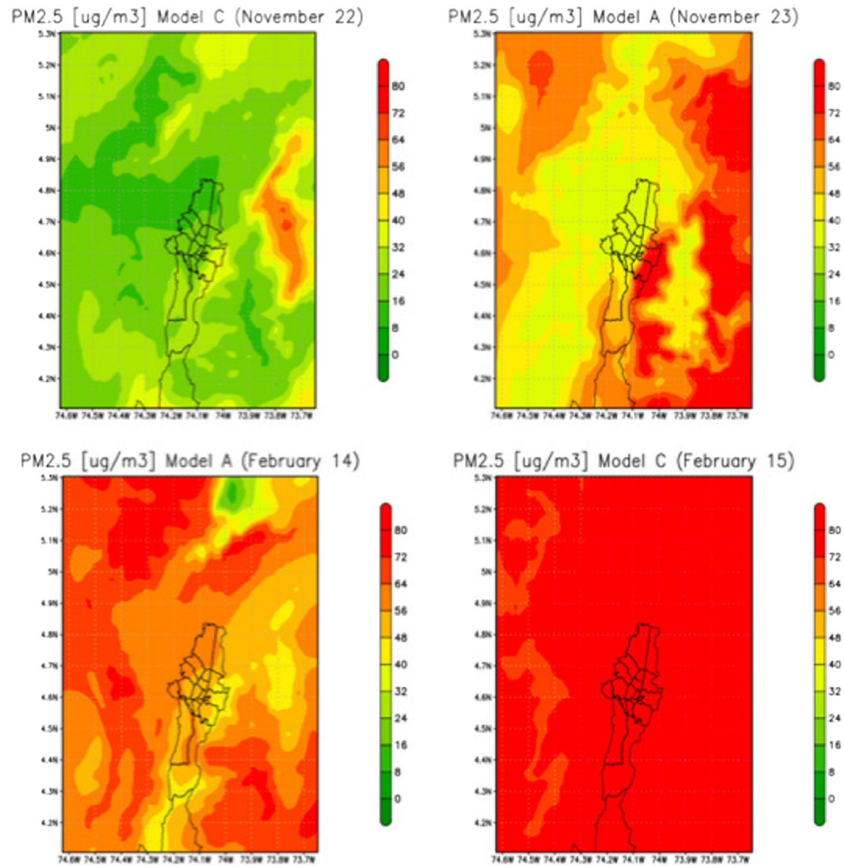


Fig. 4 Output of third domain for $PM_{2.5}$

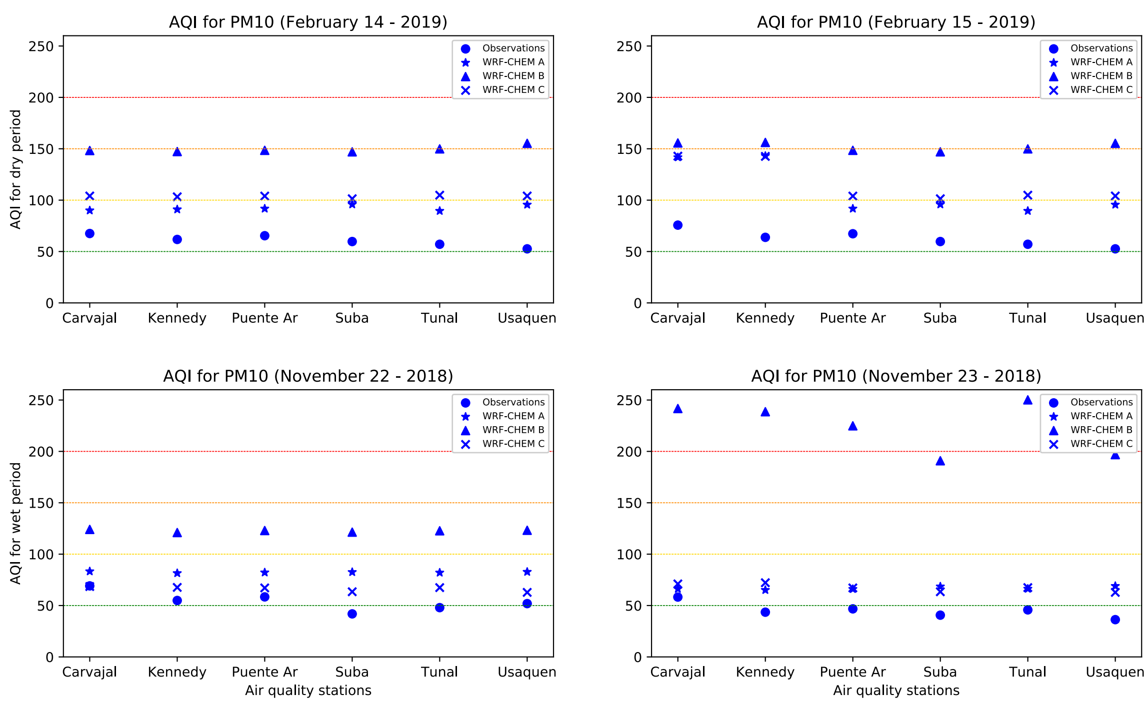


Fig. 5 AQI for PM_{10} of the stations in Carvajal, Kennedy, Puente Aranda, Suba, Tunal and Usaquén. The round points represent the values calculated with the observed concentrations, while the other icons (asterisks, triangles, and X) are the AQI values for models **A**, **B**, and **C** respectively. The horizontal lines represent the alert level (traffic light style) according to **AQI**. Green: moderate; yellow: medium; orange: bad; red: very bad

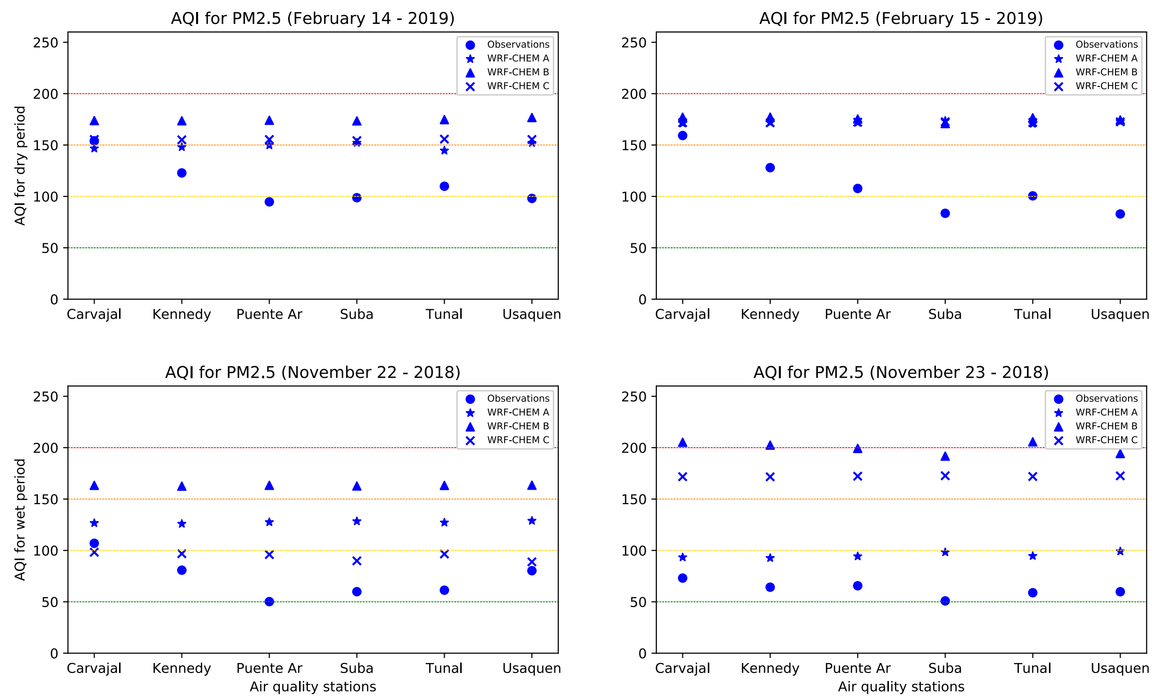


Fig. 6 AQI for $PM_{2.5}$ of the stations in Carvajal, Kennedy, Puente Aranda, Suba, Tunal, and Usaquén. The round points represent the values calculated with the observed concentrations, while the other icons (asterisks, triangles, and X) are the AQI values for models **A**, **B**, and **C** respectively. The horizontal lines represent the alert level (traffic light style) according to **AQI**. Green: moderate; yellow: medium; orange: bad; red: very bad

model is **C**. The simulation maintains the trend of the observed data and the index is in the same range. On the other hand, on November 23rd, model **A** manages to recreate the trend and keep the values of the alert range. This behavior is attributed to the atmospheric behaviors that were presented during those dates and which influenced the simulation under these parameters.

Air quality administration in Bogotá

According to SDA data, between 2012 and 2017, the concentrations of PM_{10} and $PM_{2.5}$ have been reduced due to district management strategies such as: (1) integrated management of public transportation and motor vehicle park technology; (2) monitoring and controlling atmospheric emissions of pollutants in the industry; and (3) the increase in the restriction of private cars and public service in the city (SDA 2019). At a regulatory level, Decree 595 of 2015 formalizes the Bogotá Environmental Early Alert System for its air component (SATAB-air) which activates the district action protocol for air pollution alerts in Bogotá. These standards establish the actions to be followed by the entities in charge of risk management, during the development of yellow, orange and red alert situations according to IBOCA index. It should be noted that SATAB-air has real-time information, i.e., the system does not offer a forecast of at least 24 h.

A direct relationship between changes in meteorological variables and PM concentrations has been demonstrated (Jacob and Winner 2009; von Schneidemesser et al. 2015), due to the increase in the average temperature of the atmosphere. The aftermentioned may increase the availability of air pollutants and the risk of contamination to which Bogotá's citizens are exposed. The Colombian government does not have enough strategies in order to reduce or predict the PM.

Policy makers should understand current air quality behavior and future trends, to identify problems, guide policies, and monitor their effectiveness. However, that depends on the monitoring, forecasting, and reporting of air pollution together with emission source regulation strategies. Some of the challenges associated with the design of these early alert systems include technical problems associated with the complexity of air pollution and the installed capacity in Bogotá's current monitoring network. The results of this article generate a validation of models that can be connected to the SDA forecasts, contributing to the predictions of pollution events produced by PM_{10} and $PM_{2.5}$ as a tool for an early alert at least 24 h in advance.

Likewise, the communication of information to society through mobile devices, such as cell phones, equipped with detection applications is essential. The proposed detection applications shall provide dynamic, temporary, and spatially accurate exposure measures, which may contribute to the monitoring and the quality of the reported data, allowing to initiate early alerts. This type of information allows citizens to generate self-management mechanisms, which may include modification of behaviors in a way that protects their health, such as changing the route/mode of transport or decide the right time to perform outdoor activities.

Conclusions

The behavior of PM_{10} is significantly predicted by model **A** (dry season) and by model **C** (wet season). The possible cause of the observed PM_{10} behavior may be the parametrization of PBL and microphysics.

The $PM_{2.5}$ behavior, in model **A** and model **C**, simulates the trend of the observations but overestimates the values of the pollutant. However, they may be used as a tool for the creation of an EAS given by the significant correlation, even if the RMSE and the Bias are not significant.

Models **A** and **C** successfully predict PM_{10} and $PM_{2.5}$ concentrations while model **B** does not. This may be caused by the parametrization used for convection, which would indicate that this parameter is vital for the prediction of air pollutants.

The errors of models **A** and **C** may have been generated by the emissions inventory. The EDGAR-HTAP (Janssens-Maenhout et al. 2012) emissions inventory for this region has low resolution. In order to improve the results, it is necessary to use a local emission inventory.

The results of this research provide relevant information for the generation of early air quality alerts (EAQA) in the city of Bogotá, in order to guarantee the performance of the strategies of the Ten-Year Air Decontamination Plan for Bogotá and the National Policy for the improvement of air quality (CONPES 2018).

The validation of the model in this work establishes the basis for the implementation of an *air quality prediction system* (PM_{10} and $PM_{2.5}$) by the governmental entities of the city of Bogotá of at least 24 h in advanced. Access to this information allows citizens to manage risk and socialize government efforts to improve the environmental quality of the capital of Colombia.

Future work

It is planned to use high-performance computing (HPC) in order to simulate with higher resolution. Additionally, variables such as ozone will be incorporated in the study; in this way, it is possible to compare the information of early air quality alerts with different behaviors recorded in the city of Bogotá.

According to the results obtained, it is necessary to carry out a study to find out which are the parameters that have the greatest impact on the particulate matter. Although this article has preliminary results on the importance of convection and PBL, it is necessary to deepen more and perform idealized simulations that enable the determination of relation of causation between the different variables and the PM, in order to better understand their behavior and improve the alert and prediction systems.

Additionally, the use of artificial intelligence techniques (Neural Networks and Support Vector Machines) is planned, to improve the prediction of pollutants using RMCAB data for the city of Bogotá, Colombia.

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Affiliations

Alejandro Casallas[1] · Nathalia Celis[1] · Camilo Ferro[1] · Ellie López Barrera[2] · Carlos Peña[3] · John Corredor[4] · Miguel Ballen Segura[1]

Nathalia Celis
nathalia.celis@correo.usa.edu.co

Camilo Ferro
camilo.ferro@correo.usa.edu.co

Ellie López Barrera
ellie.lopez@usa.edu.co

Carlos Peña
carlos.pena@usa.edu.co

John Corredor
john.corredor@usa.edu.co

Miguel Ballen Segura
miguel.ballen@usa.edu.co

[1] School of Exact Sciences and Engineering-ECEI, Environmental Engineering, Universidad Sergio Arboleda, Bogotá, Colombia

[2] Institute of Environmental Studies and Services IDEASA, Universidad Sergio Arboleda, Bogotá, Colombia

[3] School of Exact Sciences and Engineering-ECEI, Mathematics, Universidad Sergio Arboleda, Bogotá, Colombia

[4] School of Exact Sciences and Engineering-ECEI, System Engineering, Universidad Sergio Arboleda, Bogotá, Colombia